

Review

Application of Metal Nanoparticles for Production of Self-Sterilizing Coatings

Dariusz Góral ^{1,*}  and Małgorzata Góral-Kowalczyk ²

¹ Department of Biological Bases of Food and Feed Technologies, Faculty of Production Engineering, University of Life Sciences in Lublin, 28 Głęboka Str., 20-612 Lublin, Poland

² Department of Agricultural Forestry and Transport Machines, Faculty of Production Engineering, University of Life Sciences in Lublin, 28 Głęboka Str., 20-612 Lublin, Poland; malgorzata.goral-kowalczyk@up.lublin.pl

* Correspondence: dariusz.goral@up.lublin.pl

Abstract: Metal nanoparticles (NPs) are increasingly being used in many areas, e.g., industry, pharmacy, and biomedical engineering. NPs can be obtained through chemical and biological synthesis or using physical methods. AgNPs, AuNPs, CuNPs, FeNPs, MgNPs, SnO₂NPs, TiO₂NPs, and ZnONPs are the most commonly synthesized metal nanoparticles. Many of them have anti-microbial properties and documented activity supported by many tests against some species of pathogenic bacteria, viruses, and fungi. AgNPs, which are used for the production of commercial self-sterilizing packages, are one of the best-explored nanoparticles. Moreover, the EFSA has approved the use of small doses of silver nanoparticles (0.05 mg Ag·kg⁻¹) to food products. Recent studies have shown that metal NPs can be used for the production of coatings to prevent the spread of the SARS-CoV-2 virus, which has caused the global pandemic. Some nanoparticles (e.g., ZnONPs and MgONPs) have the Generally Recognized As Safe (GRAS) status, i.e., they are considered safe for consumption and can be used for the production of edible coatings, protecting food against spoilage. Promising results have been obtained in research on the use of more than one type of nanometals, which prevents the development of pathogen resistance through various mechanisms of inactivation thereof.



Citation: Góral, D.;

Góral-Kowalczyk, M. Application of Metal Nanoparticles for Production of Self-Sterilizing Coatings. *Coatings* **2022**, *12*, 480. <https://doi.org/10.3390/coatings12040480>

Academic Editor:
Alessandro Pezzella

Received: 5 March 2022

Accepted: 31 March 2022

Published: 1 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: metal nanoparticles; coatings; anti-microbial; self-sterilizing; packages

1. Introduction

Microbiological stability is particularly important in the case of food with a high water content (e.g., fruit and vegetables). Various physical and chemical methods are used to ensure the microbiological purity of food. There is a trend towards minimization of the use of chemical preservatives and replacement thereof with natural substances. However, this does not always yield a fully satisfactory solution. The great interest in nanoparticles can be attributed to their physicochemical properties and wide application in many industries [1–5]. In agricultural and production practice, cheap and easy protection measures against microorganisms are still a big challenge. New protection strategies against harmful microorganisms are continuously being developed. A promising approach may be the use of nanoparticles with antimicrobial and antiviral properties for the production of face masks, textiles, and other coatings [6–8]. The use of metal nanoparticles for surface functionalization has been particularly successful in obtaining unique textiles with desirable properties, such as self-cleaning, antimicrobial, antifungal, flame retardant, ultraviolet blocking, and superhydrophobicity [9]. The development of novel coatings that are safe, intelligent, and active is an important factor contributing to a reduction in food spoilage. The task of food coatings is to maintain the quality and properties of food products for as long as possible. Various additives are used to obtain intelligent and active food coatings. Nanoparticles occupy a special place among the huge variety of additives [10,11]. The term “nanoparticles” refers to solid particles with a size between 1 and 100 nm [12,13]. Nanoparticles usually have different properties than their macroscopic counterparts. In

biological applications, the reduction in the size of metal particles to the nanometer scale is associated with an increase in their cytotoxicity. This is associated with their larger active surface and thus a higher reactivity than that of conventional materials and interactions with other compounds present in the environment. They also exhibit a higher bioavailability, which makes them easier to adsorb in specific organs, tissues, and cells [14]. Another special active property of nanoparticles is their ability to absorb ultraviolet light, which is considered important for the prevention of photochemical reactions leading to the spoilage of food products. Nanoparticles also exert an antioxidant effect, which is a highly desirable property [10]. Moreover, their most noticeable trait is the lower light scattering degree accompanying a reduction in the particle size. Sufficiently small particles can form transparent coatings. Nanoparticles do not directly induce transparency, but their light scattering effect declines with the decreasing particle size. At the same time, light scattering depends on the difference in the refractive index between the particle and the surrounding medium. A close match of refractive indices promotes the formation of transparent mixtures [12]. Particles must be very well dispersed to achieve transparency in the nanoscale system, as agglomerated nanoparticles have the same optical properties as particles with the size of the agglomerate [12].

Depending on their shape, nanoparticles are classified as zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D). This classification is associated with the movement of electrons in different planes. Electrons in 0D are trapped in a dimensionless space, whereas the electrons of 1D nanomaterials can move along the x-axis. 2D and 3D nanomaterials have electrons moving along the x-y axis and the x-y-z axis, respectively [15]. One-dimensional nanomaterials form long nanostructures with thick membranes, i.e., nanotubes, nanofibers, nanowires, nanorods, and nanofilaments. Their length is greater than their width [16]. In turn, 2D nanomaterials have sheet-like structures. These nanomaterials have the largest specific surface area of all known nanoparticles [17]. Due to their high surface-to-volume ratio and the anisotropic physical and chemical properties, 2D nanomaterials are widely used against microorganisms and are attractive for food packaging applications. Large-area 2D nanomaterials directly interact with bacterial membranes, thereby enhancing the antibacterial effect [18,19].

2. Aim of the Application of Nanoparticles in Packaging

Nanotechnological inventions are used in computers, nanodiodes, nanotransistors, etc. This technology provides innovative solutions for the production of batteries, fuel cells, and solar cells, which are lighter, more durable, and stronger than those produced with other methods [20]. Nanomaterials exhibit increased catalytic activity, thermal conductivity, and chemical stability [21]. They are also used in various fields of science; in particular, biology and biomedicine. The size of nanorods, nanofibers, and other nanomaterials is comparable to the size of biological particles [22]. Metal-based nanoparticles effectively inactivate microorganisms. Hence, some of them, e.g., silver, titanium dioxide, and zinc oxide nanoparticles, are used as disinfectants and additives in food, cosmetic, and pharmaceutical packaging [14]. Another example is the use of nanoparticles for surface protection and the conservation of antiquities made of marble, stone, glass, bronze, and even objects made of bread [23].

One of the very promising approaches to fighting bacteria is the use of nanomaterial-based antimicrobials. Antimicrobial coatings can be divided into two main groups, germicidal (active) and bacteriostatic (passive). Bactericidal active coatings are able to disrupt the structural integrity of the bacterial cell or membrane. In contrast, bacteriostatic coatings can prevent or reduce the attachment of microorganisms to their surface [24]. Nanoparticles have been well documented to kill bacteria via several different mechanisms [25]. They have the ability to damage the cell membrane physically. They can also generate reactive oxygen species (ROS) and free radicals. This process intensifies oxidative stress, which enhances the fragmentation of genomic DNA and damages the structural integrity of cells [26]. Furthermore, nanoparticles penetrate cell membranes much more easily than

antibiotics [27,28]. Recent reports also indicate that nanoparticle-based antimicrobials act as efficient inhibitors of efflux pumps (proteins present in cell membranes) [29,30]. This proves that nanometals may have multiple applications as antimicrobial agents. Moreover, they are more effective than other antimicrobial agents and are less prone to induce bacterial resistance than antibiotics available on the market.

3. Methods for Production of Metal Nanoparticles

Metal nanoparticles can be produced using chemical, physical, and biological methods (Figure 1).

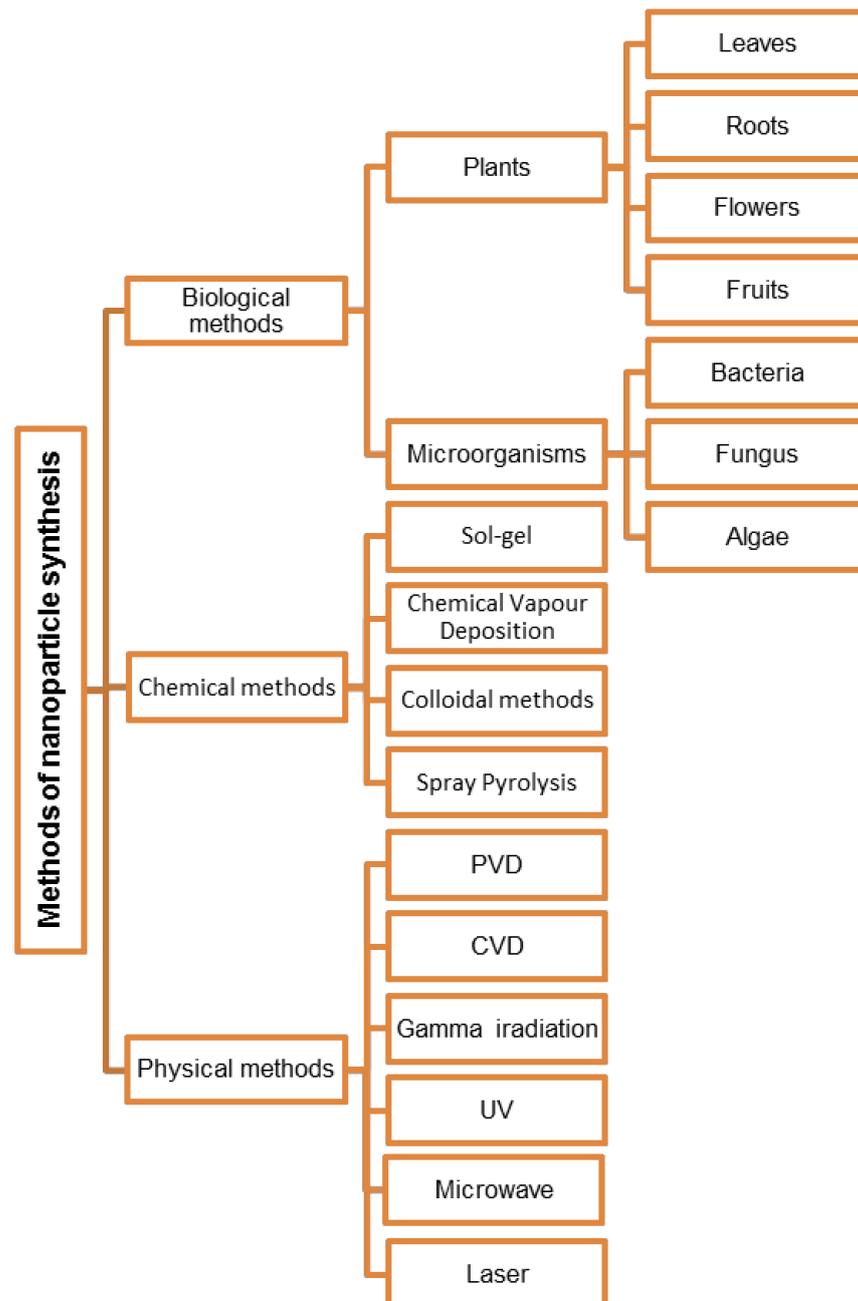


Figure 1. Methods for production of metal nanoparticles.

There are two basic strategies used in the production of nanoscale structures: bottom-up and top-down. The former approach is based on the atom-by-atom construction of a nanoparticle. Depending on the required properties of the end product, atoms, molecules,

or colloidal particles can be used as substrates. The control of the synthesis conditions and the initial size of the building material can determine the traits of the final structure. A reverse mechanism is employed in the top-down process based on dispersion methods, which are based on the fragmentation of materials, yielding a final size of the particles in the range of 1–100 nm [31].

3.1. Chemical and Physicochemical Methods

Chemical methods are currently regarded as the most popular approaches, although they are not always safe and environmentally friendly. The synthesis of metal nanoparticles using chemical methods is based primarily on chemical reduction. The reaction consists of three steps: reduction of metal salts and formation of free atoms, nucleation, i.e., formation of stable 1–2 nm nuclei, and addition of stabilizing agents to complete the reaction. Currently, this is the cheapest method. Borohydride, citrate, ascorbate, and compounds with hydroxyl or carboxyl groups, i.e., alcohols, aldehydes, carbohydrates, and their derivatives, are the most frequently used reducing agents [32–36]. The process of chemical reduction requires the use of a stabilizing substance whose main task is to protect newly formed nanoparticles against aggregation into larger aggregates [31,37,38]. Such polymers as poly(vinylpyrrolidone) (PVP) [39], poly(methylacrylic acid) (PMAA) [40], poly(methyl methacrylate) (PMMA) [41], and poly(ethylene glycol) (PEG) are used most frequently as stabilizing agents [42]. The greatest advantage of this method is the possible impact on the properties of the final product through regulation of the process conditions. For example, the shape, size, aggregation state, and stability of nanoparticles can be controlled by changing the concentration of the stabilizer or salt, the molar ratio of the reducing and stabilizing agent, temperature, and medium pH [43].

3.2. Physical Methods

Physical methods are based on the top-down strategy. Particularly popular are the methods of physical vapor deposition (PVD), in which, a solid material is converted into gas in physical processes and then deposited on the substrate [44]; chemical vapor deposition (CVD), in which, products of chemical reactions are deposited on the substrate [45]; the use of the electromagnetic microwave field, in which, a substantially faster heating rate of the reaction mixture is achieved than in the convection heating process [46]; and the method based on γ or UV radiation used as a catalyst for a chemical reaction [47,48]. Another method for the production of various types of nanoparticles is the application of laser radiation. In this approach, nanoparticles are generated by the nucleation and growth of laser-vaporized metals in background gas [49] (Figure 1).

3.3. Green Synthesis

Green synthesis is gaining increasing support as a sustainable, reliable, and environmentally friendly approach to the synthesis of various nanoparticles. It does not require the use of solvents that pose a threat to humans and the environment or additional reducing agents. This technique of producing nanoparticles is simple and cost-effective [50–53]. It is based on the production of nanoparticles with the use of plant parts or microorganisms (Figure 1, Table 1) [54]. As in the chemical and physical methods, two approaches in the generation of nanoparticles from living organisms are used, i.e., the top-down and bottom-up strategies. In the top-down methods, the material is fragmented with the use of various techniques, whereas the bottom-up methods are based on the self-organization of atoms leading to the formation of new cell nuclei in chemical or biological reactions [55]. Nanoparticles produced via green synthesis are less toxic to living organisms [56].

Table 1. Shape and size of nanoparticles obtained by green synthesis.

Nanoparticles	Shape	Size, nm	Source	References
ZnONPs	spherical	129	Daphne leaves	[57]
	plate	87		
	hexagonal	10–42	<i>Fusarium keratoplasticum</i>	[58]
	rod	8–38	<i>Aspergillus niger</i>	
	hexagonal	15.45	<i>Alternaria tenuissima</i>	[59]
	quasi-spherical	16–78	<i>Periconium</i> sp.	[60]
	star	50–80	cyanobacterium <i>Nostoc</i> sp.	[61]
AgNPs	spherical	35–42.5	cacao powder	[62]
	cubic and spherical	30–90	leaves of <i>Juniperus procera</i>	[63]
	spherical	28	tea polyphenol	[64]
		35	<i>Nyctanthes arbor-tristis</i>	[65]
	circular	100	<i>C. cladosporioides</i>	[66]
	triangular	25	<i>Talaromyces purpureogenus</i>	[67]
	spherical	30–50	coral	[68]
AuNPs	spherical	14–17	<i>Macrotyloma uniflorum</i>	[69]
	spherical	3–45	leaves of <i>Bacopa monnieri</i>	[70]
	cubic	20–50	flower of Butterfly tree	[71]
	triangular, hexagonal, pentagonal, rod, and truncated	25–100	<i>Ipomoea carnea</i>	[72]
	triangular	600–800	pumpkin	[73]
	spherical and narrow	45–75	<i>Abelmoschus esculentus</i>	[74]
CuNPs	spherical, hexagonal, cylindrical, triangular, and prismatic shapes	10–50	leaves of <i>Hagenia abyssinica</i>	[75]
	spherical	50–250	leaves of <i>Magnolia kobus</i>	[76]
	spherical	2–10	<i>Celastrus paniculatus</i>	[77]
PdNPs	spherical	50–150	<i>Prunus × yedoensis</i>	[78]
TiO ₂ NPs	different	200	<i>Sesbania grandiflora</i>	[79]
	spherical	15–20	jackfruit leaves	[80]
	spherical	20–90	<i>Trigonella foenum-graecum</i>	[81]
MgO NPs	spherical and cylindrical	67.70	<i>Persimmon</i>	[82]
FeO NPs	honeycomb	30–100	flowers of <i>Avecinnia marina</i>	[83]
	spherical	58 to 530	<i>Amaranthus spinosus</i> leaf	[84]

The most common metal nanoparticles produced via green synthesis are oxide and dioxide, including polymer-coated iron [85], zinc [86], copper [87], gold [88], silver, and their oxides [27,89,90]. Many plant species are used in the production of metal nanoparticles (Table 1). The fruits of langsat (*Lansium domesticum*) and amla (*Phyllanthus emblica*) are used for the production of gold nanoparticles with antimicrobial activity. In turn, AgNPs are rapidly synthesized with the use of *Calendula officinalis* and *Capsicum annum* seeds. Tea plant (*Camellia sinensis*) leaves serve as a catalytic agent in the synthesis of ZnONPs [3]. Younis et al. [91] used dried *Rosa floribunda* petals for the green synthesis of MgONPs. Asiya et al. [92] used lemon fruit (*Citrus limon*) to produce gold nanoparticles. Another promising

trend in the production of nanoparticles is the use of biowaste, contributing to a reduction in its amounts. This approach has been reported by Jain et al. [93], who used the skin of jackfruit (*Artocarpus heterophyllus*) to isolate iron nanoparticles.

