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Review

Antimicrobial Nanomaterials as Advanced Coatings for Self-Sanitizing of Textile Clothing and Personal Protective Equipment

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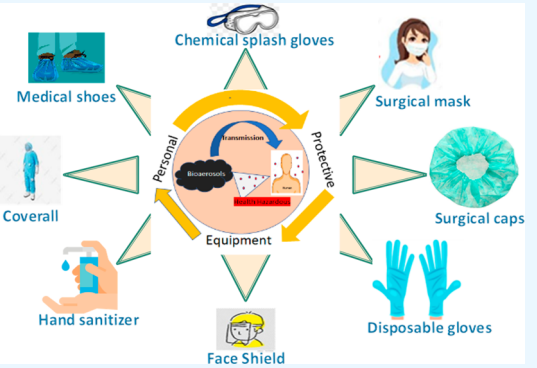
ABSTRACT: Controlling bioaerosols has become increasingly critical in affecting human health. Natural product treatment in the nano form is a potential method since it has lower toxicity than inorganic nanomaterials like silver nanoparticles. This research is important for the creation of a bioaerosol control system that is effective. Nanoparticles (NPs) are gradually being employed to use bacteria as a nonantibiotic substitute for treating bacterial infections. The present study looks at nanoparticles' antimicrobial properties, their method of action, their impact on drug-opposing bacteria, and the hazards connected with their operation as antimicrobial agents. The aspects that influence nanoparticle conduct in clinical settings, as well as their distinctive features and mode of action as antibacterial assistants, are thoroughly examined. Nanoparticles' action on bacterial cells is presently accepted by way of the introduction of oxidative stress induction, metal-ion release, and nonoxidative methods. Because many concurrent mechanisms of action against germs would necessitate multiple simultaneous gene modifications in the same bacterial cell for antibacterial protection to evolve, bacterial cells developing resistance to NPs is difficult. This review discusses the antimicrobial function of NPs against microbes and presents a comprehensive discussion of the bioaerosols: their origin, hazards, and their prevention. This state of the art method is dependent upon the use of personal protective gear against these bioaerosols. The benefit of the utmost significant categories of metal nanoparticles as antibacterial agents is given important consideration. The novelty of this review depends upon the antimicrobial properties of (a) silver (Ag), (b) zinc oxide (ZnO), and (c) copper oxide (CuO) nanoparticles. The value-added features of these nanoparticles are discussed, as well as their physicochemical characterization and pharmacokinetics, including the toxicological danger they pose to people. Lastly, the effective role of nanomaterials and their future in human wellness is discussed.



1. INTRODUCTION

1.1. What Are Bioaerosols? Bioaerosols are widespread air-borne biological particles produced by biological materials generating sufficient energy to separate small particles from bigger substances, such as air, liquid, and gas.[1] These are produced by plants, soil, water, and animals, including humans, in the environment[2] and are divided into two categories: living viable (bacteria, fungi, virus, etc.) and dead (nonviable) bioaerosols[3] (pollen, animal dander, saliva, etc.) (shown in Figure 1). Bacteria and fungus, the most common live bioaerosols responsible for the microbiological activity, can grow and are contagious or pathogenic, causing disease.[4] They can become a reason for a variety of health problems in people, including microbial infections, endotoxins, and allergies,[5] as shown in Figure 2. Allergy sufferers can be influenced by biological matter in the air, causing respiratory disorders such as asthma and emphysema, in which people develop a respiratory sensitivity that makes breathing difficult.[6] The meningococcal meningitis epidemic in Sub-Saharan Africa is a well-known example, which was linked to dust storms during dry seasons. Mycoplasma pneumonia and TB outbreaks have also been connected to dust occurrences.[7] Another occurrence was human respiratory illnesses in the Caribbean due to heavy metals, microorganism bioaerosols, and pesticides brought across the Atlantic Ocean by dust clouds.[8] As a result, airborne particle protection barriers are necessary. Depending on the location and type of bioaerosol present, different levels of protection are provided. Personal protection refers to the safeguards put in place for persons.[9] Collective protection targets, on the other hand, are designed for a larger audience, such as in hospital facilities where the risk of infection by certain viruses is fairly common.[10] To combat this, numerous disinfectant-based strategies have been utilized to minimize infections. Disinfectants are resources that are used to kill or

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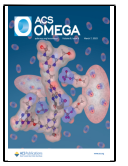

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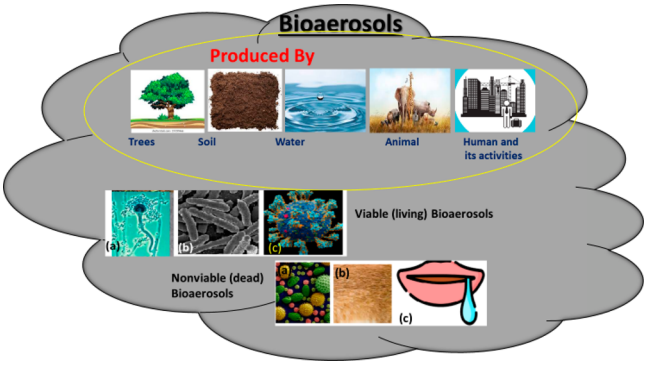

Figure 1. Bioaerosol chief producers. Viable bioaerosols: (a) fungi, (b) bacteria, (c) and viruses. Nonviable bioaerosols: (a) pollen, (b) animal dander, and (c) saliva.

decrease microorganisms on a surface. In hospitals, kitchens, and clinics, it is an excellent technique to clean diverse surfaces. They are useful in our everyday lives since they eliminate microbes while posing no health risks to us.[11] They are also an abundant, effective, less expensive antibacterial agent for short periods of time and do not produce hazardous compounds as a result. Alcohols, quaternary ammonium cations, oxidizing agents, and aldehydes including hydrogen peroxides, sodium hypochlorite, and iodine have all been applied as disinfectants with success.[12] These compounds, on the other hand, have a number of disadvantages, including toxicity, corrosivity, and bacterial resistance. As a result, UV units can be installed in the central air system or in the room to deactivate bioaerosols and limit their growth, resulting in improved protection. Using the force of an induced electrostatic charge, filtration through a central air system, and devices such as electrostatic precipitators can remove microscopic dust and smoke particles from a moving gas while restricting the flow of gases through the unit to a minimum.[13]