4. Antimicrobial Properties of Metal Nanoparticles

The direct toxic effects of metal nanoparticles on organisms depend primarily on the type and surface reactivity. Indirect effects are due to physical confinement, the release of toxic ions, or from the generation of reactive oxygen species (ROS). ROS are thought to lead to additional cellular responses classified as defense, proinflammatory effects (in plant and animal cells), and cytotoxicity [94,95]. Indirect toxicological effects of metal nanoparticles may include: oxidative stress and inflammation associated with ROS production, glutathione depletion and accumulation of oxidized glutathione in response to ROS production, protein denaturation, membrane damage, DNA damage, immune system reactivity and foreign body granuloma formation, and a reduction or loss of photosynthetic activity in algae and plants [95,96]. Much recent research has been directed toward developing self-responsive systems, e.g., triggered by specific physiological environments (local acidity, presence of substances secreted by bacteria) or external stimuli (photothermal, electrical, magnetic) [23,24,97,98].

4.1. Antibacterial Activity

The antibacterial activity of metal nanoparticles depends on their size, chemical composition, surface structure, solubility, shape, and tendency to aggregate, as well as environmental conditions, e.g., pH, salinity, and the presence of organic matter. The cell wall of Gram-positive bacteria is a complex mixture of glycopolymers and proteins. It consists of a peptidoglycan sacculus composed of long polysaccharide chains linked via peptide bridges. The wall surrounds the cytoplasmic membrane. It plays an important role in bacterial physiology, as it maintains the shape and integrity of the cell during growth and division. Additionally, it acts as an interface between the bacterium and its environment [99]. The bacterial cell wall is mostly composed of murein, which is multilayered in Gram-positive bacteria. In turn, Gram-negative bacteria have a single layer of murein additionally surrounded by an outer membrane. The potential mechanisms of the antibacterial effect of metal nanoparticles consist of their impact on the structure and function of cell membranes, disturbances in metabolic processes caused by the generation of reactive oxygen species, and a negative influence on the activity of enzymes and DNA synthesis [100]. As suggested by Wong et al. [101], nanoparticles should be smaller than 50 nm to become effective antimicrobial agents. Table 2 shows examples of the antimicrobial activity of metal nanoparticles.

The antiseptic capacity against eukaryotic cells is different. The feature that distinguishes eukaryotic cells from prokaryotic cells (bacteria, archaeons) is a very complex internal structure. Among other things, eukaryotic cells have a cytoskeleton. Nanoparticles, immobilized in a gel matrix, can exert antimicrobial activity by contacting the bacterial membrane, while they cannot be taken up and internalized by eukaryotic cells [102]. Gold and zinc nanoparticles in the form of colloidal solutions that allow penetration into cells may be effective against eukaryotic cells [103,104]. In the case of fungi, which belong to the group of eukaryotic organisms, the same interactions between nanometals and cells occur as in the case of bacteria [87].

Another important consideration is the long-term stability of nanoparticle surfaces and the ability to maintain antibacterial properties over time. A promising strategy is so-called smart antimicrobial surfaces, which can kill bacteria attached to their surface and then release dead bacteria and other contaminants on demand to reveal a clean surface under the right stimulus [105].

Table 2. Antimicrobial activity of metal nanoparticles.

Metal	Pathogens	Nanoparticles	Genus or Species	References
Ag	Bacteria		<i>Acinetobacter baumannii</i> , <i>Coliform bacteria</i> , <i>Escherichia Coli</i> , <i>Klebsiella pneumoniae</i> , <i>Listeria monocytogenes</i> , <i>Salmonella enterica</i> , <i>Salmonella typhi</i> , <i>Staphylococcus aureus</i> , <i>Vibrio cholerae</i> , <i>Pseudomonas aeruginosa</i>	[62,106–111]
	Viruses	AgNPs	Adenovirus type 3 (Ad3), Chikungunya virus (CHIKV), CoxB4, HAV-10, HSV-1, Hepatitis B virus (HBV), Herpes simplex virus (HSV), Human immunodeficiency virus (HIV), Influenza virus, Poliovirus, Respiratory syncytial virus (RSV), SARS-CoV-2	[112–120]
	Fungi		<i>Candida albicans</i> , <i>Candida parapsilosis</i> , <i>Candida tropicalis</i> , <i>Microsporium canis</i> , <i>Trichophyton mentagrophytes</i> ,	[121,122]
Au		AgNPs, AgCINPs	<i>Aspergillus flavus</i> , <i>Aspergillus niger</i> , <i>Candida albicans</i> , <i>Cladosporium cladosporioides</i>	[66,68,123]
	Bacteria	AuNPs	<i>Corynebacterium pseudotuberculosis</i> , <i>Escherichia coli</i> , <i>Streptococcus pneumoniae</i>	[124–126]
		Gold-chitosan hybrid nanoparticles	<i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i>	[127]
	Viruses	AuNPs	Dengue, Herpes simplex virus (HSV), Human papillomavirus, Influenza, Lentivirus, Measles virus (MeV), Respiratory syncytial virus (RSV), Vesicular stomatitis virus (VSV)	[128–131]
	Fungi		<i>Aspergillus flavus</i> , <i>Aspergillus niger</i> , <i>Candida albicans</i> , <i>Trichophyton rubrum</i>	[132]
Bi	Bacteria	BiNPs	<i>Enterococcus faecalis</i>	[133]
Cd	Bacteria	CdONPs	<i>Staphylococcus aureus</i>	[134]
Cu	Bacteria	CuNPs	<i>Bacillus subtilis</i> , <i>Escherichia coli</i> , <i>Listeria monocytogenes</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> ,	[75,107,135]
		CuONPs	<i>Bacillus subtilis</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , <i>Klebsiella pneumoniae</i>	[136,137]
	Viruses	CuINPs	Feline calicivirus (FCV), H1N1 influenza	[138]
		CuSNPs	Human norovirus	[139]
Cu ₂ ONPs		Hepatitis C virus (HCV)	[140]	
		CuONPs	Herpes simplex virus type 1 (HSV-1)	[141,142]
Fe	Bacteria	FeONPs	<i>Staphylococcus aureus</i>	[143]
		Fe ₂ O ₃ modified by Ag	<i>Escherichia coli</i>	[144]
	Viruses	FeONPs	Dengue virus, Influenza A subtypes: H1N1, H5N1, and H7N9, Rotavirus	[145–147]
	Fungi	FeONPs	<i>Alternaria alternate</i> , <i>Aspergillus niger</i>	[20]
Mg	Bacteria	MgONPs	<i>Acinetobacter baumannii</i> , <i>Enterobacter cloacae</i> , <i>Enterococcus faecalis</i> , <i>Escherichia coli</i> , <i>Bacillus megaterium</i> , <i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , <i>Staphylococcus epidermidis</i>	[148–150]
Mn	Bacteria	MnNPs	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i>	[151]
Ni	Bacteria	NiFe ₂ O ₄ NPs	<i>Escherichia coli</i> NCIM 2345, <i>Salmonella typhimurium</i> NCIM 2501, <i>Staphylococcus aureus</i> NCIM 5021, <i>Streptococcus pyogenes</i> NCIM 5280	[152]
		NiONPs	<i>Bacillus subtilis</i> , <i>Escherichia coli</i> , <i>Protius mirabilis</i> , <i>Staphylococcus aureu</i> , <i>Streptococcus pneumoniae</i>	[153,154]

Table 2. Cont.

Metal	Pathogens	Nanoparticles	Genus or Species	References
Pd	Bacteria	PdNPs	<i>Bacillus subtilis</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i>	[78,155]
Pt	Bacteria	PtNPs	<i>Bacillus subtilis</i> , <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i>	[151]
	Fungi		<i>Aspergillus</i> sp., <i>Candida</i> sp.	
Sn	Bacteria	SnO ₂ NPs	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i>	[156–158]
	Fungi		<i>Candida albicans</i>	[159]
Ti	Bacteria	TiO ₂ NPs	<i>Bacillus subtilis</i> , <i>Enterococcus faecalis</i> , <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , <i>Proteus vulgaris</i> , <i>Pseudomonas aeruginosa</i> , <i>Salmonella typhimurium</i> , <i>Staphylococcus aureus</i> , <i>Streptococcus faecalis</i> , <i>Yersinia enterocolitica</i>	[80,81,160]
	Viruses		Herpes simplex virus (HSV), Human norovirus, Influenza virus (A/PR8/H1N1)	[161–163]
	Fungi		<i>Aspergillus fumigatus</i> , <i>Arthrographis cuboid</i> , <i>Aspergillus niger</i> , <i>Candida albicans</i>	[81,164,165]
V	Bacteria	Nalidixic acid-vanadium (V-NA) nanoparticles	<i>Bacillus cereus</i> , <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i>	[166]
Zn	Bacteria	ZnONPs	<i>Bacillus cereus</i> , <i>Bacillus subtilis</i> , <i>Campylobacter jejuni</i> , <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , <i>Listeria monocytogenes</i> , <i>Pseudomonas aeruginosa</i> , <i>Pseudomonas vulgaris</i> , <i>Salmonella</i> spp., <i>Staphylococcus aureus</i>	[58,108,167]
	Viruses		H1N1 influenza virus, Herpes simplex virus type-1 (HSV-1)	[168,169]
	Fungi		<i>Alternaria alternata</i> (ITCC 6531), <i>Aspergillus niger</i> (ITCC 7122), <i>Candida albicans</i>	[60,170]
Zr	Bacteria	ZrO	<i>Bacillus subtilis</i> MTCC 1305, <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> MTCC 2453, <i>Staphylococcus aureus</i> MTCC 3160	[171]

4.2. Antifungal Activity

Metal nanoparticles can be used as potential inhibitors of fungal microorganisms (Table 2). To achieve the antifungal effect, nanoparticles are most often produced with the use of physical and chemical methods and less often through biosynthesis. It has been found that the mechanisms of action of nanometals against fungi are similar to those involved in their antibacterial properties, e.g., the induction of oxidative stress through ROS generation, damage to the cell wall and membrane through direct contact with nanoparticles, and cellular uptake of nanoparticles and subsequent harmful interactions with the cell interior [172]. In some cases, nanoparticles induce the deformation of fungal hyphae. Fungicidal activity is exhibited by the nano-oxides of some metals as well [173].

4.3. Antiviral Activity

Due to their unique properties, metal and metal-based nanoparticles have a number of medical applications in the treatment of diseases or as antiviral coatings of biological materials. Nanoscale metals, e.g., copper, silver, and gold, exhibit potent biocidal properties [174,175]. Their antiviral activity described in the available literature [128,176–179] consists of:

- Modification of the viral surface to prevent penetration into cells;
- Generation of virus-degrading reactive oxygen species (ROS);

- Interactions with structures present on the virus surface, proteins, and nucleic acids to destroy the integrity of the virus and inhibit its vital functions (genome replication, protein synthesis);
- Cleavage of disulfide bonds between cysteine amino acid residues to denature and inactivate viral glycoproteins.

The mechanisms through which certain nanoparticles act on different viruses are highly variable and depend both on the reactivity of the nanoparticles and on the structure of the virus [178]. Nanoparticles can be designed to contain conventional antiviral properties and traits that are unique to nanosystems, i.e., a small size, a high surface-to-volume ratio, and multi-functionality. This makes them an ideal component for the creation of anti-viral surfaces. Poorly water-soluble and unstable compounds can be modified with nanocarriers to ensure a better solubility and stability in physiological conditions [7].

5. Antimicrobial Properties and Applications of Some Metal NPs

5.1. Silver Nanoparticles (AgNPs)

Nanosilver is one of the most widely used biocidal nanometals. In fact, ionic silver has been eliminated from use by silver nanoparticles. This is mainly related to the susceptibility of silver ions to the formation of precipitation complexes inactivating the metal. Moreover, nanosilver is potentially safer, and its bactericidal properties can be additionally enhanced by, e.g., the addition of stabilizers [180]. A new technique to exploit the biocidal capacity of nanosilver is to produce biological cells with functionalized surfaces. Nanoparticles stabilized with cationic polymers adhere electrostatically to microbial cells, forming a uniform monolayer on the cell walls. “Cyborg” cells are then used to deliver the nanoparticles to the pathogenic microorganisms [181].

One of the bactericidal mechanisms of action is the binding of silver ions released from the surface of nanoparticles to the cell wall. It has been demonstrated that silver nanostructures ranging in size from several to a few dozen nanometers induce perforations in the bacterial wall, leading to bacterial death [182]. Silver nanoparticles can also cause the detachment of the wall from the cell membrane in *Staphylococcus aureus* and *Escherichia coli*, causing annihilation of these bacteria [183]. In comparison with Gram-negative bacteria, Gram-positive bacteria exhibit a greater resistance to nanosilver, as they contain greater amounts of negatively charged murein, which binds silver cations in the cell wall, thus limiting the penetration of the metal into the bacterial interior. Through damage to the cell wall, nanoparticles disrupt the electron transport chain, which results in disturbances in metabolism. This is related to the ability of nanosilver to absorb oxygen and catalyze the oxidation reaction. Oxygen absorbed on the surface of silver ions removes the hydrogen atom from cysteine thiol (–SH) groups. The removal of hydrogen yields a –S–S– bond between the amino acids. When this reaction takes place inside the electron transfer channel, the channel is closed and the bacterium loses the cellular respiration function and, consequently, dies [184]. Silver nanoparticles penetrating the cytoplasm are able to catalyze intracellular reactions and interact with cellular structures. Through reactions with functional groups of sulfur amino acids, they are responsible for damage to receptor and transport proteins, as well as enzymes, which disrupts the proper cell functioning. The bactericidal properties of silver nanoparticles are also associated with the generation of reactive oxygen species (ROS). These reactive chemical entities contain oxygen atoms with an unpaired electron. They exert a detrimental effect on microbial metabolism [185]. It was shown that 15 nm silver nanostructures were responsible for an increase in the concentration of ROS inside the cells of nitrifying bacteria. The high concentration of reactive oxygen species exhibited a strong correlation with the degree of microbial growth inhibition.

Raczkowska et al. [186] demonstrated the temperature dependence of biocidal intensity for POEGMA188 and P4VP coatings containing nanosilver. Siriwardana et al. [187] reported the ability of silver nanoparticles to bind and cleave disulfide bonds. This mechanism can potentially be used to combat the SARS-CoV-2 virus. In the case of enveloped viruses, AgNPs inhibit the process of viral nucleotide copying in infected cells, which,

in turn, prevents virus replication [188]. With its biocidal properties, Ag excellently disinfects and protects contact surfaces [113,189]. In addition to pure silver nanoparticles, functional antiviral agents containing nanoparticles of silver compounds can be successfully produced, e.g., to combat SARS-CoV-2 [190]. Silver nanoparticles can also be used to produce self-sterilizing composite polymers, custom packaging, and contact surface sterilizers [191,192]. Silver nanoparticles, with their well-explored properties, are part of commercial packaging (e.g., Duretham, DuPont, Sumitomo, Metal Ferro, NovaCentrix, US Research Nanomaterials, NANOMAS, Heraeus, and Kodak) extending the shelf life of food products [193] (Table 3).

Table 3. Application of silver and copper nanoparticles for production of self-sterilizing materials.

NPs	Concentration	Material	Patogens	References
AgNPs	0.27 ppm	Polyhydroxyalkanoate bioplastic film	Surrogates, murine norovirus (MNV), Feline calicivirus (FCV)	[192]
	1% (complete inactivation)	Poly lactide plastic	<i>Salmonella</i> spp., Feline calicivirus FCV	[191]
	AgNO ₃ (0.5 M, 35 mL) and ethylene glycol, 25% inhibition of infection	Graphene oxide sheets	Feline coronavirus (FCoV)	[194]
	Less than 1 mg per 10 mL	PLA/silver-based nanoclay (organomodified MMT)	<i>Salmonella</i> spp.	[195]
	20 mg AgNPs per 150 mL	Agar nanocomposite films	<i>Escherichia coli</i> , <i>Listeria monocytogenes</i>	[38]
	MSF-Ag at 110 µg per mL of <i>S. aureus</i> and 70 µg per mL of <i>E. coli</i>	Mesoporous silica flakes (MSF)	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i>	[196]
	25 mg L ⁻¹ (silver content 1.5 mg L ⁻¹)	Monodispersed silica spheres	<i>Escherichia coli</i>	[89]
	0.005 M AgNO ₃ solution	Temperature-responsive POEGMA188 and P4VP grafted polymer brush coatings attached to a glass surface	<i>Escherichia coli</i> ATCC 25922, <i>Staphylococcus aureus</i> ATCC 25923	[186]
	0.04–1.18 silver nitrate (mol L ⁻¹)	Poly(N-isopropylacrylamide) (PNIPAAm) glass surfaces	<i>Escherichia coli</i>	[197]
	CuONPs	0.1% or 0.05%	Electrospun poly(3-hydroxybutyrate-co-hydroxyvalerate) PHBV polymers	Murine norovirus
Cu ₂ ONPs	2%	Face mask	Influenza A viruses (H1N1)	[199]
CuNPs	0.01–0.15 g L ⁻¹ Cu ²⁺	Cotton and polyester substrates	<i>Staphylococcus aureus</i> ATCC 25923	[200]

5.2. Titanium Dioxide Nanoparticles (TiO₂NPs)

TiO₂ is a well-known and relatively cheap metal oxide used in the photocatalysis process. It has a number of desirable properties, e.g., it is an excellent inhibitor of UV-activated viruses [201]. In industry, TiO₂ nanoparticles are used in filters, cosmetics, toothpaste, and soaps; they have strong bactericidal properties, remove odors, and, in combination with silver, serve as antibacterial agents. Titanium oxide nanoparticles generated through green synthesis exhibit very good antibacterial activity [81]. However, in 2016, the EFSA outlined the need for further research into the safety of TiO₂. Since that year, TiO₂ has no longer been regarded as a safe food additive. Its genotoxicity and accumulation in the organ-

ism after ingestion cannot be ruled out. Nevertheless, there is no ban on the use of TiO₂ nanoparticles in the food industry [202]. There is ample evidence in the literature showing the effects of TiO₂NPs on such viruses as human norovirus [161], human influenza virus (A/PR8/H1N1) [162], and herpes simplex virus [163]. However, TiO₂ is activated only by UVA photons ($\lambda < 387$ nm), which may limit its use in rooms with dominant visible-range lighting. Nakano et al. [162] confirmed that TiO₂-coated glass exhibited virucidal activity. In turn, the reduction in influenza virus titers below the limit of detection at typical indoor lighting intensity (~ 0.01 mW·cm⁻²) required an almost 24 h exposure. Park et al. [161] showed that TiO₂ combined with fluorine exhibited better virucidal activity. The authors suggest that the surface fluorination of TiO₂ reduces UV reflection and generates additional free OH⁻ and O₂, which can damage viruses. The TiO₂ photodegradation mechanism is effective in the inactivation of both non-enveloped viruses (noroviruses) and enveloped viruses, such as HSV-1. The SARS-CoV-2 virus is an enveloped virus, similar to HSV-1, with a similar lipid bilayer shell, and may be susceptible to the effects of TiO₂ [202]. As reported by Srivastava et al. [187], titanium oxide nanoparticles are effective in killing Newcastle disease viruses (NDV). Similar studies were conducted by Mazurkova et al. [203], who demonstrated the antiviral effect of these nanoparticles against the influenza virus, even when no UV radiation was used. As suggested in their study, TiO₂NPs can inactivate viruses through the penetration and disintegration of their envelope. It has been shown that TiO₂ nanoparticle coatings are a promising solution for the production of sterile surfaces and prevention of virus transmission.

5.3. Magnesium Oxide Nanoparticles (MgONPs)

MgONPs have many properties, e.g., antimicrobial activity, chemical inertness, thermal stability, photostability, electrical insulation, non-toxicity, good biocompatibility and biodegradability, high surface area-to-volume ratio, low production cost, UV-blocking ability, and photocatalytic activity [204]. Hence, they are widely applied in such areas as food packaging, pharmacy, and medical sciences [46]. Magnesium oxide nanoparticles exert an extremely potent antibacterial effect, and their safety has been confirmed by the FDA (Food and Drug Administration) [205]. Mg is an essential element for living organisms; nevertheless, its nanoxide form makes magnesium highly active. Its antimicrobial activity is based on ROS production and lipid peroxidation [206]. MgO nanoparticles can also adhere to cell walls and break peptide bonds [207]. As reported by Huang et al. [208], nano-MgO used both directly and as an additive to interior wall paint has more potent bactericidal activity than TiO₂. Moreover, nano-MgO is active even in the absence of radiation.

5.4. Zinc Oxide Nanoparticles (ZnONPs)

Due to their unique properties, ZnO nanoparticles are used in medicine. There are many methods for ZnONPs synthesis and each yields nanoparticles with different morphological structures determining their properties. The nanoparticles have been shown to have antibacterial activity against a wide range of microorganisms, e.g., *Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Pseudomonas vulgaris*, and *Campylobacter jejuni* [209]. Additionally, they are used as drug transporters, in cancer therapy, and as strong antibacterial agents [210]. The US FDA has registered ZnO nanoparticles as GRAS [21]; hence, they are regarded as safe for the skin and can be used as dietary supplements [211]. The high toxicity of ZnO to pathogens and its minimal impact on human health facilitates the use of its nanoscale form for the production of food packaging and plastics with antimicrobial properties. Zinc oxide can be blended with petroleum-based biodegradable PHBV polymers to improve food stability and safety [192]. The bactericidal activity of ZnONPs consists of destructive diffusion through the cell membrane leading to bacterial cell lysis [212]. Moreover, ZnONPs have similar properties to TiO and can act as an effective, low-cost photocatalyst in the presence of water and sunlight or UV radiation [213]. The highest antibacterial activity against *E. coli* and *S. aureus* was achieved through the synthesis of ZnO nanospheres, with an average diameter of approx. 30 nm and largest

specific surface area of 25.70 mg [214]. In addition, in the case of viruses, ZnO nanoparticles induce the inhibition of protease and viral RNA and DNA polymerase [169,215]. As demonstrated by AbouAitah et al. [215], a nanoformulation with zinc nanoparticles is a potentially safe and low-cost hybrid agent that can be used as a new alternative strategy against the SARS-CoV-2 virus. This has been confirmed in the study conducted by El-Megharbel [216] showing virucidal properties of low concentrations of zinc nanoparticles (IC_{50} 526 ng/mL) against the SARS-CoV-2 virus. Biosynthesized ZnONPs have been found to exhibit antimicrobial activity against a wide variety of microorganisms (Table 2). This activity is associated with ROS production, cell membrane damage, and interactions of ZnONPs with intracellular components [217,218]. Schwartz et al. [219] have developed an antimicrobial hydrogel composite coating by mixing poly(N-isopropylacrylamide) with zinc oxide nanoparticles. The coating was effective in the complete inactivation of *E. coli* bacteria at a low zinc oxide concentration of 1.33 mM. Other studies have also shown that the process of coating the surface of ZnO nanoparticles with polyethylene glycol may increase their antiviral efficacy and reduce their in vitro cytotoxicity [169].

5.5. Gold Nanoparticles (AuNPs)

Gold is known for its stability and ability to form complexes with biomolecules that support its antiviral and antibacterial properties. One of the properties of gold-based nanoparticles is the ability to block viral surface receptors, preventing viruses from the attachment and penetration of host cells. With their virucidal activity, AuNPs may be used to prevent infections with MEV and other enveloped viruses, such as SARS-CoV-2 [128]. Many researchers have observed that the size of gold nanoparticles is important for their antiviral activity. Gold nanoparticles that are equal to or greater than viruses can act as effective cross-linkers, binding multivalently and entrapping many virions. In contrast, smaller gold nanoparticles are less effective in covering the surface of individual viruses [130,131,220]. AuNPs have bacteriostatic activity against various bacterial strains through two of the most important mechanisms: the inhibition of ATPase activity, which blocks energy metabolism, and the inhibition of transcription via the prevention of tRNA ribosome interactions [221]. There are few literature reports on the use of AuNPs for the production of biocidal surface coatings or personal protective equipment. This is most probably related to the relatively high cost of gold nanoparticles compared with the cost of other metals.

5.6. Iron Oxide Nanoparticles (FeONPs)

Iron oxide nanoparticles have many biomedical applications, from nanotherapy to imaging contrast agents [222]. They are characterized by a high biocompatibility and magnetic properties, which are used to induce local hyperthermia, e.g., in cancer therapy [223]. With their properties, FeONPs have been approved by the American Food and Drug Administration (FDA) and other European Union agencies [224]. These nanoparticles have antibacterial properties against both Gram-positive and Gram-negative pathogenic bacterial strains [225,226] and against such viruses as influenza virus [145], rotavirus [147], and dengue virus [146]. The main mechanism of the antimicrobial activity of iron nanoparticles is the oxidative stress generated by ROS. Superoxide radicals (O_2^-), hydroxyl radicals ($-OH$), hydrogen peroxide (H_2O_2), and singlet oxygen (1O_2) can damage bacterial proteins and DNA [225]. Researchers are investigating the potential use of iron nanoparticles for the inactivation of the SARS-CoV-2 virus. Abo-Zeid and Williams [226] carried out detailed theoretical analyses of the possibility of binding Fe_3O_4 (magnetite) and Fe_2O_3 (hematite) nanoparticles with the binding domain of SARS-CoV-2 protein receptors and the E1 and E2 glycoproteins of hepatitis C virus (HCV). Coating nanoparticles with, e.g., polyvinylpyrrolidone (PVP), polyethylene glycol (PEG), or glycine polymers can enhance their antiviral activity, increase their stability, and reduce their toxicity [227,228]. The degradation of rotavirus virion capsids has been induced by the mechanism of electrostatic adsorption

to large-surface nanoparticles [147]. This phenomenon can be employed in the design of surface coatings [229].

5.7. Copper-Based Nanoparticles

In contrast to some other nanoparticles (gold, silver), copper is an essential trace element for the human organism and can be used safely in small doses [230]. Due to their properties, copper nanoparticles and compounds have been applied as part of biocidal preparations. CuNPs have been found to exert numerous toxic effects on bacteria, e.g., reactive oxygen generation, lipid peroxidation, protein oxidation, and DNA degradation in *E. coli* cells [231]. The antiviral properties of cuprous iodide nanoparticles, which are devoid of brown color in contrast to other copper compounds, have been investigated. CuI nanoparticles have been shown to dissociate into Cu^+ and generate highly reactive hydroxyl (OH^-) radicals in phosphate-buffered saline [138]. It is well known that ROS cause oxidative damage to biological molecules by inducing nucleic acid mutations and random amino acid modifications [232]. CuI nanoparticles may exert such an effect against SARS-CoV-2 and other similar viruses. Both Cu(I) and Cu(II) oxides have been shown to be effective antiviral agents and to have antibacterial activity against both Gram-positive and Gram-negative bacteria [233]. Cu_2ONPs are effective in the fight against the highly mutagenic and drug-resistant hepatitis C virus (HCV). These nanoparticles block HCV attachment to host cells, thus inhibiting viral entry [141]. There are many studies on the use of nanoparticles for the production of packaging and personal protective equipment. For instance, biodegradable polymers and filtering masks containing CuNPs oxides have been investigated in this respect [198,199]. Some personal protective equipment has been approved by the FDA or the US Environmental Protection Agency (EPA) and is now available on the market [234,235].

5.8. Tin(IV) Oxide Nanoparticles (SnO_2NPs)

Tin(IV) oxide nanoparticles (SnO_2NPs) are inexpensive, non-toxic, and exhibit a high electron mobility, high photosensitivity, and good stability [236]. They exert potent anti-fungal effects on *C. albicans*, as confirmed in numerous studies [237]. Moreover, promising fungicidal effects were achieved with the use of various concentrations of tin-doped indium oxide nanoparticles [158]. Rehman et al. [159] investigated the antifungal activity of SnO_2 nanoparticles. They reported minimal fungicidal activity against *C. albicans* at a concentration >16 mg/mL. Maximum effects were achieved on *Escherichia coli* as well.

6. Hybrid Surfaces with More Than One Type of Nanoparticles

Given the different mechanisms of the biocidal activity of nanoparticles, a promising approach is to create hybrid surfaces with more than one type of particles to increase the self-sterilization efficiency. Hodek et al. [238] developed a hybrid polymethyl methacrylate (PMMA) surface coating containing silver, copper, and zinc cations to combat viruses present on surfaces. The HIV-1 titer was reduced by 99.5–100% after only a 20 min exposure to the coating. Other viruses were reduced by 97% (dengue virus), 100% (herpes simplex virus), and 77% (influenza virus). The researchers evidenced that the coating stably released ions at a sufficient rate to elicit virucidal activity but was safe for human cells. Nangmenyi et al. [144] developed a hybrid material composed of Ag-modified Fe_2O_3 nanoparticles embedded in fiberglass. Within the first minute of contact with the Ag/ Fe_2O_3 fiberglass, a 99% inactivation of the *E. coli* cultures was already observed. The combined use of metal nanoparticles may reduce the risk of the development of pathogen resistance via many different inactivation mechanisms [144].

7. Biocompatibility of Metal Nanoparticles

Biocompatibility is the property of a material or substance functioning properly in a living organism. This means that, in addition to being present in living tissues, it must fulfill certain functions [239]. Biocompatibility depends on many factors: the targeted delivery

mechanism, coating, biodegradability, chemistry of surface phenomena, structure, stability of nanoparticle colloidal solutions, and their ability to integrate into a cell or tissue without causing adverse effects (Figure 2). A lack of biocompatibility for nanoparticles means a disruption of cellular and tissue metabolism leading to toxic effects in the body [240].

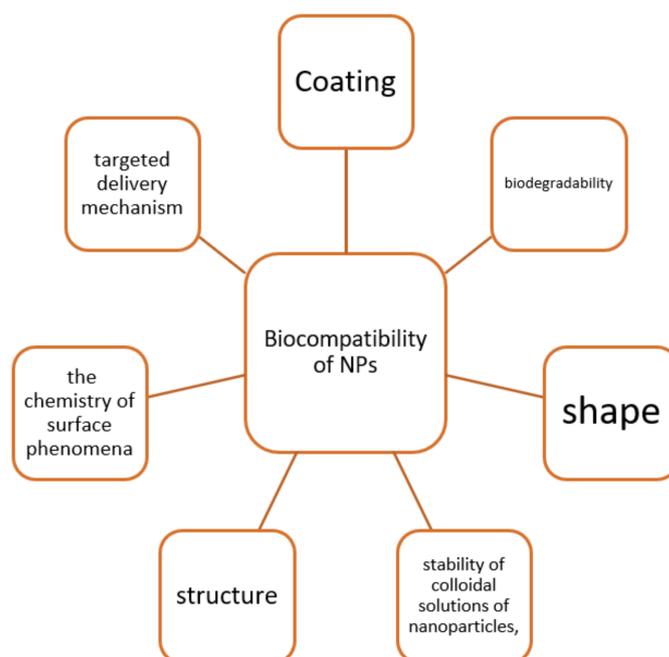


Figure 2. Chosen properties determining the biocompatibility of nanoparticles.

Nanoparticles show a higher biocompatibility than metal ions, which can attack both normal mammalian cells and pathogenic bacteria. The biocompatibility of antimicrobial agents with metal ions is often a major clinical problem. Pure metal nanoparticles with the highest biocompatibility include AuNPs. Compared with Ag and Cu nanoparticles, Au nanoparticles are much more biocompatible and therefore represent a potentially more therapeutically promising antimicrobial agent. In addition to pure metals, nanoparticles also exist in the form of metal oxides. Among the most biocompatible ones is ZnONPs. It is characterized by a low toxicity to living cells and can be successfully used for drug delivery, edible coatings, and, supportively, as a cosmetic additive [241]. Minimizing the toxicity of metal-based nanoparticles to normal eukaryotic cells without compromising their antimicrobial activity remains a major challenge. A future direction leading to an improved biocompatibility of nanoparticles may be the modification of their surface with polymers and peptides or polysaccharides [242,243].