2. PREVENTION FROM BIOAEROSOLS

Bioaerosols are biological aerosols that can contain complete microorganisms as well as organism components or products. Airborne viruses, bacteria, and fungi have been examined extensively because airborne infections can become a source for a range of disorders, including allergic rhinitis, asthma, chronic obstructive pulmonary disease (COPD), influenza, and severe acute respiratory syndrome (SARS).[14] Over the last several decades, thermal treatments, ultraviolet (UV) irradiation, antimicrobial filters, and titanium dioxide (TiO_2) catalysis have all been employed to develop effective bioaerosol management methods and technology. Antimicrobial air filtration techniques are particularly capable because they can be simply integrated into existing air-conditioning systems. Previous research has demonstrated that antibacterial inorganic nanoparticles used in air filtration can effectively suppress bacterial aerosols. The antibacterial efficacy of these systems is determined by exposure time, particle size, and concentration.[15] Hand hygiene and personal protection equipment are also part of the prevention and control of bioaerosol infections. Gear such as hand gloves, face masks, body coveralls, face shields, head covers, rubber long boots, and other personal protective equipment (PPE) is shown in Figure 3. Conventional procedures are used to safeguard healthcare professionals and other people from becoming sick. The "Centers for Disease Control and Prevention" (CDCP), the "Occupational Safety and Health Administration" (OSHA), the "World Health Organization" (WHO), and Indian bodies such as the "Ministry of Health and Family Welfare" (MHFW), among others, all recommend that patients and healthcare providers wear PPE.[16,17]

3. PERSONAL PROTECTIVE EQUIPMENT (PPE)

Many employees, such as those who serve in the medical, dental, and veterinary fields, use personal protective equipment (PPE) to guard their face, nose, eyes, and mouth against splashes and sprays of body fluids during examinations, surgery, and post-treatment care. Surgical masks, N95 respirators, face shields, and protective medical garments

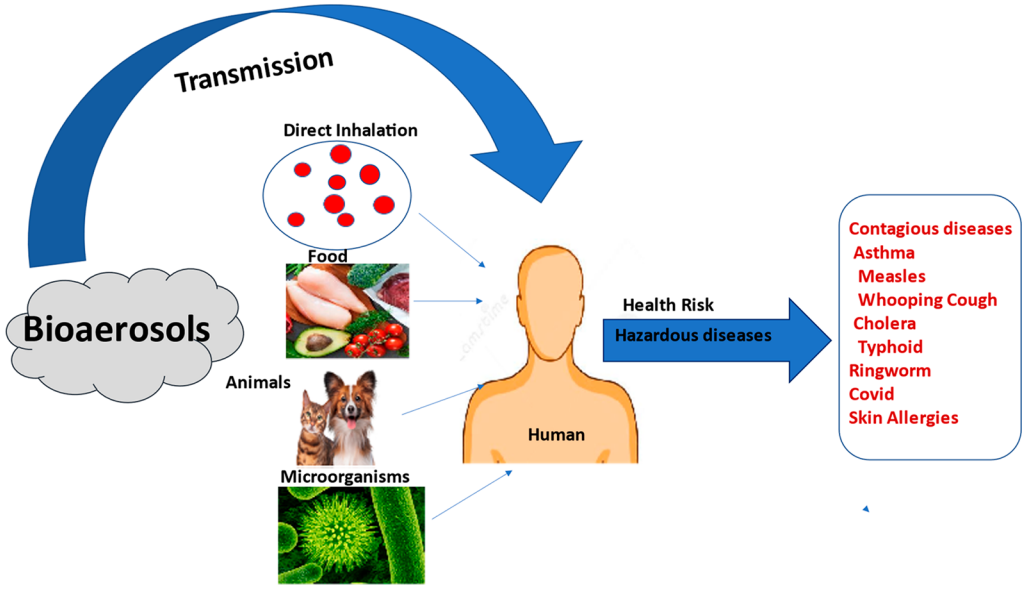

Figure 2. Transmission of bioaerosols in humans leads to hazardous diseases.

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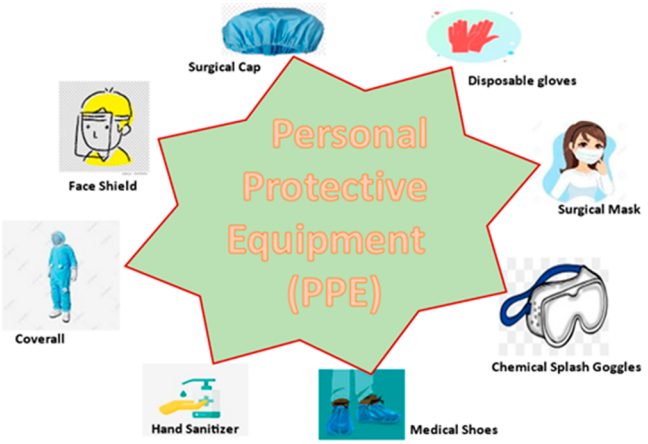

Figure 3. Personal protective equipment.

help as a primary defense for frontline health workers and clinicians in operating rooms and hospital wards against disease transmission via physical contact with aerosols and body fluids.[18] Surgical masks are similar to respirators in appearance, but they do not provide as effective protection against airborne particulates (particularly bioaerosols) and are frequently used to guard against direct droplets from a person's mouth or nose when sneezing or coughing.[19] Surgical masks, in addition to having poor filtration efficiency, also allow leakage around the edges when inhaled, making them inappropriate for giving complete protection to the user. In this scenario, healthcare personnel dealing with patients infected with infectious agents such as the Swine Flu (H_1N_1 influenza virus) are merely wearing surgical masks as a type of personal protective equipment, which may have negative health consequences.[20]

The PPE (Figure 3) kits (surgical masks, gowns, etc.) are made up of nonwoven fine fiber material such as polypropylene. Surgical masks are made of nonwoven mats of fine fibers that are flat and nonwoven. The fiber is laid so that the long portion is perpendicular to the air passing through the passage, allowing many particles to be caught along the axis. The nonwoven layer of this mask inhibits viruses from passing through the mask, either from the environment to the user or from the wearer to the environment, due to its pore size.[21] The trapped germs, on the other hand, remain stuck to the mask's surface, posing a risk not just to the wearer but also to others if not properly disposed of.[22]

As a result, adding antiviral/bacterial or self-sanitizing properties to surgical masks is projected to significantly minimize the risk of infection. These masks can be worn multiple times and readily discarded with little risk of cross-infection.[23] The development of medical apparel with additional self-sanitization or antiviral characteristics is equally critical for the same reason. Nanoparticle-based antimicrobial compounds have been found to have potential applications as a coating on the surface of protective gowns, gloves, and other equipment to lower the hazard of infectious disease communication, such as SARS-CoV2, in this regard.[24] As the multidisciplinary field of nanoparticles expands in materials science, photonics, electronic goods, mechanics, polymers, and textile manufacturing and the biomedical field for applications such as sensors, electro-optic displays, water resistance, wrinkle resistance, strength enhancement, UV blocking, computing, and antimicrobial resistance, nanoparticles are being used in a variety of ways.[25,26]

With the current pandemic situation in mind, the focus of this analysis is to examine the antimicrobial action of nanoparticles coated on nonwoven-based fabrics and used in surgical masks and medical protective clothing such as gowns or coveralls, which can help to protect against infectious agents that can kill or inhibit microorganism growth. As a result, organizing a setup for the antimicrobial activity for deactivating bacteria utilizing nanoparticles is a credible contribution of researchers toward a healthier environment. The importance of nanotechnology is discussed in this review, primarily in terms of antibacterial activity and nontoxic interaction with human skin. Thus, nanotechnology is a useful technique for inactivating bioaerosol. Here, we discussed silver, zinc oxide, and copper oxide nanomaterials as efficient antimicrobial properties as reported in recent years.

4. IMPORTANCE OF NANOTECHNOLOGY FOR DEACTIVATING BIOAEROSOLS (IN TERMS OF SARS-COVID)

Nanoparticles (NPs) have a standard size range of 1−100 nm. Because of their unusually small size, they have innovative qualities such as increased cell contact which causes a higher surface area-to-mass ratio, in addition to a varied and controllable application[27] to work as an antimicrobial agent. The SARS virus is found to be highly stable at ambient conditions at a temperature of ∼4 °C, but it can be deactivated after exposure to UV radiation at 254 nm or at a very acidic (pH ≤ 3) or alkaline pH (pH ≥ 12). Even 5 min of heating at ∼65 °C would create a similar effect.[28] SARS-CoV-2 is likely to be very sensitive in similar ways. Researchers discovered that traditional disinfectants such as ethanol, bleach, povidone-iodine, chloroxylenol, chlorohexidine, and benzalkonium chloride can inactivate these viruses.[29] The stability of the virus depends upon the infected material composition where it gets inactivated in less than 3 h on tissue paper, less than 2 days on wood and linen, 4 days on treated glass and banknotes, and about 7 days on steel and plastic.[30] Active viruses, on the other hand, can survive for a period of 7 days on the external facet of a surgical mask. Viable virus surface and aerosol stability remain in infected aerosol for more than 3 h.[31] As a result, we could hypothesize that NP-based surface modifications improve the viral stability, as studied by scientists.[32] The most popular disinfection strategies used in healthcare settings include chemical disinfection with a hydrogen peroxide (H_2O_2) stream or metal-ion-coated facets, biological disinfection using probiotics, and physical disinfection with ultraviolet (UV) radiation. Nanotechnology can propose alternatives to these methods. It may pave the way for progress in self-disinfecting surfaces that protect healthcare and housekeeping personnel from contamination.[33]

For virus inactivation, researchers have proposed the use of nanoparticles and nanomaterials with inherent antipathogenic characteristics, such as NPs based on metal and graphene, for their potential to deactivate viruses, bacteria, fungi, or yeasts photothermally or via photocatalysis-induced "ROS generation".[34] NPs slowly and gradually release harmful metal ions just where antibacterial operation is required, and they can collect within cells and not be removed by specific efflux pumps. Instead of bulk materials or metal ions, it is preferred to employ NPs made up of these metals. Silver, copper, and zinc nanoparticles have inherent antibacterial qualities and, so

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far, are active in medical gear and healthcare establishments; for instance, silver is utilized for wound dressings and urinary and intravascular catheters.[35,36]

5. WIDELY USED NANOPARTICLE(S) FOR DEACTIVATING BIOAEROSOLS WITH THEIR TOXICITY EFFECT ON HUMAN SKIN

5.1. Silver Nanoparticles. Silver (Ag) ions and silver-based nanoparticles (Ag NPs) attract a lot of attention because of their unique optical, chemical, electrical, and catalytic capabilities that can be tuned by facet nature, size, morphology, and other parameters. As a result, these crystals have been used in a variety of disciplines in the health industry, including catalysis, sensors, electrical components, and antibacterial agents. Silver-based nanoparticles are used in our daily lives in silver-coating-based air/water filters, textiles, animal husbandry, biomedical applications such as the disinfection of medical devices, burn and wound dressings, food packaging, water purification, paints with silver zeolites, and food trays. Furthermore, they are found in various products such as shirts, textiles, and medical masks, as well as toothpaste, hand soap, shampoo, toys, detergent, and humidifiers.[37−40] These materials have been extensively explored and employed in a variety of industries, including indoor air quality (IAQ) and human health, air filtration, garment making, electronics, food processing, cosmetics, and medical devices, due to their outstanding antimicrobial activity.[41,42] Ali and his colleagues investigated the limitations of conventional air-cleaning filters in detecting and deactivating aerosolized microorganisms in order to evaluate new Ag, Zn, and Fe nanoparticle-doped cotton (Ct) filters (AgCt, ZnCt, and FeCt) as biocidal filters for bioaerosol attenuation. To test the biocidal effect of nanocomposite filters, the survival of lab-generated *E. coli* after collection on each filter material was contrasted to collection on an undoped cotton control filter and in a Biosampler.[43] The doped filters showed 100% viable removal efficiency (VRE). The physical removal efficiency (PRE) evaluated by an optical particle counter was 99.9% for ZnCt, 97.4% for AgCt, and 97.3%for FeCt, compared to just 77.4% for particles larger than 500 nm in the control. The AgCt filters also showed a lower pressure drop than the FeCt and ZnCt filters as well as the cotton standard. The cotton control filter had a permeability of (3.38×10^{-11}) m^2, whereas the AgCt filter had a slightly higher permeability (3.64×10^{-11}) m^2 than the other filters. Summing up, this research suggests that nanocomposite-doped filter media, particularly AgCt, can provide effective protection against airborne pathogens with a lower pressure drop, higher collection efficiency, and better disinfection capability than untreated cotton filters, demonstrating Ag particle biocidal applications.