8. Use of Metal Nanoparticles in Protective Edible Coatings

The appropriate packaging and coating of fresh fruit and vegetables is essential to prevent quick drying, loss of firmness, and exposure to pathogens. Coatings have an impact on water vapor permeability, which should be low in order to reduce the drying rate. Additionally, the oxygen permeability should be reduced to slow down respiration without the creation of anaerobic conditions promoting the emergence of bad taste and production of ethanol. Ideal coatings ensure resistance and durability during the distribution and transport of food products and high antimicrobial properties to minimize microbial growth [244]. Various active packaging systems are used to extend the shelf life of fruits and vegetables, e.g., oxygen and moisture absorbers, CO₂ emitters, and antioxidant/antimicrobial composites. In recent years, an increase in the use of bio/polymer nanocomposites based on nanoparticles (NPs) has been reported. The use of NPs in bio/polymers offers many advantages over other packaging systems. Submicron-

sized metal nanoparticles exhibit various possibilities for incorporation into food-grade polymer matrices serving as support systems. Metal nanosystems help to modify the properties of edible coatings. These properties are useful in solving food safety problems associated with pathogenic microorganisms, as they can limit the growth of yeasts, molds, and bacteria degrading the quality of food during storage and reducing the food shelf life [10]. Table 4 presents some studies on bio-nanocomposite films and edible coatings used to improve physicochemical properties of food and extend its shelf life.

Table 4. Examples of the use of metal nanoparticles in edible coatings.

NPs	Coating	Food	References
ZnONps	soy protein isolate	banana	[245]
	chitosan/gum arabic		[246]
	chitosan	papaya	[247]
	carboxymethyl-cellulose	pomegranate fruit	[248]
		tomato	[249]
		avocado	[250]
		tomato and apple	[251]
chitosan/alginate	guava	[252]	
AgNps	polylactic acid film	mango	[253]
	polyvinylpyrrolidone	asparagus	[254]
	carboxymethyl cellulose (CMC)-guar gum	strawberry	[255]
		black grapes	[256]
	sodium alginate-gum		
TiO ₂ NPs	chitosan/polyvinyl alcohol	cheese	[257]
	chitosan	tomato	[258]
Zn-MgONps	alginate solution	cold-smoked salmon	[259]
AgTiO ₂ NPs	chitosan	fruit	[260]

The use of metal nanoparticles in edible coatings poses several problems that have to be solved. One of them is associated with the achievement of uniform dispersion of NPs and the problem of the agglomeration of nanoparticles [261]. Edible coatings must be appropriately applied to the raw material. The coating process consists of wetting the food surface with the coating solution followed by an adhesion step, in which, the coating solution penetrates the fruit or vegetable peel. Therefore, a high affinity between the coating solution and the food surface is necessary to facilitate the spread of the coating over the surface. Dipping, brushing, spraying, pan-coating, and fluidized bed coating are well-known techniques, while electrostatic spraying has been used more recently [262].

Another issue is the undesirable effect of metal nanoparticles on the human organism [263]. Some nanoparticles have been approved for consumption, e.g., ZnONPs, which have been classified as GRAS by the FDA (21CFR73.1991) and as a safe additive (E6) by the EFSA [264]. Silver is on the EFSA list of the Scientific Committee for Food (SCF), i.e., a group of additives with no established daily intake recommendations but with an accepted level limited to 0.05 mg Ag/kg food, based on a maximum concentration that does not cause any detectable adverse changes in morphology, functional capacity, growth performance, or survival in humans [265].

Recently, due to the suspicion of some metal nanoparticles as carcinogens, many studies on non-toxicity and biocompatibility with the human body have been generated [266]. Tan et al. [267] investigated a polysaccharide coating based on metallic nanoparticles that was used as a packaging material to encapsulate curcumin. According to the authors, excellent biocompatibility properties were obtained. Pandey et al. [268] tested a protein-based

silver nanoparticle coating and found its low toxicity, effective application as a coating material for food products, and its high biocompatibility. Gnanasekar et al. [269] developed a material containing palladium nanoparticles that was safe for use in food and did not interact with red blood cells. It also destroyed bacterial cells and showed anti-cancer properties. Li et al. [270] used AuNPs to produce a β -glucan-based coating that was applied to edible mushrooms. This coating had beneficial effects in the gastrointestinal tract by causing the growth and activity of gut microbiota.

One of the trends in the latest research is the use of mixed nanomaterials, such as Zn-MgO, which is formed through association of zinc with highly biocompatible magnesium oxide (MgO) nanoparticles. The new material has been shown to retain strong antibacterial activity against Gram-positive bacteria, similar to ZnONPs, and to be safe for mammalian cells, similar to nano-MgO [259].

When analyzing the suitability of metal nanoparticles for commercial application in the production of self-sterilizing surfaces, several issues must be considered. Modified surfaces or new biocidal formulations in general face some serious challenges before they reach the market. Problems such as manufacturing costs, production scalability, intellectual property issues, or regulatory aspects are just some of the major hurdles that these products will have to overcome in order to be commercialized [271]. Some products, even with great lab results, fail when introduced on a larger scale due to high production costs, making them unattractive from a commercial standpoint. On the other hand, studies on the effects of a new product on human health are very time- and cost-intensive. However, the benefits of such materials may influence attempts to commercialize them [272].

9. Conclusions

1. Self-sterilizing coatings are widely used in many areas where pathogenic bacteria, viruses, and fungi are present. Their use seems to be one of the potential solutions to the problem of increasingly frequent global epidemics;
2. Zinc oxide nanoparticles are currently most widely used for surface coating due to their unique low cytotoxicity towards human cells, ROS-generating photocatalysis, and efficacy in damaging lipid membranes through diffusion and accumulation;
3. Similar to Ag and Cu, gold nanoparticles exhibit antiviral activity through binding to viral surface structures and thus inhibiting their function;
4. Iron oxide nanoparticles are characterized by a potent virus inhibition capability and biocompatibility, which can be increased via the modification of the polymer surface or hybridization with other particles. Moreover, they exhibit magnetic activity. Encapsulated iron and zinc nanoparticles have a greater antiviral activity and lower toxicity than non-encapsulated nanoparticles;
5. Given the evidenced effectiveness, low cytotoxicity, and relatively low cost of production, it is advisable to incorporate copper oxide NPs into the structures of self-sterilizing materials, including biodegradable polymers. Cu_2O -NPs are a promising option for the design of a new antiviral agent, and prompt further research into their practical application;
6. Some non-toxic nanometal particles are used for the production of edible coatings to prevent food spoilage.

Author Contributions: Conceptualization, D.G. and M.G.-K.; writing—original draft preparation, M.G.-K.; writing—review and editing, D.G.; visualization, M.G.-K.; supervision, D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jung, S.; Myung, Y.; Das, G.S.; Bhatnagar, A.; Park, J.W.; Tripathi, K.M.; Kim, T. Carbon nano-onions from waste oil for application in energy storage devices. *New J. Chem.* **2020**, *44*, 7369–7375. [[CrossRef](#)]
2. Tripathi, K.M.; Tyagi, A.; Ashfaq, M.; Gupta, R.K. Temperature dependent, shape variant synthesis of photoluminescent and biocompatible carbon nanostructures from almond husk for applications in dye removal. *RSC Adv.* **2016**, *6*, 29545–29553. [[CrossRef](#)]
3. El-Seedi, H.R.; El-Shabasy, R.M.; Khalifa, S.A.M.; Saeed, A.; Shah, A.; Shah, R.; Iftikhar, F.J.; Abdel-Daim, M.M.; Omri, A.; Hajrahand, N.H.; et al. Metal nanoparticles fabricated by green chemistry using natural extracts: Biosynthesis, mechanisms, and applications. *RSC Adv.* **2019**, *9*, 24539–24559. [[CrossRef](#)]
4. Lyagin, I.; Stepanov, N.; Frolov, G.; Efremenko, E. Combined Modification of Fiber Materials by Enzymes and Metal Nanoparticles for Chemical and Biological Protection. *Int. J. Mol. Sci.* **2022**, *23*, 1359. [[CrossRef](#)]
5. Chandrakala, V.; Aruna, V.; Angajala, G. Review on metal nanoparticles as nanocarriers: Current challenges and perspectives in drug delivery systems. *Emergent Mater.* **2022**, *1*, 1–23. [[CrossRef](#)]
6. Milovanovic, M.; Arsenijevic, A.; Milovanovic, J.; Kanjevac, T.; Arsenijevic, N. Nanoparticles in Antiviral Therapy. In *Antimicrobial Nanoarchitectonics: From Synthesis to Applications*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 383–410, ISBN 9780323527347.
7. Singh, L.; Kruger, H.G.; Maguire, G.E.M.; Govender, T.; Parboosing, R. The role of nanotechnology in the treatment of viral infections. *Ther. Adv. Infect. Dis.* **2017**, *4*, 105–131. [[CrossRef](#)]
8. Stewart, J.M.; Keselowsky, B.G. Combinatorial drug delivery approaches for immunomodulation. *Adv. Drug Deliv. Rev.* **2017**, *114*, 161–174. [[CrossRef](#)] [[PubMed](#)]
9. Jafari-Kiyan, A.; Karimi, L.; Davodiroknabadi, A. Producing colored cotton fabrics with functional properties by combining silver nanoparticles with nano titanium dioxide. *Cellulose* **2017**, *24*, 3083–3094. [[CrossRef](#)]
10. Kritchenkov, A.S.; Egorov, A.R.; Dubashynskaya, N.V.; Volkova, O.V.; Zabodalova, L.A.; Suchkova, E.P.; Kurliuk, A.V.; Shakola, T.V.; Dysin, A.P. Natural polysaccharide-based smart (temperature sensing) and active (antibacterial, antioxidant and photo-protective) nanoparticles with potential application in biocompatible food coatings. *Int. J. Biol. Macromol.* **2019**, *134*, 480–486. [[CrossRef](#)]
11. Moradi, M.; Razavi, R.; Omer, A.K.; Farhangfar, A.; McClements, D.J. Interactions between nanoparticle-based food additives and other food ingredients: A review of current knowledge. *Trends Food Sci. Technol.* **2022**, *120*, 75–87. [[CrossRef](#)]
12. Pilotek, S.; Tabellion, F. Nanoparticles in coatings. *Eur. Coat. J.* **2005**, *4*, 170.
13. Hansjosten, I.; Takamiya, M.; Rapp, J.; Reiner, L.; Fritsch-Decker, S.; Mattern, D.; Andraschko, S.; Anders, C.; Pace, G.; Dickmeis, T.; et al. Surface functionalisation-dependent adverse effects of metal nanoparticles and nanoplastics in zebrafish embryos. *Environ. Sci. Nano* **2022**, *9*, 375–392. [[CrossRef](#)]
14. Swaminathan, M.; Sharma, N.K. Antimicrobial Activity of the Engineered Nanoparticles Used as Coating Agents. In *Handbook of Ecomaterials*; Springer: Cham, Switzerland, 2018; pp. 1–15.
15. Jeevanandam, J.; Barhoum, A.; Chan, Y.S.; Dufresne, A.; Danquah, M.K. Review on nanoparticles and nanostructured materials: History, sources, toxicity and regulations. *Beilstein J. Nanotechnol.* **2018**, *9*, 1050–1074. [[CrossRef](#)]
16. Liu, J.L.; Bashir, S. *Advanced Nanomaterials and Their Applications in Renewable Energy*; Elsevier Inc.: Amsterdam, The Netherlands, 2015; ISBN 9780128017081.
17. Tan, C.; Cao, X.; Wu, X.J.; He, Q.; Yang, J.; Zhang, X.; Chen, J.; Zhao, W.; Han, S.; Nam, G.H.; et al. Recent Advances in Ultrathin Two-Dimensional Nanomaterials. *Chem. Rev.* **2017**, *117*, 6225–6331. [[CrossRef](#)] [[PubMed](#)]
18. Hu, T.; Mei, X.; Wang, Y.; Weng, X.; Liang, R.; Wei, M. Two-dimensional nanomaterials: Fascinating materials in biomedical field. *Sci. Bull.* **2019**, *64*, 1707–1727. [[CrossRef](#)]
19. Mei, L.; Zhu, S.; Yin, W.; Chen, C.; Nie, G.; Gu, Z.; Zhao, Y. Two-dimensional nanomaterials beyond graphene for antibacterial applications: Current progress and future perspectives. *Theranostics* **2020**, *10*, 757–781. [[CrossRef](#)]
20. Parveen, K.; Banse, V.; Ledwani, L. Green synthesis of nanoparticles: Their advantages and disadvantages. In *Proceedings of the AIP Conference Proceedings*; AIP Publishing LLC: Melville, NY, USA, 2016; Volume 1724, p. 020048.
21. Agarwal, H.; Venkat Kumar, S.; Rajeshkumar, S. A review on green synthesis of zinc oxide nanoparticles—An eco-friendly approach. *Resour. Technol.* **2017**, *3*, 406–413. [[CrossRef](#)]
22. Bhat, S.S.; Qurashi, A.; Khanday, F.A. ZnO nanostructures based biosensors for cancer and infectious disease applications: Perspectives, prospects and promises. *TrAC Trends Anal. Chem.* **2017**, *86*, 1–13. [[CrossRef](#)]
23. Shevtsova, T.; Cavallaro, G.; Lazzara, G.; Milioto, S.; Donchak, V.; Harhay, K.; Korolko, S.; Budkowski, A.; Stetsyshyn, Y. Temperature-responsive hybrid nanomaterials based on modified halloysite nanotubes uploaded with silver nanoparticles. *Colloids Surfaces A Physicochem. Eng. Asp.* **2022**, *641*, 128525. [[CrossRef](#)]
24. Hadzhieva, Z.; Boccaccini, A.R. Recent developments in electrophoretic deposition (EPD) of antibacterial coatings for biomedical applications—A review. *Curr. Opin. Biomed. Eng.* **2022**, *21*, 100367. [[CrossRef](#)]
25. Begum, S.; Pramanik, A.; Davis, D.; Patibandla, S.; Gates, K.; Gao, Y.; Ray, P.C. 2D and Heterostructure Nanomaterial Based Strategies for Combating Drug-Resistant Bacteria. *ACS Omega* **2020**, *5*, 3116–3130. [[CrossRef](#)] [[PubMed](#)]