The efficiency of antibacterial nanoparticles is determined by their size. Despite the fact that the mechanism of Ag NP activity is unknown, smaller Ag NPs have a better antibacterial effect than larger Ag NPs.[44,45] Furthermore, the antibacterial role of Ag NPs is higher than that of their bulk counterparts. However, because of their proclivity to aggregate into big particles and lose their antibacterial activity, their efficacy may be limited by their high surface energy. When penicillin and later antibiotics were found, silver (Ag), like other nonantibiotic therapies, was almost forgotten. With the rise of antibiotic-resistant germs, however, it has emerged as a point of contention.[46] Through in vitro and in vivo testing for a variety of disorders, silver has been demonstrated to be an effective bactericidal antibacterial agent. Furthermore, bacteria appear to be less likely than conventional antibiotics to develop resistance to Ag.[47−49] Bacterial cell membranes with sulfur-containing proteins and amino acids can interact with silver on both the inner and outer layers of the cell membrane, leading to bacterial deactivation. Furthermore, the silver ion produced by Ag NPs interacts with phosphorus in DNA and sulfur-containing proteins, limiting enzyme activity. Antibacterial activity is influenced by the size and shape of the particles. The size-dependent study discovered that if the NPs are smaller than 20 nm they can demonstrate better attachment to the membrane's sulfur-containing protein, resulting in maximal permeability across the membrane and, last, leading to cell death of bacteria.[50] The shape of nanocrystals is one of the other criteria that determines how they interact with the bacteria's cell walls. Truncated triangle-shaped silver nanoplates demonstrated stronger antibacterial action against "*E. coli* bacteria" than round and rodlike shaped NPs.[51] Ag-based NPs smaller than 10 nm have recently been discovered to generate pores on cell membranes, through which cytoplasmic material is ejected through the medium, causing cell destruction without interfering with the bacteria's intracellular and extracellular proteins and nucleic acids. The interaction of Ag NPs with a few cells may cause apoptosis (programmed cell death).[52] Ag NP's ability to link with bacteria's sulfur- and phosphorus-functionalized proteins for cell death can be increased by tweaking their physicochemical properties.[53] The physicochemical features of Ag NPs show a critical role in bacterial deactivation or death, which is important in biomedical domains such as therapeutics, textile consumer items, and dressings. Ag NPs are utilized as an effective disinfectant in a variety of commercialized goods, including silverline polyurethane ventricular catheters, silva sorption hand gels, wound dressings, cavity fillers, and drug delivery catheters.[54] They have bactericide effects on *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Bacillus cereus*, *Listeria innocua*, and *Salmonella choleraesu*. Silver (Ag) nanoparticles, in particular, are antimicrobial agents in a wide range of the antibacterial spectrum. By reducing enzyme function, Ag NPs disturb bacterial cell membranes and cause metabolic alterations.[55] According to Choi et al., the Ag^+ ions, which have a sulfur and nitrogen affinity, can inhibit and disrupt protein structure by adhering to the thiol and amino groups.[56] Later, Kumar et al., Ningana Gouda et al., Carlson et al., and Pio et al. in their individual experiments proposed that silver nanomaterials are photocatalytic and capable of producing reactive oxygen species (ROS).[57−59] Others have shown that this impact is cell-type dependent, at least in eukaryotic cells, an observation that has been challenged by others. Ag NPs have been shown to have synergistic antibacterial effects when coupled with antibiotics against both Gram-positive and Gram-negative bacteria.[60−64] Ag NPs have been shown to have antiviral action against a range of viruses, including HIV-1,[65] the monkeypox virus,[66] bacteriophages UZ1 and MS2,[67,68] the murine norovirus MNV1, HSV,[69] the hepatitis B virus (HBV),[70] and, most recently, the swine widespread diarrhea virus (PEDV).[71] They show antiviral effects due to three main processes. To begin, Ag(0) NPs dissolve and release poisonous Ag(I) forms (including Ag^+ ions), which could be the cause of their virucidal effect.[72] Because it is a soft metal with a significant attraction for sulfur, Ag has a strong relationship with thiols from tiny molecules like cysteine or glutathione as well as

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sulfhydryl groups in many enzymes' active sites.[73] Ag(I) may bind to virus surface proteins or accumulate in host cells, where it then binds to thiol-containing enzymes essential in virus replication, impairing their function. Zodrow et al. presented this idea to explain Ag NP's antiviral properties against bacteriophage MS2, while De Gusseme et al. proved it to be a counter to MNV-1.[74] Furthermore, Ag_2S nanoclusters (NCs) with diameters of 2.5 and 4 nm suppressed PEDV growth in Vero cells by limiting viral negative-strand RNA synthesis and virus egress but not by preventing the virus from anchoring on cell membranes or penetrating into the cells. The scientists concluded that the antiviral effect of Ag NPs was independent of the release of Ag^+ ions because virus replication was not inhibited when cells were exposed to the same concentration of Ag^+ ions. Because the methods by which Ag^+ ions and Ag NPs enter cells differ, their local distribution and management inside the cells also change. When it comes to viruses that contain infected cells, this distinction could lead to various sorts of toxicity for Ag^+ ions and Ag NPs. For example, Ag NPs may clump together in intracellular parts where important steps of the viral cycle occur, such as protein or genome growth or nucleocapsid accumulation before discharge into the extracellular space, whereas Ag(I) may clump together in other parts of the cells or become quickly unoccupied.[75]

Second, Ag NP's antiviral efficacy would be derived from physical interactions with virus surfaces, which would prevent viruses from attaching to host cells and limiting their contagion. Elechiguerra et al. showed this process in HIV-1 when exposed to 10 nm Ag NPs, and Orlowski et al. showed it in HSV-2 when exposed to 13, 33, and 46 nm Ag NPs coated through tannic acid. Elechiguerra et al. discovered that the ideal Ag NP size was approximately 10 nm, with bigger or smaller NP sizes indicating faint physical interactions with the virus. Orlowski et al., on the other hand, discovered that the greater the NP, the more operative it was at preventing virus adhesion to the host cell. De Gusseme et al. postulated a similar process, in combination with the production of Ag(I), to explain why MNV-1 virus infectivity was reduced when subjected to 11.2 nm biogenic Ag NPs. Finally, the local discharge of ROS from the Ag NP surface, which disrupts the virus's membrane, could be linked to the anchoring of Ag NPs on virus surfaces. Hydrogels, syringes, and other medical equipment already contain Ag NPs. The utilization of paints, air filters, and face masks with NPs in healthcare settings should be studied. The antiviral potential of Ag NPs on filters toward bacteriophage MS2 decreased with dust loading. The filtration efficiency and pressure drop increased with dust loading, while the antiviral ability decreased.[76−79]

5.1.1. Toxic Impact of Silver (Ag) and Silver Nanoparticles (Ag NPs) in Humans. Silver has low toxicity in the human body, and clinical exposure via inhalation, ingestion, dermal application, or the urological or hematogenous route is expected to pose minimal risks. Chronic ingestion or inhalation of silver preparations (particularly colloidal silver) can result in silver metal/silver sulfide particle deposition in the skin (argyria), eye (argyrosis), and other organs. These are not life-threatening circumstances, but they are unsightly. Silver is absorbed by the human body and enters the bloodstream as a protein complex, where it is eliminated by the liver and kidneys. Induction and binding to metallothioneins influence silver metabolism. This complex reduces silver's cellular toxicity and aids in tissue repair. Silver allergy is a known contra-indication for using silver in medical devices or antibiotic textiles.[80] The hazardous effect of Ag NPs is discharged into the environment, which is quickly absorbed by aquatic animals. Furthermore, the widespread adoption of Ag NPs in the role of a disinfectant may increase the likelihood of microbial resistance, limiting its utility. The toxicity of nano-Ag causes the skin to turn a bluish-gray color. This term is known as Argyria illness. Although silver's toxicity is low, it has been shown to have effects other than Argyria at higher doses; extant evidence suggests that 0.9 g is the upper limit for Argyria problems throughout life.[81] Furthermore, the limit for nano-Ag components in drinking water is 100 g/L. There is a lot of disagreement about whether toxicity emerges from nanosilver or dissolved silver, but current research findings show that toxicity arises from the release of silver in the environment in particulate form as well as nanosized rather than dissolved silver. When compared to humans and mammals, the sensitivity of Ag NP toxicity is higher in aquatic species with concentrations of 1−5 g/L_3.[82] The environment, as well as the toxicity of Ag at the nanoscale, is depicted in a succession of patterns, including nano-Ag discharge from the product, emission, distribution, and aquatic life impact. According to Asha Rani et al., Ag NPs are likely to be hazardous to human cell lines based on cytotoxicity, genotoxicity, and antiproliferative characteristics.[83] Levard et al. evaluated the toxicity of Ag nanoparticles on aquatic living creatures in 2012. They also confirmed Ag NP toxicity to aquatic, terrestrial, plant, algae, fungal, vertebrate, and human skin cells (keratinocytes, lun fibroblast cells, and glioblastoma cells).[84] Gliga et al. presented a detailed nanotoxicology study of Ag NPs, involving particle agglomeration in cell media, cellular uptake, and intracellular localization, and revealed that intracellular Ag discharge is responsible for toxicity in human lung cells.[85] Despite obtaining a greater grasp of Ag NP's perilous consequences, some aspects must be analyzed and addressed, such as the toxicity range, dose, and concentration that are safe for aquatic living organisms and humans, before it can be employed cautiously and efficiently in a variety of applications. The cytotoxicity, antibacterial processes, biodistribution, organ accumulation, degradation, and adverse effects of Ag NPs must all be investigated. The rapid commercialization of agricultural nanoparticles needs thorough environmental, health, and safety investigations, which should lead to a public discussion of the broader social consequences and immediate toxicological oversight. Ag NP control is still experiencing substantial variations in response to environmental, health, and safety concerns.[86] Despite the current disputes and issues, Ag NPs are likely the most promising antibacterial and antiviral nanomaterial.[87]

5.2. Zinc Oxide (ZnO) Nanoparticles. Zinc oxide (ZnO) is a white powder that is made up of inorganic metal oxide. It is a multipurpose material that is versatile, nontoxic, and simple to make, with low manufacturing costs and excellent thermal, chemical, and mechanical stability.[88] ZnO is a promising material for use in semiconductor devices. In the UVA (315−400 nm) and UVB (280−315 nm) portions, it has a strong optical absorption[89] at room temperature, and the free-exciton binding energy is 60 meV, with a direct and wide band gap of 3 eV in the near-UV spectral region, so that excitonic emission can persist at room temperature or even higher than that.[90,91] The optical and chemical sensing, semiconducting, electric conductivity, and piezoelectric properties of ZnO make it ideal for a wide range of applications.[92] Zinc oxide nanoparticles (ZnO NPs) have acquired significance in the textile sector due

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to their high efficiency and diverse uses in antimicrobial UV protection, photocatalytic, and self-cleaning qualities.[93] The antibacterial activity of ZnO NPs against a variety of microorganisms has been shown to be strongly dependent on particle size and concentration.[94]

Nanosized ZnO has a variety of morphologies and has substantial antibacterial action against a wide range of bacteria explored by researchers.[95] It is now being studied as an antibacterial agent in both micro- and nanoscale formulations.[96,97] Many microorganisms have sizes ranging from hundreds of nanometers to tens of micrometers. ZnO NPs have appealing antibacterial capabilities due to their increased specific facet zone and compact particle size, which results in higher particle facet reactivity. It is a biocompatible substance with photocatalytic and photo-oxidizing effects on chemical and biological species.[98] The antibacterial activity of ZnO NPs was reviewed by Sirelkhatim et al., who included testing procedures, the effect of UV irradiation, ZnO particle properties (size, concentration, shape, and defects), particle surface modification, and the minimal inhibitory concentration. They discovered that, in comparison to hydrogen peroxide (H_2O_2), OH^- (hydroxyl radicals), and O_2^{-2} (peroxide), ROS (reactive oxygen species) have been a critical aspect in cell wall disruption due to ZnO-localized interaction, increased membrane permeability, internalization of NPs due to proton motive force loss, and uptake of toxic dissolved zinc ions (peroxide). This resulted in mitochondrial weakening, intracellular outflow, and oxidative stress gene expression release, resulting in cell growth inhibition and death. Surface imperfections on ZnO abrasive surface roughness have been linked to increased antibacterial activity in some circumstances.[99] As a result, when the size of the ZnO particle is reduced to the nanometer range, it can interact with the bacterial facet and core, where it enters the cell and exhibits distinct bactericidal processes.[100] In addition, it has been found to inhibit the growth of methicillin-sensitive *S. aureus* (MSSA), methicillin-resistant *S. aureus* (MRSA), and methicillin-resistant *Epidermidisa* (MRSE) strains, demonstrating that they are effective bactericidal agents that are unaffected by MRSA and MRSE drug-resistant mechanisms.[101] ZnO NMs are generally inexpensive and efficient against a wide spectrum of bacteria like *Klebsiella pneumoniae*, *Listeria monocytogenes*, *Salmonella enteritidis*, *Streptococcus mutants*, *Lactobacillus*, and *E. coli* pathogens with little toxicity to human cells.[102]