26. Alimohammadi, F.; Sharifian, M.; Attanayake, N.H.; Thenuwara, A.C.; Gogotsi, Y.; Anasori, B.; Strongin, D.R. Antimicrobial Properties of 2D MnO₂ and MoS₂ Nanomaterials Vertically Aligned on Graphene Materials and Ti₃C₂ MXene. *Langmuir* **2018**, *34*, 7192–7200. [[CrossRef](#)] [[PubMed](#)]
27. Salem, S.S.; Fouda, A. Green Synthesis of Metallic Nanoparticles and Their Prospective Biotechnological Applications: An Overview. *Biol. Trace Elem. Res.* **2021**, *199*, 344–370. [[CrossRef](#)] [[PubMed](#)]
28. Viraka Nellore, B.P.; Kanchanapally, R.; Pedraza, F.; Sinha, S.S.; Pramanik, A.; Hamme, A.T.; Arslan, Z.; Sardar, D.; Ray, P.C. Bio-Conjugated CNT-Bridged 3D Porous Graphene Oxide Membrane for Highly Efficient Disinfection of Pathogenic Bacteria and Removal of Toxic Metals from Water. *ACS Appl. Mater. Interfaces* **2015**, *7*, 19210–19218. [[CrossRef](#)]
29. Zucker, I.; Werber, J.R.; Fishman, Z.S.; Hashmi, S.M.; Gabinet, U.R.; Lu, X.; Osuji, C.O.; Pfefferle, L.D.; Elimelech, M. Loss of Phospholipid Membrane Integrity Induced by Two-Dimensional Nanomaterials. *Environ. Sci. Technol. Lett.* **2017**, *4*, 404–409. [[CrossRef](#)]
30. El Meouche, I.; Dunlop, M.J. Heterogeneity in efflux pump expression predisposes antibiotic-resistant cells to mutation. *Science* **2018**, *362*, 686–690. [[CrossRef](#)]
31. Iravani, S.; Korbekandi, H.; Mirmohammadi, S.V.; Zolfaghari, B. Synthesis of silver nanoparticles: Chemical, physical and biological methods. *Res. Pharm. Sci.* **2014**, *9*, 385–406.
32. Saravanan, B.; Manivannan, V. Synthesis and characterization of copper nanoparticles and evaluation of antibacterial activity. *Res. J. Life Sci. Bioinform. Pharm. Chem. Sci.* **2018**, *11*, 1451–1457. [[CrossRef](#)]
33. Vaid, K.; Dhiman, J.; Sarawagi, N.; Kumar, V. Experimental and Computational Study on the Selective Interaction of Functionalized Gold Nanoparticles with Metal Ions: Sensing Prospects. *Langmuir* **2020**, *36*, 12319–12326. [[CrossRef](#)]
34. Khan, S.B. Metal nanoparticles containing chitosan wrapped cellulose nanocomposites for catalytic hydrogen production and reduction of environmental pollutants. *Carbohydr. Polym.* **2020**, *242*, 116286. [[CrossRef](#)]
35. Ahmad, R.; Bedük, T.; Majhi, S.M.; Salama, K.N. One-step synthesis and decoration of nickel oxide nanosheets with gold nanoparticles by reduction method for hydrazine sensing application. *Sens. Actuators B Chem.* **2019**, *286*, 139–147. [[CrossRef](#)]
36. Zhang, S.; Tang, Y.; Vlahovic, B. A Review on Preparation and Applications of Silver-Containing Nanofibers. *Nanoscale Res. Lett.* **2016**, *11*, 80. [[CrossRef](#)] [[PubMed](#)]
37. Syafiuddin, A.; Salmiati; Salim, M.R.; Beng Hong Kueh, A.; Hadibarata, T.; Nur, H. A Review of Silver Nanoparticles: Research Trends, Global Consumption, Synthesis, Properties, and Future Challenges. *J. Chin. Chem. Soc.* **2017**, *64*, 732–756. [[CrossRef](#)]
38. Rhim, J.W.; Wang, L.F.; Lee, Y.; Hong, S.I. Preparation and characterization of bio-nanocomposite films of agar and silver nanoparticles: Laser ablation method. *Carbohydr. Polym.* **2014**, *103*, 456–465. [[CrossRef](#)] [[PubMed](#)]
39. Hirai, H.; Yakura, N. Protecting polymers in suspension of metal nanoparticles. *Polym. Adv. Technol.* **2001**, *12*, 724–733. [[CrossRef](#)]
40. Mahltig, B.; Cheval, N.; Gohy, J.F.; Fahmi, A. Preparation of gold nanoparticles under presence of the diblock polyampholyte PMAA-b-PDMAEMA. *J. Polym. Res.* **2010**, *17*, 579–588. [[CrossRef](#)]
41. Guo, Z.; Henry, L.L.; Palshin, V.; Podlaha, E.J. Synthesis of poly(methyl methacrylate) stabilized colloidal zero-valence metallic nanoparticles. *J. Mater. Chem.* **2006**, *16*, 1772–1777. [[CrossRef](#)]
42. Wang, W.; Wei, Q.Q.; Wang, J.; Wang, B.C.; Zhang, S.H.; Yuan, Z. Role of thiol-containing polyethylene glycol (thiol-PEG) in the modification process of gold nanoparticles (AuNPs): Stabilizer or coagulant? *J. Colloid Interface Sci.* **2013**, *404*, 223–229. [[CrossRef](#)]
43. Zhang, W.; Qiao, X.; Chen, J. Synthesis of silver nanoparticles-Effects of concerned parameters in water/oil microemulsion. *Mater. Sci. Eng. B Solid-State Mater. Adv. Technol.* **2007**, *142*, 1–15. [[CrossRef](#)]
44. Jimenez-Cadena, G.; Comini, E.; Ferroni, M.; Vomiero, A.; Sberveglieri, G. Synthesis of different ZnO nanostructures by modified PVD process and potential use for dye-sensitized solar cells. *Mater. Chem. Phys.* **2010**, *124*, 694–698. [[CrossRef](#)]
45. Gutiérrez, A.; Carraro, C.; Maboudian, R. Single-layer CVD-grown graphene decorated with metal nanoparticles as a promising biosensing platform. *Biosens. Bioelectron.* **2012**, *33*, 56–59. [[CrossRef](#)] [[PubMed](#)]
46. Marquardt, D.; Xie, Z.; Taubert, A.; Thomann, R.; Janiak, C. Microwave synthesis and inherent stabilization of metal nanoparticles in 1-methyl-3-(3-carboxyethyl)-imidazolium tetrafluoroborate. *Dalt. Trans.* **2011**, *40*, 8290–8293. [[CrossRef](#)]
47. Tamai, T.; Watanabe, M.; Hatanaka, Y.; Tsujiwaki, H.; Nishioka, N.; Matsukawa, K. Formation of metal nanoparticles on the surface of polymer particles incorporating. Polysilane by UV irradiation. *Langmuir* **2008**, *24*, 14203–14208. [[CrossRef](#)] [[PubMed](#)]
48. Flores-Rojas, G.G.; López-Saucedo, F.; Bucio, E. Gamma-irradiation applied in the synthesis of metallic and organic nanoparticles: A short review. *Radiat. Phys. Chem.* **2020**, *169*, 107962. [[CrossRef](#)]
49. Semaltianos, N.G. Nanoparticles by laser ablation. *Crit. Rev. Solid State Mater. Sci.* **2010**, *35*, 105–124. [[CrossRef](#)]
50. Celik, C.; Ildiz, N.; Ocoy, I. Building block and rapid synthesis of catecholamines-inorganic nanoflowers with their peroxidase-mimicking and antimicrobial activities. *Sci. Rep.* **2020**, *10*, 2903. [[CrossRef](#)] [[PubMed](#)]
51. Koca, F.D.; Demirezen Yilmaz, D.; Ertas Onmaz, N.; Yilmaz, E.; Ocoy, I. Green synthesis of allicin based hybrid nanoflowers with evaluation of their catalytic and antimicrobial activities. *Biotechnol. Lett.* **2020**, *42*, 1683–1690. [[CrossRef](#)]
52. Koca, F.D.; Demirezen Yilmaz, D.; Ertas Onmaz, N.; Ocoy, I. Peroxidase-like activity and antimicrobial properties of curcumin-inorganic hybrid nanostructure. *Saudi J. Biol. Sci.* **2020**, *27*, 2574–2579. [[CrossRef](#)]
53. Some, S.; Sarkar, B.; Biswas, K.; Jana, T.K.; Bhattacharjya, D.; Dam, P.; Mondal, R.; Kumar, A.; Deb, A.K.; Sadat, A.; et al. Bio-molecule functionalized rapid one-pot green synthesis of silver nanoparticles and their efficacy toward the multidrug resistant (MDR) gut bacteria of silkworms (*Bombyx mori*). *RSC Adv.* **2020**, *10*, 22742–22757. [[CrossRef](#)]

54. Naikoo, G.A.; Mustaqeem, M.; Hassan, I.U.; Awan, T.; Arshad, F.; Salim, H.; Qurashi, A. Bioinspired and green synthesis of nanoparticles from plant extracts with antiviral and antimicrobial properties: A critical review. *J. Saudi Chem. Soc.* **2021**, *25*, 101304. [CrossRef]
55. Lu, J.; Guo, J.; Song, S.; Yu, G.; Liu, H.; Yang, X.; Lu, Z. Preparation of Ag nanoparticles by spark ablation in gas as catalysts for electrocatalytic hydrogen production. *RSC Adv.* **2020**, *10*, 38583–38587. [CrossRef]
56. Mařátková, O.; Michailidu, J.; Miřkovská, A.; Kolouchová, I.; Masák, J.; Čejková, A. Antimicrobial properties and applications of metal nanoparticles biosynthesized by green methods. *Biotechnol. Adv.* **2022**, *11*, 107905. [CrossRef] [PubMed]
57. Aljelehaw, Q.; Karimi, N.; Alavi, M. Comparison of antibacterial and cytotoxic activities of phytosynthesized ZnONPs by leaves extract of *Daphne mucronata* at different salt sources. *Mater. Technol.* **2021**, *36*, 747–759. [CrossRef]
58. Mohamed, A.A.; Fouda, A.; Abdel-Rahman, M.A.; Hassan, S.E.D.; El-Gamal, M.S.; Salem, S.S.; Shaheen, T.I. Fungal strain impacts the shape, bioactivity and multifunctional properties of green synthesized zinc oxide nanoparticles. *Biocatal. Agric. Biotechnol.* **2019**, *19*, 101103. [CrossRef]
59. Abdelhakim, H.K.; El-Sayed, E.R.; Rashidi, F.B. Biosynthesis of zinc oxide nanoparticles with antimicrobial, anticancer, antioxidant and photocatalytic activities by the endophytic *Alternaria tenuissima*. *J. Appl. Microbiol.* **2020**, *128*, 1634–1646. [CrossRef] [PubMed]
60. Ganesan, V.; Hariram, M.; Vivekanandhan, S.; Muthuramkumar, S. Periconium sp. (endophytic fungi) extract mediated sol-gel synthesis of ZnO nanoparticles for antimicrobial and antioxidant applications. *Mater. Sci. Semicond. Process.* **2020**, *105*, 104739. [CrossRef]
61. Ebadi, M.; Zolfaghari, M.R.; Aghaei, S.S.; Zargar, M.; Shafiei, M.; Zahiri, H.S.; Noghabi, K.A. A bio-inspired strategy for the synthesis of zinc oxide nanoparticles (ZnO NPs) using the cell extract of cyanobacterium: *Nostoc* sp. EA03: From biological function to toxicity evaluation. *RSC Adv.* **2019**, *9*, 23508–23525. [CrossRef]
62. Chowdhury, N.R.; MacGregor-Ramiasa, M.; Zilm, P.; Majewski, P.; Vasilev, K. ‘Chocolate’ silver nanoparticles: Synthesis, antibacterial activity and cytotoxicity. *J. Colloid Interface Sci.* **2016**, *482*, 151–158. [CrossRef]
63. Ibrahim, E.H.; Kilany, M.; Ghramh, H.A.; Khan, K.A.; ul Islam, S. Cellular proliferation/cytotoxicity and antimicrobial potentials of green synthesized silver nanoparticles (AgNPs) using *Juniperus procera*. *Saudi J. Biol. Sci.* **2019**, *26*, 1689–1694. [CrossRef]
64. Zhang, W.; Jiang, W. Antioxidant and antibacterial chitosan film with tea polyphenols-mediated green synthesis silver nanoparticle via a novel one-pot method. *Int. J. Biol. Macromol.* **2020**, *155*, 1252–1261. [CrossRef]
65. Gond, S.K.; Mishra, A.; Verma, S.K.; Sharma, V.K.; Kharwar, R.N. Synthesis and Characterization of Antimicrobial Silver Nanoparticles by an Endophytic Fungus Isolated from *Nyctanthes arbor-tristis*. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2020**, *90*, 641–645. [CrossRef]
66. Manjunath Hulikere, M.; Joshi, C.G. Characterization, antioxidant and antimicrobial activity of silver nanoparticles synthesized using marine endophytic fungus- *Cladosporium cladosporioides*. *Process Biochem.* **2019**, *82*, 199–204. [CrossRef]
67. Hu, X.; Saravanakumar, K.; Jin, T.; Wang, M.H. Mycosynthesis, characterization, anticancer and antibacterial activity of silver nanoparticles from endophytic fungus *Talaromyces purpureogenus*. *Int. J. Nanomed.* **2019**, *14*, 3427–3438. [CrossRef] [PubMed]
68. Divya, M.; Kiran, G.S.; Hassan, S.; Selvin, J. Biogenic synthesis and effect of silver nanoparticles (AgNPs) to combat catheter-related urinary tract infections. *Biocatal. Agric. Biotechnol.* **2019**, *18*, 101037. [CrossRef]
69. Aromal, S.A.; Vidhu, V.K.; Philip, D. Green synthesis of well-dispersed gold nanoparticles using *Macrotyloma uniflorum*. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2012**, *85*, 99–104. [CrossRef]
70. Babu, P.J.; Sharma, P.; Saranya, S.; Bora, U. Synthesis of gold nanoparticles using ethonolic leaf extract of *Bacopa monnieri* and UV irradiation. *Mater. Lett.* **2013**, *93*, 431–434. [CrossRef]
71. Radha, R.; Murugalakshmi, M.; Kokila, S. Eco friendly synthesis and characterization of Gold Nanoparticles from *Bauhinia purpurea* flower extract. *Imp. J. Interdiscip. Res.* **2016**, *2*, 306–310.
72. Abbasi, T.; Anuradha, J.; Ganaie, S.U.; Abbasi, S.A. Gainful utilization of the highly intransigent weed ipomoea in the synthesis of gold nanoparticles. *J. King Saud Univ. Sci.* **2015**, *27*, 15–22. [CrossRef]
73. Gonnelli, C.; Cacioppo, F.; Giordano, C.; Capozzoli, L.; Salvatici, M.C.; Colzi, I.; del Bubba, M.; Ancillotti, C.; Ristori, S. Cucurbita pepo L. extracts as a versatile hydrotropic source for the synthesis of gold nanoparticles with different shapes. *Green Chem. Lett. Rev.* **2015**, *8*, 39–47. Available online: <http://mc.manuscriptcentral.com/tgcl> (accessed on 2 February 2022). [CrossRef]
74. Jayaseelan, C.; Ramkumar, R.; Rahuman, A.A.; Perumal, P. Green synthesis of gold nanoparticles using seed aqueous extract of *Abelmoschus esculentus* and its antifungal activity. *Ind. Crops Prod.* **2013**, *45*, 423–429. [CrossRef]
75. Murthy, H.C.A.; Desalegn, T.; Kassa, M.; Abebe, B.; Assefa, T. Synthesis of Green Copper Nanoparticles Using Medicinal Plant *Hagenia abyssinica* (Brace) JF. Gmel. Leaf Extract: Antimicrobial Properties. *J. Nanomater.* **2020**, *2020*, 1–12. [CrossRef]
76. Lee, H.J.; Song, J.Y.; Kim, B.S. Biological synthesis of copper nanoparticles using *Magnolia kobus* leaf extract and their antibacterial activity. *J. Chem. Technol. Biotechnol.* **2013**, *88*, 1971–1977. [CrossRef]
77. Mali, S.C.; Dhaka, A.; Githala, C.K.; Trivedi, R. Green synthesis of copper nanoparticles using *Celastrus paniculatus* Willd. leaf extract and their photocatalytic and antifungal properties. *Biotechnol. Rep.* **2020**, *27*, e00518. [CrossRef] [PubMed]
78. Manikandan, V.; Velmurugan, P.; Park, J.H.; Lovanh, N.; Seo, S.K.; Jayanthi, P.; Park, Y.J.; Cho, M.; Oh, B.T. Synthesis and antimicrobial activity of palladium nanoparticles from *Prunus × yedoensis* leaf extract. *Mater. Lett.* **2016**, *185*, 335–338. [CrossRef]