Zinc treatment has also been approved by the FDA, and Zn is now available as a food additive. It impacts bacterial cells via the two methods discussed above by adhering to membranes, changing their potential and integrity, and triggering ROS production. As a result, the Zn NM is also a mutagen, albeit a weak one.[103] The relations between these unusual materials and bacteria are mainly harmful, which has led to antimicrobial uses in the food business as multiple researchers have revealed that ZnO NPs are nontoxic to living organisms.[104] This necessitates their use as antibacterial drugs that are toxic to microbes and have good biocompatibility with human cells. One application of their antibacterial bioactivity is in the food packaging industry, where ZnO NPs are used as an antibacterial agent against foodborne diseases. When ZnO NPs are correctly included in packaging materials, they can interact with foodborne pathogens by releasing NPs onto the food surface, where they come into contact with hazardous bacteria and kill or inhibit them.[105] The antiviral reaction of zinc oxide is reported by Yogendra et al.[106] in which they proved that negatively charged ZnO NPs trap the herpes simplex virus type-1 (HSV-1) and prevent it from adhering to host cells. The author revealed that the slightly negatively charged ZnO NPs efficiently trap the virions via a unique virostatic mechanism, preventing them from infecting human corneal fibroblasts, which are natural target cells for HSV-1 infection. After producing extra oxygen vacancies under UV-light illumination at 254 nm for 30 min at room temperature, the anti-HSV-1 activity of ZnO NPs was dramatically increased. Furthermore, by conjugating peptides to specific virus envelopes, glycoproteins will provide the benchmark for developing further antiviral medicines against many other viruses. Additionally, they can be utilized to deliver antiviral peptides with low pharmacokinetic issues and increased therapeutic activity for the treatment of HSV infection.[107]

5.2.1. Toxicity Effect of Nanoparticles Consisting of Zinc Oxide (ZnO NPs). Zinc is quite safe in relation to other metal ions with similar chemical characteristics. ZnO has been identified in more sunscreens, food additives, pigments, and biosensors than previously thought. The toxicity of these manufactured ZnO NPs has been examined in a range of cell lines and animal models by a number of researchers. ZnO NPs have been demonstrated to have cytotoxicity and genotoxicity in vitro and in vivo.[108] Further research demonstrated that ZnO NPs impair cell feasibility in a dose- and time-dependent manner. The metallothionein gene, which is used as a biomarker in metal-induced toxicity, is thought to be increased by ZnO NPs. Investigations have confirmed the dose-dependent hepatotoxicity and significant increase in oxidative stress by a rise in malondialdehyde (MDA) concentration and a reduction in superoxide dismutase (SOD) and glutathione peroxidase (GPx) enzyme activity in the liver. They are also found to raise plasma aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase (ALP) levels.[109]

Further research has found that ZnO NPs reduces cell viability in a dose- and time-dependent way.[110] The metallothionein gene, which is used as a biomarker in metal-induced toxicity, is thought to be increased by ZnO NPs.[111] Increased malondialdehyde (MDA) levels and reduced superoxide dismutase (SOD) and glutathione peroxidase (GPx) enzyme activity in the liver were found to cause dose-dependent hepatotoxicity and a considerable increase in oxidative stress. Plasma aspartate aminotransferase (AST), alanine aminotransferase (ALT), and alkaline phosphatase (ALP) levels are also increased by ZnO NPs.[112]

Acute zinc poisoning is an uncommon occurrence when humans are exposed to large quantities of zinc oxide. Long-duration, high doses of zinc supplementation interfere with copper uptake, in addition to intoxication. As a result, copper deficiency is to blame for many of its harmful effects. During systemic homeostasis, effective cellular regulatory operations normally prevent the receipt of lethal quantities of exogenous zinc. Endogenous zinc plays an important role in cytotoxic events in single cells. Zinc regulates apoptosis via interacting with caspases and proteins from the Bcl and Bax families, as well as other apoptotic molecular regulators. It plays an important part in the death of brain cells, and cytotoxicity caused by ischemia or trauma requires an increased amount of free zinc. It is a vital trace element rather than a poisonous metal ion. While intoxication from enormous exposure is uncommon, zinc insufficiency is common and has a negative

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effect on development, brain growth, and immunity, with potentially fatal consequences in severe cases.[113]

5.3. Copper Nanoparticles (Cu NPs). NPs made up of copper (Cu) are commonly employed in industrial and commercial applications because of their cheap value, stability, and extensive antibacterial capabilities.[114,115] Sensors, catalysts, surfactants, antimicrobials, and other applications including antifouling coatings are among their various uses.[116] For ages, copper[117] and its compounds have been employed as disinfectants.[118−120] Cu's antibacterial properties have been known since antiquity, and facets containing a large quantity of Cu have been presented to be effective at deactivating viruses.[121] Cu nanoparticles, meanwhile, are well-known antibacterial agents found to be toxic against *Staphylococcus aureus, Escherichia coli, Bacillus subtilis, Klebsiella pneumoniae,* and *Pseudomonas aeruginosa*.[122] Cu ions are released when Cu and CuO NPs come into contact with living cells. NPs have a large surface area due to their small size, which gives them a higher reactivity than their bulk counterpart and speeds up Cu ion discharge kinetics. The application of nanostructured Cu surfaces would improve their antibacterial properties even more. Furthermore, if spattered on infected areas or put onto the surface of textiles to bestow antimicrobial qualities, these NPs could inactivate viruses (masks, gowns, etc.). In simulated breathing situations, CuO-impregnated masks demonstrated outstanding anti-influenza virus (H1N1 and H9N2) activity, and the materials' usefulness against SARS should be investigated.[123−125]

CuO-based NP antiviral activities and processes have been examined by a small number of researchers. Murray et al.[126] displayed Cu efficiency with poliovirus in the year 1979. This metal oxide, particularly its nanoparticles, can damage the virus's integrity and cause its DNA to degrade. CuO NPs exhibit remarkable anti-*HSV-1* virus activity, according to Ahmad et al., and CuO NPs were cocultured with *HSV-1* infected cells at the highest nontoxic concentration of CuO NPs (100 g/mL), which resulted in an 83.3% cell survival rate. CuO NPs release copper ions, which catalyze the formation of reactive oxygen species, which can compromise the integrity of the *HSV* capsid and destroy the whole genome.[127] In vitro, Hang et al. looked into the antiviral activity of Cu_2O NPs contrary to the *hepatitis C* virus. When the HCV virus was stimulated with Cu_2O NPs at a concentration of 4 g/mL, the infection rate against cells was reduced by 90%. These NPs' antiviral effect is thought to prevent HCV virions from adhering to host cells and penetrating them. HCV viruses (30 nm) were prevented from adhering to cells by larger Cu_2O NPs (50 nm) by multivalent virion binding, preventing the virus from entering the cell.[128] Mazurkow et al. used calcination at various atmospheres to create multiphase Cu_xO_y (CuO and Cu_2O) hybrids in order to investigate the antiviral activity of copper compounds with different valences. Cu_2O was found to have higher antiviral properties, according to the researchers. The difference in antiviral activity between CuO and Cu_2O was established by zeta-potential testing. Cu_2O has a higher isoelectric point of 11.0, which makes it better for viral contact.[129,130] Other Cu-based chemical NPs have also been investigated for potential antiviral resources. The antiviral activity of nanosized copper(I) iodide (CuI) particles with an average size of 160 nm was examined by Yoshie et al. At a dosage of 17 g/mL, CuI particles showed a strong antiviral response to influenza A viruses (*HIN1*). In an aqueous solution, CuI also creates hydroxyl radicals, which damage the virus's surficial lipid groups, rendering it inactive. Cu_2S and CuCl, two more cuprous compounds, have also been found to be anti-infectious.[131,132]

Cu's efficacy against the *HuCoV-229E* coronavirus was recently demonstrated; its ability to inactivate other types of coronaviruses suggests that it may have a comparable efficacy against SARS-infected diseases like Covid-19. On smoother surfaces (Teflon, poly(vinyl chloride), ceramic tiles, glass, and stainless steel), *HuCoV-229E* can survive in infective form for more than 6 days; however, it is destroyed in less than 60 min on brasses with at least 70% Cu or CuNi alloys which are made up of at least 90% Cu. The viral DNA becomes fragmented when incubated on Cu-consisting surfaces, ensuring that inactivation is irreversible. Cu ions produced through the Cu-consisting surface are hazardous to virions, and according to the postulated inactivation mechanisms, ROS produced by Cu reacting with external hydrogen or molecular oxygen via Fenton-like or Haber Weiss processes damage viral proteins and lipids.[133] Gadi et al. created an antiviral respiratory protective face mask by impregnating CuO NPs into an N95 mask in order to investigate the use of CuO NPs in respiratory protective equipment. There were four layers to the antiviral respirator. The inner and outer layers (A, B) of the fiber were different in fineness, and CuO NPs were evenly disseminated across the surface of the fiber. CuO NPs in the masks kill the virions that have survived the physical barrier while maintaining the mask's physical barrier properties. The antiviral role of N95 face masks was boosted through five guidelines of magnitude using this method.[134]

5.3.1. Toxicity of Copper Oxide. Copper-based NPs pose an ecological risk due to their high manufacturing volume and rising use. Metallic copper oxide (Cu and CuO NPs) is the most often utilized copper-based NP; yet, its environmental toxicity varies substantially based on its physio-chemical features, which are dissolution, aggregation behavior, and reactive oxygen species formation.[135,136]

6. RE-EVALUATING THE FUTURE OF NANOMATERIALS CONSIDERING THE WELLNESS AND EXPERT VIEWS

Nanoparticles have received considerable attention in biological applications due to their use in highly sensitive investigative assays, radiotherapy advancement, targeted therapies, thermal ablation, drug delivery, and antimicrobial agents.[137] Metal nanoparticles with unique physicochemical properties such as Ag, Au, Zn, Cu, and others that exhibit resonance electron oscillation (also known as localized surface plasmon resonance) due to their photothermal and optical properties have shown significant therapeutic effects in medical science. The mechanisms of nanoparticle interaction with animal and plant cells can be used to establish their impact and optimize their activity in health and medical applications for developing better medical care and diagnostic equipment.[138−140]

Antimicrobial nanoparticles, such as Ag, could be used in therapeutics and the manufacture of autoinfected medical devices. Because of their excellent antimicrobial properties against lethal viruses, microbes/germs, and other nucleus-containing microorganisms, silver nanoparticles have been proven to be the most useful widely used material. It is very likely that simple low-cost antimicrobial agents can be developed using metal, metal oxide, or metal oxide/metal-doped composite nanomaterials. It will be used in place of

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traditional antibiotics.[141] It has also been used as an antimicrobial agent in different textile industries.[142]

Nanocoatings have been found to be 99.99% effective against various viruses, molds, and bacteria in most products on the market. Nanocoatings enable the creation of a dual-purpose single coating that can provide both antiviral and antibacterial activity while remaining environmentally friendly and biocompatible. The use of nanomaterials in coatings such as silver, carbon nanotubes, and titanium dioxide nanoparticles reduces surface contamination because the coating provides the surface with self-cleaning, hydrophobic, and odor-masking properties, requiring less cleaning effort. The nanocoating, which is a few nanometers thick, allows for material functionality and creation by acting as an interface between the substrate and the surrounding environment. Such coatings are so thin that they are visible to the naked eye, yet they are applicable to a wide range of surfaces and materials and are effective at eliminating microbes.[143]