79. Srinivasan, M.; Venkatesan, M.; Arumugam, V.; Natesan, G.; Saravanan, N.; Murugesan, S.; Ramachandran, S.; Ayyasamy, R.; Pugazhendhi, A. Green synthesis and characterization of titanium dioxide nanoparticles (TiO₂ NPs) using *Sesbania grandiflora* and evaluation of toxicity in zebrafish embryos. *Process Biochem.* **2019**, *80*, 197–202. [[CrossRef](#)]
80. Atique Ullah, A.K.M.; Tamanna, A.N.; Hossain, A.; Akter, M.; Kabir, M.F.; Tareq, A.R.M.; Fazle Kibria, A.K.M.; Kurasaki, M.; Rahman, M.M.; Khan, M.N.I. In vitro cytotoxicity and antibiotic application of green route surface modified ferromagnetic TiO₂ nanoparticles. *RSC Adv.* **2019**, *9*, 13254–13262. [[CrossRef](#)]
81. Subhapiya, S.; Gomathipriya, P. Green synthesis of titanium dioxide (TiO₂) nanoparticles by *Trigonella foenum-graecum* extract and its antimicrobial properties. *Microb. Pathog.* **2018**, *116*, 215–220. [[CrossRef](#)]
82. Ali, R.; Shanan, Z.J.; Saleh, G.M.; Abass, Q. Green synthesis and the study of some physical properties of MgO nanoparticles and their antibacterial activity. *Iraqi J. Sci.* **2020**, *61*, 266–276. [[CrossRef](#)]
83. Karpagavinayagam, P.; Vedhi, C. Green synthesis of iron oxide nanoparticles using *Avicennia marina* flower extract. *Vacuum* **2019**, *160*, 286–292. [[CrossRef](#)]
84. Muthukumar, H.; Matheswaran, M. Amaranthus spinosus Leaf Extract Mediated FeO Nanoparticles: Physicochemical Traits, Photocatalytic and Antioxidant Activity. *ACS Sustain. Chem. Eng.* **2015**, *3*, 3149–3156. [[CrossRef](#)]
85. Ulbrich, K.; Holá, K.; Šubr, V.; Bakandritsos, A.; Tuček, J.; Zbořil, R. Targeted Drug Delivery with Polymers and Magnetic Nanoparticles: Covalent and Noncovalent Approaches, Release Control, and Clinical Studies. *Chem. Rev.* **2016**, *116*, 5338–5431. [[CrossRef](#)] [[PubMed](#)]
86. Fouda, A.; EL-Din Hassan, S.; Salem, S.S.; Shaheen, T.I. In-Vitro cytotoxicity, antibacterial, and UV protection properties of the biosynthesized Zinc oxide nanoparticles for medical textile applications. *Microb. Pathog.* **2018**, *125*, 252–261. [[CrossRef](#)] [[PubMed](#)]
87. Hassan, S.; Salem, S.S.; Fouda, A.; El-Gamal, M.S.; Abdo, A.M.; Awad, M.A. New approach for antimicrobial activity and bio-control of various pathogens by biosynthesized copper nanoparticles using endophytic actinomycetes. *J. Radiat. Res. Appl. Sci.* **2018**, *11*, 262–270. [[CrossRef](#)]
88. Keijok, W.J.; Pereira, R.H.A.; Alvarez, L.A.C.; Prado, A.R.; da Silva, A.R.; Ribeiro, J.; de Oliveira, J.P.; Guimaraes, M.C.C. Controlled biosynthesis of gold nanoparticles with *Coffea arabica* using factorial design. *Sci. Rep.* **2019**, *9*, 16019. [[CrossRef](#)]
89. Cai, Y.; Tan, F.; Qiao, X.; Wang, W.; Chen, J.; Qiu, X. Room-temperature synthesis of silica supported silver nanoparticles in basic ethanol solution and their antibacterial activity. *RSC Adv.* **2016**, *6*, 18407–18412. [[CrossRef](#)]
90. Fouda, A.; Hassan, S.E.D.; Abdo, A.M.; El-Gamal, M.S. Antimicrobial, Antioxidant and Larvicidal Activities of Spherical Silver Nanoparticles Synthesized by *Endophytic streptomyces* spp. *Biol. Trace Elem. Res.* **2020**, *195*, 707–724. [[CrossRef](#)]
91. Younis, I.Y.; El-Hawary, S.S.; Eldahshan, O.A.; Abdel-Aziz, M.M.; Ali, Z.Y. Green synthesis of magnesium nanoparticles mediated from *Rosa floribunda* charisma extract and its antioxidant, antiaging and antibiofilm activities. *Sci. Rep.* **2021**, *11*, 16868. [[CrossRef](#)]
92. SI, A.; Pal, K.; Kralj, S.; El-Sayyad, G.S.; de Souza, F.G.; Narayanan, T. Sustainable preparation of gold nanoparticles via green chemistry approach for biogenic applications. *Mater. Today Chem.* **2020**, *17*, 100327. [[CrossRef](#)]
93. Jain, R.; Mendiratta, S.; Kumar, L.; Srivastava, A. Green synthesis of iron nanoparticles using *Artocarpus heterophyllus* peel extract and their application as a heterogeneous Fenton-like catalyst for the degradation of Fuchsin Basic dye. *Curr. Res. Green Sustain. Chem.* **2021**, *4*, 100086. [[CrossRef](#)]
94. Quigg, A.; Chin, W.C.; Chen, C.S.; Zhang, S.; Jiang, Y.; Miao, A.J.; Schwehr, K.A.; Xu, C.; Santschi, P.H. Direct and indirect toxic effects of engineered nanoparticles on algae: Role of natural organic matter. *ACS Sustain. Chem. Eng.* **2013**, *1*, 686–702. [[CrossRef](#)]
95. Nel, A.E.; Mädler, L.; Velegol, D.; Xia, T.; Hoek, E.M.V.; Somasundaran, P.; Klaessig, F.; Castranova, V.; Thompson, M. Understanding biophysicochemical interactions at the nano-bio interface. *Nat. Mater.* **2009**, *8*, 543–557. [[CrossRef](#)] [[PubMed](#)]
96. Clément, L.; Hurel, C.; Marmier, N. Toxicity of TiO₂ nanoparticles to cladocerans, algae, rotifers and plants—Effects of size and crystalline structure. *Chemosphere* **2013**, *90*, 1083–1090. [[CrossRef](#)] [[PubMed](#)]
97. Wei, T.; Yu, Q.; Chen, H. Responsive and Synergistic Antibacterial Coatings: Fighting against Bacteria in a Smart and Effective Way. *Adv. Healthc. Mater.* **2019**, *8*, 1801381. [[CrossRef](#)] [[PubMed](#)]
98. Zhang, S.; Liang, R.; Xu, K.; Zheng, S.; Mukherjee, S.; Liu, P.; Wang, C.; Chen, Y. Construction of multifunctional micro-patterned PALNMA/PDADMAC/PEGDA hydrogel and intelligently responsive antibacterial coating HA/BBR on Mg alloy surface for orthopedic application. *Mater. Sci. Eng. C* **2022**, *132*, 112636. [[CrossRef](#)] [[PubMed](#)]
99. Chapot-Chartier, M.P.; Kulakauskas, S. Cell wall structure and function in lactic acid bacteria. *Microb. Cell Fact.* **2014**, *13*, S9. [[CrossRef](#)]
100. Slavin, Y.N.; Asnis, J.; Häfeli, U.O.; Bach, H. Metal nanoparticles: Understanding the mechanisms behind antibacterial activity. *J. Nanobiotechnol.* **2017**, *15*, 65. [[CrossRef](#)]
101. Wong, C.W.; Chan, Y.S.; Jeevanandam, J.; Pal, K.; Bechelany, M.; Abd Elkodous, M.; El-Sayyad, G.S. Response Surface Methodology Optimization of Mono-dispersed MgO Nanoparticles Fabricated by Ultrasonic-Assisted Sol–Gel Method for Outstanding Antimicrobial and Antibiofilm Activities. *J. Clust. Sci.* **2020**, *31*, 367–389. [[CrossRef](#)]
102. Travan, A.; Pelillo, C.; Donati, I.; Marsich, E.; Benincasa, M.; Scarpa, T.; Semeraro, S.; Turco, G.; Gennaro, R.; Paoletti, S. Non-cytotoxic silver nanoparticle-polysaccharide nanocomposites with antimicrobial activity. *Biomacromolecules* **2009**, *10*, 1429–1435. [[CrossRef](#)]
103. Marsich, E.; Travan, A.; Donati, I.; Di Luca, A.; Benincasa, M.; Crosera, M.; Paoletti, S. Biological response of hydrogels embedding gold nanoparticles. *Colloids Surf. B Biointerfaces* **2011**, *83*, 331–339. [[CrossRef](#)]

104. Canta, M.; Cauda, V. The investigation of the parameters affecting the ZnO nanoparticle cytotoxicity behaviour: A tutorial review. *Biomater. Sci.* **2020**, *8*, 6157–6174. [[CrossRef](#)]
105. Wei, T.; Tang, Z.; Yu, Q.; Chen, H. Smart Antibacterial Surfaces with Switchable Bacteria-Killing and Bacteria-Releasing Capabilities. *ACS Appl. Mater. Interfaces* **2017**, *9*, 37511–37523. [[CrossRef](#)] [[PubMed](#)]
106. Mirzajani, F.; Ghassempour, A.; Aliahmadi, A.; Esmaeili, M.A. Antibacterial effect of silver nanoparticles on *Staphylococcus aureus*. *Res. Microbiol.* **2011**, *162*, 542–549. [[CrossRef](#)] [[PubMed](#)]
107. Tamayo, L.A.; Zapata, P.A.; Vejar, N.D.; Azócar, M.I.; Gulppi, M.A.; Zhou, X.; Thompson, G.E.; Rabagliati, F.M.; Páez, M.A. Release of silver and copper nanoparticles from polyethylene nanocomposites and their penetration into *Listeria monocytogenes*. *Mater. Sci. Eng. C* **2014**, *40*, 24–31. [[CrossRef](#)] [[PubMed](#)]
108. Siddique, M.H.; Aslam, B.; Imran, M.; Ashraf, A.; Nadeem, H.; Hayat, S.; Khurshid, M.; Afzal, M.; Malik, I.R.; Shahzad, M.; et al. Effect of Silver Nanoparticles on Biofilm Formation and EPS Production of Multidrug-Resistant *Klebsiella pneumoniae*. *Biomed Res. Int.* **2020**, *2020*, 1–9. [[CrossRef](#)]
109. Guzman, M.; Dille, J.; Godet, S. Synthesis and antibacterial activity of silver nanoparticles against gram-positive and gram-negative bacteria. *Nanomed. Nanotechnol. Biol. Med.* **2012**, *8*, 37–45. [[CrossRef](#)]
110. Banerjee, A.; Das, D.; Rudra, S.G.; Mazumder, K.; Andler, R.; Bandopadhyay, R. Characterization of Exopolysaccharide Produced by *Pseudomonas* sp. PFAB4 for Synthesis of EPS-Coated AgNPs with Antimicrobial Properties. *J. Polym. Environ.* **2020**, *28*, 242–256. [[CrossRef](#)]
111. Shariq Ahmed, M.; Soundhararajan, R.; Akther, T.; Kashif, M.; Khan, J.; Waseem, M.; Srinivasan, H. Biogenic AgNPs synthesized via endophytic bacteria and its biological applications. *Environ. Sci. Pollut. Res.* **2019**, *26*, 26939–26946. [[CrossRef](#)]
112. Lu, L.; Sun, R.W.Y.; Chen, R.; Hui, C.K.; Ho, C.M.; Luk, J.M.; Lau, G.K.K.; Che, C.M. Silver nanoparticles inhibit hepatitis B virus replication. *Antivir. Ther.* **2008**, *13*, 252–262. [[CrossRef](#)]
113. Lara, H.H.; Garza-Treviño, E.N.; Ixtepan-Turrent, L.; Singh, D.K. Silver nanoparticles are broad-spectrum bactericidal and virucidal compounds. *J. Nanobiotechnol.* **2011**, *9*, 30. [[CrossRef](#)]
114. Baram-Pinto, D.; Shukla, S.; Perkas, N.; Gedanken, A.; Sarid, R. Inhibition of herpes simplex virus type 1 infection by silver nanoparticles capped with mercaptoethane sulfonate. *Bioconjug. Chem.* **2009**, *20*, 1497–1502. [[CrossRef](#)]
115. Sharma, V.; Kaushik, S.; Pandit, P.; Dhull, D.; Yadav, J.P.; Kaushik, S. Green synthesis of silver nanoparticles from medicinal plants and evaluation of their antiviral potential against chikungunya virus. *Appl. Microbiol. Biotechnol.* **2019**, *103*, 881–891. [[CrossRef](#)] [[PubMed](#)]
116. Xiang, D.; Zheng, Y.; Duan, W.; Li, X.; Yin, J.; Shigdar, S.; O'Connor, M.L.; Marappan, M.; Zhao, X.; Miao, Y.; et al. Inhibition of A/Human/Hubei/3/2005 (H3N2) influenza virus infection by silver nanoparticles in vitro and in vivo. *Int. J. Nanomed.* **2013**, *8*, 4103–4114. [[CrossRef](#)] [[PubMed](#)]
117. Huy, T.Q.; Hien Thanh, N.T.; Thuy, N.T.; Van Chung, P.; Hung, P.N.; Le, A.T.; Hong Hanh, N.T. Cytotoxicity and antiviral activity of electrochemical—synthesized silver nanoparticles against poliovirus. *J. Virol. Methods* **2017**, *241*, 52–57. [[CrossRef](#)] [[PubMed](#)]
118. Morris, D.; Ansar, M.; Speshock, J.; Ivanciuc, T.; Qu, Y.; Casola, A.; Garofalo, R. Antiviral and immunomodulatory activity of silver nanoparticles in experimental rsv infection. *Viruses* **2019**, *11*, 732. [[CrossRef](#)] [[PubMed](#)]
119. Chen, N.; Zheng, Y.; Yin, J.; Li, X.; Zheng, C. Inhibitory effects of silver nanoparticles against adenovirus type 3 in vitro. *J. Virol. Methods* **2013**, *193*, 470–477. [[CrossRef](#)]
120. Haggag, E.G.; Elshamy, A.M.; Rabeh, M.A.; Gabr, N.M.; Salem, M.; Youssif, K.A.; Samir, A.; Bin Muhsinah, A.; Alsayari, A.; Abdelmohsen, U.R. Antiviral potential of green synthesized silver nanoparticles of *lampranthus coccineus* and *malephora lutea*. *Int. J. Nanomed.* **2019**, *14*, 6217–6229. [[CrossRef](#)]
121. Paulkumar, K.; Rajeshkumar, S.; Gnanajobitha, G.; Vanaja, M.; Malarkodi, C.; Annadurai, G. Eco-friendly Synthesis of Silver Chloride Nanoparticles using *Klebsiella planticola* (MTCC 2277). *Int. J. Green Chem. Bioprocess* **2013**, *2013*, 12–16.
122. Rajeshkumar, S.; Malarkodi, C.; Paulkumar, K.; Vanaja, M.; Gnanajobitha, G.; Annadurai, G. Algae Mediated Green Fabrication of Silver Nanoparticles and Examination of Its Antifungal Activity against Clinical Pathogens. *Int. J. Met.* **2014**, *2014*, 692643. [[CrossRef](#)]
123. Panáček, A.; Kolář, M.; Večeřová, R.; Pucek, R.; Soukupová, J.; Kryštof, V.; Hamal, P.; Zbořil, R.; Kvítek, L. Antifungal activity of silver nanoparticles against *Candida* spp. *Biomaterials* **2009**, *30*, 6333–6340. [[CrossRef](#)]
124. Mohamed, M.M.; Fouad, S.A.; Elshoky, H.A.; Mohammed, G.M.; Salaheldin, T.A. Antibacterial effect of gold nanoparticles against *Corynebacterium pseudotuberculosis*. *Int. J. Vet. Sci. Med.* **2017**, *5*, 23–29. [[CrossRef](#)]
125. Purbowati, R.; Sugiharto, S.; Listyawati, A.F.; Masfufatun, M.; Tjandra, L.; Indahsari, N.K. Antibacterial and antibiofilm effect of silver and gold nanoparticles in Uropathogenic *Escherichia coli*. *Berk. Penelit. Hayati* **2022**, *27*, 67–72. [[CrossRef](#)]
126. Ortiz-Benítez, E.A.; Velázquez-Guadarrama, N.; Durán Figueroa, N.V.; Quezada, H.; De Jesús Olivares-Trejo, J. Antibacterial mechanism of gold nanoparticles on: *Streptococcus pneumoniae*. *Metallomics* **2019**, *11*, 1265–1276. [[CrossRef](#)] [[PubMed](#)]
127. Mohamady Hussein, M.A.; Baños, F.G.D.; Grinholc, M.; Abo Dena, A.S.; El-Sherbiny, I.M.; Megahed, M. Exploring the physico-chemical and antimicrobial properties of gold-chitosan hybrid nanoparticles composed of varying chitosan amounts. *Int. J. Biol. Macromol.* **2020**, *162*, 1760–1769. [[CrossRef](#)]
128. Meléndez-Villanueva, M.A.; Morán-Santibañez, K.; Martínez-Sanmiguel, J.J.; Rangel-López, R.; Garza-Navarro, M.A.; Rodríguez-Padilla, C.; Zarate-Triviño, D.G.; Trejo-Ávila, L.M. Virucidal activity of gold nanoparticles synthesized by green chemistry using garlic extract. *Viruses* **2019**, *11*, 1111. [[CrossRef](#)] [[PubMed](#)]

129. Cagno, V.; Andreozzi, P.; D'Alicarnasso, M.; Silva, P.J.; Mueller, M.; Galloux, M.; Goffic, R.L.; Jones, S.T.; Vallino, M.; Hodek, J.; et al. Broad-spectrum non-toxic antiviral nanoparticles with a virucidal inhibition mechanism. *Nat. Mater.* **2018**, *17*, 195–203. [[CrossRef](#)] [[PubMed](#)]
130. Papp, I.; Sieben, C.; Ludwig, K.; Roskamp, M.; Böttcher, C.; Schlecht, S.; Herrmann, A.; Haag, R. Inhibition of influenza virus infection by multivalent sialic-acid- functionalized gold nanoparticles. *Small* **2010**, *6*, 2900–2906. [[CrossRef](#)]
131. Vonnemann, J.; Sieben, C.; Wolff, C.; Ludwig, K.; Böttcher, C.; Herrmann, A.; Haag, R. Virus inhibition induced by polyvalent nanoparticles of different sizes. *Nanoscale* **2014**, *6*, 2353–2360. [[CrossRef](#)]
132. Vinay Gopal, J.; Thenmozhi, M.; Kannabiran, K.; Rajakumar, G.; Velayutham, K.; Rahuman, A.A. Actinobacteria mediated synthesis of gold nanoparticles using *Streptomyces* sp. VITDDK3 and its antifungal activity. *Mater. Lett.* **2013**, *93*, 360–362. [[CrossRef](#)]
133. Azad, A.; Rostamifar, S.; Modaresi, F.; Bazrafkan, A.; Rezaie, Z. Assessment of the antibacterial effects of bismuth nanoparticles against enterococcus faecalis. *BioMed Res. Int.* **2020**, *2020*, 1–7. [[CrossRef](#)]
134. Salehi, B.; Mehrabian, S.; Ahmadi, M. Investigation of antibacterial effect of Cadmium Oxide nanoparticles on *Staphylococcus Aureus* bacteria. *J. Nanobiotechnol.* **2014**, *12*, 26. [[CrossRef](#)]
135. Sampath Kumar, V.; Raja, C.; Jayakumar, C. A review on solubility enhancement using hydrotropic phenomena. *Int. J. Pharm. Pharm. Sci.* **2014**, *6*, 1–7.
136. Ruparelia, J.P.; Chatterjee, A.K.; Duttgupta, S.P.; Mukherji, S. Strain specificity in antimicrobial activity of silver and copper nanoparticles. *Acta Biomater.* **2008**, *4*, 707–716. [[CrossRef](#)] [[PubMed](#)]
137. Azam, A.; Ahmed, A.S.; Oves, M.; Khan, M.S.; Memic, A. Size-dependent antimicrobial properties of CuO nanoparticles against Gram-positive and -negative bacterial strains. *Int. J. Nanomed.* **2012**, *7*, 3527–3535. [[CrossRef](#)] [[PubMed](#)]
138. Fujimori, Y.; Sato, T.; Hayata, T.; Nagao, T.; Nakayama, M.; Nakayama, T.; Sugamat, R.; Suzuki, K. Novel antiviral characteristics of nanosized copper(i) iodide particles showing inactivation activity against 2009 pandemic H1N1 influenza virus. *Appl. Environ. Microbiol.* **2012**, *78*, 951–955. [[CrossRef](#)] [[PubMed](#)]
139. Shionoiri, N.; Sato, T.; Fujimori, Y.; Nakayama, T.; Nemoto, M.; Matsunaga, T.; Tanaka, T. Investigation of the antiviral properties of copper iodide nanoparticles against feline calicivirus. *J. Biosci. Bioeng.* **2012**, *113*, 580–586. [[CrossRef](#)]
140. Broglie, J.J.; Alston, B.; Yang, C.; Ma, L.; Adcock, A.F.; Chen, W.; Yang, L. Antiviral activity of gold/copper sulfide core/shell nanoparticles against human norovirus virus-like particles. *PLoS ONE* **2015**, *10*, e0141050. [[CrossRef](#)]
141. Hang, X.; Peng, H.; Song, H.; Qi, Z.; Miao, X.; Xu, W. Antiviral activity of cuprous oxide nanoparticles against Hepatitis C Virus in vitro. *J. Virol. Methods* **2015**, *222*, 150–157. [[CrossRef](#)]
142. Tavakoli, A.; Hashemzadeh, M.S. Inhibition of herpes simplex virus type 1 by copper oxide nanoparticles. *J. Virol. Methods* **2020**, *275*, 113688. [[CrossRef](#)]
143. Tran, N.; Mir, A.; Mallik, D.; Sinha, A.; Nayar, S.; Webster, T.J. Bactericidal effect of iron oxide nanoparticles on *Staphylococcus aureus*. *Int. J. Nanomed.* **2010**, *5*, 277–283. [[CrossRef](#)]
144. Nangmenyi, G.; Li, X.; Mehrabi, S.; Mintz, E.; Economy, J. Silver-modified iron oxide nanoparticle impregnated fiberglass for disinfection of bacteria and viruses in water. *Mater. Lett.* **2011**, *65*, 1191–1193. [[CrossRef](#)]
145. Qin, T.; Ma, R.; Yin, Y.; Miao, X.; Chen, S.; Fan, K.; Xi, J.; Liu, Q.; Gu, Y.; Yin, Y.; et al. Catalytic inactivation of influenza virus by iron oxide nanozyme. *Theranostics* **2019**, *9*, 6920–6935. [[CrossRef](#)]
146. Murugan, K.; Wei, J.; Alsalhi, M.S.; Nicoletti, M.; Paulpandi, M.; Samidoss, C.M.; Dinesh, D.; Chandramohan, B.; Paneerselvam, C.; Subramanian, J.; et al. Magnetic nanoparticles are highly toxic to chloroquine-resistant *Plasmodium falciparum*, dengue virus (DEN-2), and their mosquito vectors. *Parasitol. Res.* **2017**, *116*, 495–502. [[CrossRef](#)] [[PubMed](#)]
147. Gutierrez, L.; Li, X.; Wang, J.; Nangmenyi, G.; Economy, J.; Kuhlenschmidt, T.B.; Kuhlenschmidt, M.S.; Nguyen, T.H. Adsorption of rotavirus and bacteriophage MS2 using glass fiber coated with hematite nanoparticles. *Water Res.* **2009**, *43*, 5198–5208. [[CrossRef](#)] [[PubMed](#)]
148. Krishnamoorthy, K.; Manivannan, G.; Kim, S.J.; Jeyasubramanian, K.; Premanathan, M. Antibacterial activity of MgO nanoparticles based on lipid peroxidation by oxygen vacancy. *J. Nanopart. Res.* **2012**, *14*, 1063. [[CrossRef](#)]
149. Saied, E.; Eid, A.M.; Hassan, S.E.D.; Salem, S.S.; Radwan, A.A.; Halawa, M.; Saleh, F.M.; Saad, H.A.; Saied, E.M.; Fouda, A. The catalytic activity of biosynthesized magnesium oxide nanoparticles (Mgo-nps) for inhibiting the growth of pathogenic microbes, tanning effluent treatment, and chromium ion removal. *Catalysts* **2021**, *11*, 821. [[CrossRef](#)]
150. El-Sayyad, G.S.; Mosallam, F.M.; El-Batal, A.I. One-pot green synthesis of magnesium oxide nanoparticles using *Penicillium chrysogenum* melanin pigment and gamma rays with antimicrobial activity against multidrug-resistant microbes. *Adv. Powder Technol.* **2018**, *29*, 2616–2625. [[CrossRef](#)]
151. Kumar, P.V.; Jelastin Kala, S.M.; Prakash, K.S. Green synthesis derived Pt-nanoparticles using *Xanthium strumarium* leaf extract and their biological studies. *J. Environ. Chem. Eng.* **2019**, *7*, 103146. [[CrossRef](#)]
152. Bhosale, S.V.; Ekambe, P.S.; Bhoraskar, S.V.; Mathe, V.L. Effect of surface properties of NiFe₂O₄ nanoparticles synthesized by dc thermal plasma route on antimicrobial activity. *Appl. Surf. Sci.* **2018**, *441*, 724–733. [[CrossRef](#)]
153. Angel Ezhilarasi, A.; Judith Vijaya, J.; Kaviyarasu, K.; John Kennedy, L.; Ramalingam, R.J.; Al-Lohedan, H.A. Green synthesis of NiO nanoparticles using *Aegle marmelos* leaf extract for the evaluation of in-vitro cytotoxicity, antibacterial and photocatalytic properties. *J. Photochem. Photobiol. B Biol.* **2018**, *180*, 39–50. [[CrossRef](#)]

154. Khan, A.; Shkir, M.; Ibrahim, E.H.; Kilany, M.; AlFaify, S.; Sayed, M.A.; El-Toni, A.M.; Aldalbahi, A.; Rahaman, H.; Siddiquei, M.M. Effect of Bi contents on key physical properties of NiO NPs synthesized by flash combustion process and their cytotoxicity studies for biomedical applications. *Ceram. Int.* **2020**, *46*, 19691–19700. [[CrossRef](#)]
155. da Silva Ferreira, V.; ConzFerreira, M.E.; Lima, L.M.T.R.; Frases, S.; de Souza, W.; Sant'Anna, C. Green production of microalgae-based silver chloride nanoparticles with antimicrobial activity against pathogenic bacteria. *Enzyme Microb. Technol.* **2017**, *97*, 114–121. [[CrossRef](#)] [[PubMed](#)]
156. Ayeshamariam, A.; Begam, M.; Jayachandran, M.; Kumar, G.P.; Bououdina, M. Green Synthesis of Nanostructured Materials for Antibacterial and Antifungal Activities. *Int. J. Bioassays* **2012**, *2*, 304–311.
157. Kamaraj, P.; Vennila, R.; Arthanareeswari, M. Biological Activities Of Tin Oxide Nanoparticles Synthesized Using Plant Extract. *World J. Pharm. Pharm. Sci.* **2014**, *3*, 382–388.
158. Rehman, S.; Asiri, S.M.; Khan, F.A.; Jermy, B.R.; Ravinayagam, V.; Alsalem, Z.; Al Jindan, R.; Qurashi, A. Anticandidal and In vitro Anti-Proliferative Activity of Sonochemically synthesized Indium Tin Oxide Nanoparticles. *Sci. Rep.* **2020**, *10*, 3228. [[CrossRef](#)]
159. Rehman, S.; Asiri, S.M.; Khan, F.A.; Jermy, B.R.; Khan, H.; Akhtar, S.; Al Jindan, R.; Khan, K.M.; Qurashi, A. Biocompatible Tin Oxide Nanoparticles: Synthesis, Antibacterial, Anticandidal and Cytotoxic Activities. *ChemistrySelect* **2019**, *4*, 4013–4017. [[CrossRef](#)]
160. Besinis, A.; De Peralta, T.; Handy, R.D. The antibacterial effects of silver, titanium dioxide and silica dioxide nanoparticles compared to the dental disinfectant chlorhexidine on *Streptococcus mutans* using a suite of bioassays. *Nanotoxicology* **2014**, *8*, 1–16. [[CrossRef](#)]
161. Park, G.W.; Cho, M.; Cates, E.L.; Lee, D.; Oh, B.T.; Vinjé, J.; Kim, J.H. Fluorinated TiO₂ as an ambient light-activated virucidal surface coating material for the control of human norovirus. *J. Photochem. Photobiol. B Biol.* **2014**, *140*, 315–320. [[CrossRef](#)]
162. Nakano, R.; Ishiguro, H.; Yao, Y.; Kajioaka, J.; Fujishima, A.; Sunada, K.; Minoshima, M.; Hashimoto, K.; Kubota, Y. Photocatalytic inactivation of influenza virus by titanium dioxide thin film. *Photochem. Photobiol. Sci.* **2012**, *11*, 1293–1298. [[CrossRef](#)]
163. Hajkova, P.; Spatenka, P.; Horsky, J.; Horska, I.; Kolouch, A. Photocatalytic effect of TiO₂ films on viruses and bacteria. In *Proceedings of the Plasma Processes and Polymers*; Wiley-VCH: Weinheim, Germany, 2007; Volume 4.
164. Wang, Z.L.; Gao, R.P.; Nikoobakht, B.; El-Sayed, M.A. Surface reconstruction of the unstable {110} surface in gold nanorods. *J. Phys. Chem. B* **2000**, *104*, 5417–5420. [[CrossRef](#)]
165. Haghighi, F.; Mohammadi, S.R.; Mohammadi, P.; Hosseinkhani, S.; Shidpour, R. Antifungal Activity of TiO₂ nanoparticles and EDTA on *Candida albicans* Biofilms. *Infect. Epidemiol. Med.* **2013**, *1*, 33–38.
166. Bueloni, B.; Sanna, D.; Garrriba, E.; Castro, G.R.; León, I.E.; Islan, G.A. Design of nalidixic acid-vanadium complex loaded into chitosan hybrid nanoparticles as smart strategy to inhibit bacterial growth and quorum sensing. *Int. J. Biol. Macromol.* **2020**, *161*, 1568–1580. [[CrossRef](#)] [[PubMed](#)]
167. Basak, G.; Das, D.; Das, N. Dual role of acidic diacetate sophorolipid as biostabilizer for ZnO nanoparticle synthesis and biofunctionalizing agent against *Salmonella enterica* and *Candida albicans*. *J. Microbiol. Biotechnol.* **2014**, *24*, 87–96. [[CrossRef](#)] [[PubMed](#)]
168. O'Donnell, C.D.; Shukla, D. The importance of heparan sulfate in herpesvirus infection. *Viol. Sin.* **2008**, *23*, 383–393. [[CrossRef](#)] [[PubMed](#)]
169. Ghaffari, H.; Tavakoli, A.; Moradi, A.; Tabarraei, A.; Bokharaei-Salim, F.; Zahmatkeshan, M.; Farahmand, M.; Javanmard, D.; Kiani, S.J.; Eshghaei, M.; et al. Inhibition of H1N1 influenza virus infection by zinc oxide nanoparticles: Another emerging application of nanomedicine. *J. Biomed. Sci.* **2019**, *26*, 70. [[CrossRef](#)] [[PubMed](#)]
170. Jamdagni, P.; Khatri, P.; Rana, J.S. Green synthesis of zinc oxide nanoparticles using flower extract of *Nyctanthes arbor-tristis* and their antifungal activity. *J. King Saud Univ. Sci.* **2018**, *30*, 168–175. [[CrossRef](#)]
171. Fathima, J.B.; Pugazhendhi, A.; Venis, R. Synthesis and characterization of ZrO₂ nanoparticles-antimicrobial activity and their prospective role in dental care. *Microb. Pathog.* **2017**, *110*, 245–251. [[CrossRef](#)]
172. Sousa, F.; Ferreira, D.; Reis, S.; Costa, P. Current insights on antifungal therapy: Novel nanotechnology approaches for drug delivery systems and new drugs from natural sources. *Pharmaceuticals* **2020**, *13*, 248. [[CrossRef](#)]
173. Sharmin, S.; Rahaman, M.M.; Sarkar, C.; Atolani, O.; Islam, M.T.; Adeyemi, O.S. Nanoparticles as antimicrobial and antiviral agents: A literature-based perspective study. *Heliyon* **2021**, *7*, e06456. [[CrossRef](#)]
174. Rai, M.; Deshmukh, S.D.; Ingle, A.P.; Gupta, I.R.; Galdiero, M.; Galdiero, S. Metal nanoparticles: The protective nanoshield against virus infection. *Crit. Rev. Microbiol.* **2016**, *42*, 46–56. [[CrossRef](#)]
175. Prasher, P.; Singh, M.; Mudila, H. Oligodynamic Effect of Silver Nanoparticles: A Review. *Bionanoscience* **2018**, *8*, 951–962. [[CrossRef](#)]
176. Bawage, S.S.; Tiwari, P.M.; Singh, A.; Dixit, S.; Pillai, S.R.; Dennis, V.A.; Singh, S.R. Gold nanorods inhibit respiratory syncytial virus by stimulating the innate immune response. *Nanomed. Nanotechnol. Biol. Med.* **2016**, *12*, 2299–2310. [[CrossRef](#)] [[PubMed](#)]
177. Watanabe, Y.; Allen, J.D.; Wrapp, D.; McLellan, J.S.; Crispin, M. Site-specific glycan analysis of the SARS-CoV-2 spike. *Science* **2020**, *369*, 330–333. [[CrossRef](#)] [[PubMed](#)]
178. Lin, N.; Verma, D.; Saini, N.; Arbi, R.; Munir, M.; Jovic, M.; Turak, A. Antiviral nanoparticles for sanitizing surfaces: A roadmap to self-sterilizing against COVID-19. *Nano Today* **2021**, *40*, 101267. [[CrossRef](#)] [[PubMed](#)]