The present review focus is on establishing a surface modification technique for enveloped RNA viruses, like the SARS-Covid virus, on porous filter substances (e.g., air purification units, face masks) as well as solid facets for enveloped RNA viruses. Antimicrobial coatings of nanoparticles produced via aerosol self-assembly are the basis for these solutions, which can effortlessly merge into product manufacturing or be added to objects after they have been manufactured. Keeping this in view, Merkl et al.[144] explored the excellent antimicrobial properties of three different combinable nanomaterials: silver, copper oxide, and zinc oxide. Direct deposition of flame aerosol, a highly scalable and repeatable nanomanufacturing procedure that combines particle creation and nanocoating assembly in one step, was employed to manufacture these nanoparticle coatings. To demonstrate the adaptability of this nanomanufacturing technique, thermophoresis and filtering were used to apply nanocoatings on both flat solid substrates and filter materials. The antiviral potential of these nanoparticle coatings to SARS-CoV-2 was assessed with a plaque test after their morphological and physicochemical features were described. A viral plaque assay was used to examine the effect of nanoparticle coating reactions with three antimicrobial materials (Ag, CuO, and ZnO) on both solid flat facets and porous filter media against SARS-CoV-2 survival. During the flame synthesis of these nanocoatings, an aerosol nanoparticle self-assembly property was used to create them. The antiviral activity of nanosilver particles used as a facet coating is the most effective of the three nanomaterials investigated, while copper oxide exhibits minimal reactivity and zinc oxide does not appear to reduce virucidal activity significantly. As a result, the authors were able to demonstrate that nanosilver and copper oxide can be used as antiviral coatings on the solid facet and filter media to limit communication and antiviral superspreading reactivity, as well as provide crucial information for current and future pandemic mitigation efforts.[144] Because viruses can last on contaminated facets for long periods, the utilization of metal nanoparticles to create self-disinfecting facets has grown in prominence in the past decades.[145] Viruses in touch with self-disinfecting surfaces are inactivated in situ, minimizing the risk of infection and transmission through human contact with infected areas. In one concept, photoactive metal nanocrystals were used to create a self-disinfecting surface that required visible-light stimulation to inactivate the virus. These surfaces, which were made from $CuInZn_4S_6$ (CIZS) nanocrystals with visible-light band gaps, could absorb visible light and form active oxidative species, which inactivated the influenza A virus by oxidizing the amino acid residues of the viral envelope proteins. While extremely virucidal, visible light is required to ensure the self-sanitizing action, limiting the system's applicability.[146]

Since the outbreak of Covid-19, nanomaterial-processed face masks have received a lot of attention. Several researchers created antiviral face masks and personal protective equipment (PPE) kits capable of filtering a variety of pathogens, including SARS-CoV-2. Talebian and co-workers proposed two methods to control COVID-19 involving nanomaterial-based disinfectants and biosensors, respectively, on mask or PPE fabrics. Because of their excellent antiviral properties, they proposed that metallic nanoparticles such as Ag, Cu, TiO_2, and others can be used as alternatives to traditional disinfectants such as chlorides, quaternary amines, peroxides, and alcohols. They also propose that highly efficient biosensors be integrated into face masks or PPE kits to allow for early detection.[147] Lustig and colleagues created multilayered face masks with alternate hydrophilic and hydrophobic layers. They discovered that the hydrophobic layer repels aqueous aerosol on the hydrophilic layer, preventing wicking movement. These face masks are proposed to prevent virus transmission through sneezing and coughing.[148] El-Atab and colleagues created a nanoporous and flexible Si-based template for a flexible and lightweight polymeric membrane. The membrane was attached to a reusable N95 mask that could filter microbes as small as 5 nm.[149] Thus, various nanomaterial combinations can be integrated with textile fibers by drawing them into nanofibers or coating methods, resulting in optimal activity.[150−152]

Humans are facing unprecedented challenges as a result of the COVID-19 global emergency. In the future, the common good must be managed with the "One Health" concept in mind, based on evidence that the wellness of humans is inextricably connected to that of animals and the environment. The present scenario should be viewed as a fantastic occasion to represent to the globalized world that multidisciplinary and interdisciplinary methodologies involving transversal disciplines and critical scientific solutions can yield significant results, as has been demonstrated in other scientific contexts. Nanomaterials have been employed to introduce in a sustainable manner antimicrobial, ultraviolet-resistant, electrically conductive, optical, hydrophobic, and flame-retardant properties into textiles and garments. Nanomaterial-based smart devices are now also being integrated with textiles to perform various functions such as energy harvesting and storage, sensing, drug release, and optics. These advancements have found wide applications in the fashion industry also. Nanotechnology is fundamentally a sector in which scientists with unbelievably various backgrounds have come together to work on multidimensional challenges in beneficial collaborations. Nanotechnology is more important than ever in laying new foundations for addressing the current global public health crisis, anticipating potential new threats such as infectious illnesses and envisioning a more science-based future.[153,154]

7. CONCLUSION

Advances in antimicrobial agents, as well as ways to prepare protective materials and personal protective gear, like face masks, have gotten plenty of attention recently, in academic and industrial research. The majority of existing masks is incapable of filtering the viruses' tiny aerogels effectively.

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Microbes stick to the filtering resources, which can transfer through the moist mask and intensify the hazard of infection. This analysis looks at how the nanomaterial's small size makes it ideal for antimicrobial biological processes. Nanoparticles have been shown to be effective antibacterial reagents during wound care and other medical difficulties, suggesting their potential as bactericidal components. The effectiveness of such nanoparticles is determined by their measurement and concentration. Furthermore, the atomic mass on the surface layer of the particle stimulates the characteristics of such resources. As the particle size reduces in proportion to the total atoms of the material, the fraction of atoms on the particle's surface rises, boosting the antibacterial action, contrary to various pathogenic viral and bacterial species. Because of the advantages of antimicrobial nanomaterials, researchers have attempted to use them as contact surfaces for medical devices, fibers/fabrics, and antibacterial coatings. With the advanced research in clinical investigations, this study has offered an outline of the existing indication of the antimicrobial approach of silver, zinc, and copper in health care, as well as their hazardous consequences to living beings. Silver, zinc, and copper contain hard and soft surfaces, like textiles and polymers, which may provide a fresh and revolutionary improvement to counter healthcare-associated illnesses due to their continuous and quick broad-spectrum biocidal capabilities. Given the rise in antibiotic resistance, these nanoparticles have pharmacological benefits for humans in safeguarding and treating infectious disorders. These benefits are anticipated to have a higher impact in low-resource nations with limited access to treatment, particularly antibiotics. Antimicrobial NMs will help meet the requirement for improved quality of life through advanced research, focused efforts, successful application, and commercialization. The antiviral competence of PPE kits and face masks can be improved to prevent the danger of cross-infection or any kind of secondary infection while using or during treatment. Recent advancements in this arena suggest that nanotechnology has the potential to fundamentally alter the form and efficacy of conventional respiratory protection systems.

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Notes

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