179. Demchenko, V.; Kobylinskyi, S.; Iurzhenko, M.; Riabov, S.; Vashchuk, A.; Rybalchenko, N.; Zahorodnia, S.; Naumenko, K.; Demchenko, O.; Adamus, G.; et al. Nanocomposites based on polylactide and silver nanoparticles and their antimicrobial and antiviral applications. *React. Funct. Polym.* **2022**, *170*, 105096. [[CrossRef](#)]
180. Wolska, K.I.; Markowska, K.; Wypij, M.; Golińska, P.; Dahm, H. Nanocząstki srebra, synteza i biologiczna aktywność. *Kosmos* **2017**, *66*, 125–138.
181. Konnova, S.A.; Danilushkina, A.A.; Fakhrullina, G.I.; Akhatova, F.S.; Badrutdinov, A.R.; Fakhrullin, R.F. Silver nanoparticle-coated “cyborg” microorganisms: Rapid assembly of polymer-stabilised nanoparticles on microbial cells. *RSC Adv.* **2015**, *5*, 13530–13537. [[CrossRef](#)]
182. Gogoi, S.K.; Gopinath, P.; Paul, A.; Ramesh, A.; Ghosh, S.S.; Chattopadhyay, A. Green fluorescent protein-expressing *Escherichia coli* as a model system for investigating the antimicrobial activities of silver nanoparticles. *Langmuir* **2006**, *22*, 9322–9328. [[CrossRef](#)]
183. Feng, Q.L.; Wu, J.; Chen, G.Q.; Cui, F.Z.; Kim, T.N.; Kim, J.O. A mechanistic study of the antibacterial effect of silver ions on *Escherichia coli* and *Staphylococcus aureus*. *J. Biomed. Mater. Res.* **2000**, *52*, 662–668. [[CrossRef](#)]
184. Wzorek, Z.; Konopka, M. Nanosrebro—nowy środek bakteriobójczy. *Czas. Tech. Chem.* **2007**, *104*, 175–181.
185. Marambio-Jones, C.; Hoek, E.M.V. A review of the antibacterial effects of silver nanomaterials and potential implications for human health and the environment. *J. Nanoparticle Res.* **2010**, *12*, 1531–1551. [[CrossRef](#)]
186. Raczowska, J.; Stetsyshyn, Y.; Awsiak, K.; Brzychczy-Włoch, M.; Gosiewski, T.; Jany, B.; Lishchynskyi, O.; Shymborska, Y.; Nastyshyn, S.; Bernasik, A.; et al. “Command” surfaces with thermo-switchable antibacterial activity. *Mater. Sci. Eng. C* **2019**, *103*, 109806. [[CrossRef](#)] [[PubMed](#)]
187. Srivastava, D.N.; Perkas, N.; Gedanken, A.; Felner, I. Sonochemical synthesis of mesoporous iron oxide and accounts of its magnetic and catalytic properties. *J. Phys. Chem. B* **2002**, *106*, 1878–1883. [[CrossRef](#)]
188. Galdiero, S.; Falanga, A.; Vitiello, M.; Cantisani, M.; Marra, V.; Galdiero, M. Silver nanoparticles as potential antiviral agents. *Molecules* **2011**, *16*, 8894–8918. [[CrossRef](#)] [[PubMed](#)]
189. Morones, J.R.; Elechiguerra, J.L.; Camacho, A.; Holt, K.; Kouri, J.B.; Ramírez, J.T.; Yacaman, M.J. The bactericidal effect of silver nanoparticles. *Nanotechnology* **2005**, *16*, 2346–2353. [[CrossRef](#)] [[PubMed](#)]
190. Du, T.; Liang, J.; Dong, N.; Lu, J.; Fu, Y.; Fang, L.; Xiao, S.; Han, H. Glutathione-Capped Ag₂S Nanoclusters Inhibit Coronavirus Proliferation through Blockage of Viral RNA Synthesis and Budding. *ACS Appl. Mater. Interfaces* **2018**, *10*, 4369–4378. [[CrossRef](#)]
191. Martínez-Abad, A.; Ocio, M.J.; Lagarón, J.M.; Sánchez, G. Evaluation of silver-infused polylactide films for inactivation of *Salmonella* and feline calicivirus in vitro and on fresh-cut vegetables. *Int. J. Food Microbiol.* **2013**, *162*, 89–94. [[CrossRef](#)] [[PubMed](#)]
192. Castro-Mayorga, J.L.; Fabra, M.J.; Pourrahimi, A.M.; Olsson, R.T.; Lagaron, J.M. The impact of zinc oxide particle morphology as an antimicrobial and when incorporated in poly(3-hydroxybutyrate-co-3-hydroxyvalerate) films for food packaging and food contact surfaces applications. *Food Bioprod. Process.* **2017**, *101*, 32–44. [[CrossRef](#)]
193. Priyadarshi, R.; Roy, S.; Ghosh, T.; Biswas, D.; Rhim, J.-W. Antimicrobial nanofillers reinforced biopolymer composite films for active food packaging applications—A review. *Sustain. Mater. Technol.* **2021**, e00353. [[CrossRef](#)]
194. Chen, Y.N.; Hsueh, Y.H.; Te Hsieh, C.; Tzou, D.Y.; Chang, P.L. Antiviral activity of graphene–silver nanocomposites against non-enveloped and enveloped viruses. *Int. J. Environ. Res. Public Health* **2016**, *13*, 430. [[CrossRef](#)]
195. Busolo, M.A.; Fernandez, P.; Ocio, M.J.; Lagaron, J.M. Novel silver-based nanoclay as an antimicrobial in polylactic acid food packaging coatings. *Food Addit. Contam. Part A Chem. Anal. Control. Expo. Risk Assess.* **2010**, *27*, 1617–1626. [[CrossRef](#)]
196. Ghosh, S.; Vandana, V. Nano-structured mesoporous silica/silver composite: Synthesis, characterization and targeted application towards water purification. *Mater. Res. Bull.* **2017**, *88*, 291–300. [[CrossRef](#)]
197. Yang, H.; Li, G.; Stansbury, J.W.; Zhu, X.; Wang, X.; Nie, J. Smart Antibacterial Surface Made by Photopolymerization. *ACS Appl. Mater. Interfaces* **2016**, *8*, 28047–28054. [[CrossRef](#)] [[PubMed](#)]
198. Castro Mayorga, J.L.; Fabra Rovira, M.J.; Cabedo Mas, L.; Sánchez Moragas, G.; Lagarón Cabello, J.M. Antimicrobial nanocomposites and electrospun coatings based on poly(3-hydroxybutyrate-co-3-hydroxyvalerate) and copper oxide nanoparticles for active packaging and coating applications. *J. Appl. Polym. Sci.* **2018**, *135*, 45673. [[CrossRef](#)]
199. Borkow, G.; Zhou, S.S.; Page, T.; Gabbay, J. A novel anti-influenza copper oxide containing respiratory face mask. *PLoS ONE* **2010**, *5*, e11295. [[CrossRef](#)]
200. Sun, C.; Li, Y.; Li, Z.; Su, Q.; Wang, Y.; Liu, X. Durable and Washable Antibacterial Copper Nanoparticles Bridged by Surface Grafting Polymer Brushes on Cotton and Polymeric Materials. *J. Nanomater.* **2018**, *2018*, 1–7. [[CrossRef](#)]
201. Shakeel, M.; Jabeen, F.; Shabbir, S.; Asghar, M.S.; Khan, M.S.; Chaudhry, A.S. Toxicity of Nano-Titanium Dioxide (TiO₂-NP) Through Various Routes of Exposure: A Review. *Biol. Trace Elem. Res.* **2016**, *172*, 1–36. [[CrossRef](#)] [[PubMed](#)]
202. Nikolic, M.V.; Vasiljevic, Z.Z.; Auger, S.; Vidic, J. Metal oxide nanoparticles for safe active and intelligent food packaging. *Trends Food Sci. Technol.* **2021**, *116*, 655–668. [[CrossRef](#)]
203. Mazurkova, N.A.; Spitsyna, Y.E.; Shikina, N.V.; Ismagilov, Z.R.; Zagrebel’nyi, S.N.; Ryabchikova, E.I. Interaction of titanium dioxide nanoparticles with influenza virus. *Nanotechnologies Russ.* **2010**, *5*, 417–420. [[CrossRef](#)]
204. Shahbazi, Y.; Shavisi, N. Current advancements in applications of chitosan based nano-metal oxides as food preservative materials. *Nanomed. Res. J.* **2019**, *4*, 122–129. [[CrossRef](#)]
205. Kumar, H.; Bhardwaj, K.; Kuča, K.; Kalia, A.; Nepovimova, E.; Verma, R.; Kumar, D. Flower-based green synthesis of metallic nanoparticles: Applications beyond fragrance. *Nanomaterials* **2020**, *10*, 766. [[CrossRef](#)]

206. Nguyen, N.Y.T.; Grelling, N.; Wetteland, C.L.; Rosario, R.; Liu, H. Antimicrobial Activities and Mechanisms of Magnesium Oxide Nanoparticles (nMgO) against Pathogenic Bacteria, Yeasts, and Biofilms. *Sci. Rep.* **2018**, *8*, 16260. [[CrossRef](#)] [[PubMed](#)]
207. Mirtalebi, S.S.; Almasi, H.; Alizadeh Khaledabad, M. Physical, morphological, antimicrobial and release properties of novel MgO-bacterial cellulose nanohybrids prepared by in-situ and ex-situ methods. *Int. J. Biol. Macromol.* **2019**, *128*, 848–857. [[CrossRef](#)]
208. Huang, L.; Li, D.Q.; Lin, Y.J.; Wei, M.; Evans, D.G.; Duan, X. Controllable preparation of Nano-MgO and investigation of its bactericidal properties. *J. Inorg. Biochem.* **2005**, *99*, 986–993. [[CrossRef](#)] [[PubMed](#)]
209. Stoimenov, P.K.; Klinger, R.L.; Marchin, G.L.; Klabunde, K.J. Metal oxide nanoparticles as bactericidal agents. *Langmuir* **2002**, *18*, 6679–6686. [[CrossRef](#)]
210. Hameed, A.S.H.; Karthikeyan, C.; Ahamed, A.P.; Thajuddin, N.; Alharbi, N.S.; Alharbi, S.A.; Ravi, G. In vitro antibacterial activity of ZnO and Nd doped ZnO nanoparticles against ESBL producing Escherichia coli and Klebsiella pneumoniae. *Sci. Rep.* **2016**, *6*, 24312. [[CrossRef](#)]
211. Gupta, M.; Mahajan, V.K.; Mehta, K.S.; Chauhan, P.S. Zinc therapy in dermatology: A review. *Dermatol. Res. Pract.* **2014**, *2014*, 709152. [[CrossRef](#)]
212. Siddiqi, K.S.; ur Rahman, A.; Tajuddin; Husen, A. Properties of Zinc Oxide Nanoparticles and Their Activity Against Microbes. *Nanoscale Res. Lett.* **2018**, *13*, 141. [[CrossRef](#)]
213. Premanathan, M.; Karthikeyan, K.; Jeyasubramanian, K.; Manivannan, G. Selective toxicity of ZnO nanoparticles toward Gram-positive bacteria and cancer cells by apoptosis through lipid peroxidation. *Nanomed. Nanotechnol. Biol. Med.* **2011**, *7*, 184–192. [[CrossRef](#)]
214. Talebian, N.; Amininezhad, S.M.; Douidi, M. Controllable synthesis of ZnO nanoparticles and their morphology-dependent antibacterial and optical properties. *J. Photochem. Photobiol. B Biol.* **2013**, *120*, 66–73. [[CrossRef](#)]
215. Abouaitah, K.; Allayh, A.K.; Wojnarowicz, J.; Shaker, Y.M.; Swiderska-Sroda, A.; Lojkowski, W. Nanoformulation Composed of Ellagic Acid and Functionalized Zinc Oxide Nanoparticles Inactivates DNA and RNA Viruses. *Pharmaceutics* **2021**, *13*, 2174. [[CrossRef](#)]
216. El-Megharbel, S.M.; Alsawat, M.; Al-Salmi, F.A.; Hamza, R.Z. Utilizing of (Zinc oxide nano-spray) for disinfection against “sars-cov-2” and testing its biological effectiveness on some biochemical parameters during (covid-19 pandemic)—“zno nanoparticles have antiviral activity against (sars-cov-2)”. *Coatings* **2021**, *11*, 388. [[CrossRef](#)]
217. Singh, P.; Garg, A.; Pandit, S.; Mokkalpati, V.R.S.S.; Mijakovic, I. Antimicrobial effects of biogenic nanoparticles. *Nanomaterials* **2018**, *8*, 1009. [[CrossRef](#)] [[PubMed](#)]
218. Saravanan, M.; Gopinath, V.; Chaurasia, M.K.; Syed, A.; Ameen, F.; Purushothaman, N. Green synthesis of anisotropic zinc oxide nanoparticles with antibacterial and cytofriendly properties. *Microb. Pathog.* **2018**, *115*, 57–63. [[CrossRef](#)] [[PubMed](#)]
219. Schwartz, V.B.; Thétiot, F.; Ritz, S.; Pütz, S.; Choritz, L.; Lappas, A.; Förch, R.; Landfester, K.; Jonas, U. Antibacterial surface coatings from zinc oxide nanoparticles embedded in poly(N-isopropylacrylamide) hydrogel surface layers. *Adv. Funct. Mater.* **2012**, *22*, 2376–2386. [[CrossRef](#)]
220. Bowman, M.C.; Ballard, T.E.; Ackerson, C.J.; Feldheim, D.L.; Margolis, D.M.; Melander, C. Inhibition of HIV fusion with multivalent gold nanoparticles. *J. Am. Chem. Soc.* **2008**, *130*, 6896–6897. [[CrossRef](#)] [[PubMed](#)]
221. Singh, A.K.; Tiwari, R.; Singh, V.K.; Singh, P.; Khadim, S.R.; Singh, U.; Laxmi; Srivastava, V.; Hasan, S.H.; Asthana, R.K. Green synthesis of gold nanoparticles from *Dunaliella salina*, its characterization and in vitro anticancer activity on breast cancer cell line. *J. Drug Deliv. Sci. Technol.* **2019**, *51*, 164–176. [[CrossRef](#)]
222. Vallabani, N.V.S.; Singh, S. Recent advances and future prospects of iron oxide nanoparticles in biomedicine and diagnostics. *3 Biotech* **2018**, *8*, 279. [[CrossRef](#)]
223. Winiarczyk, K.; Gac, W.; Góral-Kowalczyk, M.; Surowiec, Z. Magnetic properties of iron oxide nanoparticles with a DMSA-modified surface. *Hyperfine Interact.* **2021**, *242*, 48. [[CrossRef](#)]
224. Bobo, D.; Robinson, K.J.; Islam, J.; Thurecht, K.J.; Corrie, S.R. Nanoparticle-Based Medicines: A Review of FDA-Approved Materials and Clinical Trials to Date. *Pharm. Res.* **2016**, *33*, 2373–2387. [[CrossRef](#)]
225. Behera, S.S.; Patra, J.K.; Pramanik, K.; Panda, N.; Thatoi, H. Characterization and Evaluation of Antibacterial Activities of Chemically Synthesized Iron Oxide Nanoparticles. *World J. Nano Sci. Eng.* **2012**, *02*, 196–200. [[CrossRef](#)]
226. Abo-zeid, Y.; Williams, G.R. The potential anti-infective applications of metal oxide nanoparticles: A systematic review. *Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol.* **2020**, *12*, e1592. [[CrossRef](#)] [[PubMed](#)]
227. Kumar, S.R.; Paulpandi, M.; Manivelraja, M.; Mangalaraj, D.; Viswanathan, C.; Kannan, S.; Ponpandian, N. An in vitro analysis of H1N1 viral inhibition using polymer coated superparamagnetic Fe₃O₄ nanoparticles. *RSC Adv.* **2014**, *4*, 13409–13418. [[CrossRef](#)]
228. Kumar, R.; Nayak, M.; Sahoo, G.C.; Pandey, K.; Sarkar, M.C.; Ansari, Y.; Das, V.N.R.; Topno, R.K.; Bhawna; Madhukar, M.; et al. Iron oxide nanoparticles based antiviral activity of H1N1 influenza A virus. *J. Infect. Chemother.* **2019**, *25*, 325–329. [[CrossRef](#)] [[PubMed](#)]
229. Ryan, J.N.; Harvey, R.W.; Metge, D.; Elimelech, M.; Navigato, T.; Pieper, A.P. Field and laboratory investigations of inactivation of viruses (PRD1 and MS2) attached to iron oxide-coated quartz sand. *Environ. Sci. Technol.* **2002**, *36*, 2403–2413. [[CrossRef](#)] [[PubMed](#)]
230. Arredondo, M.; Núñez, M.T. Iron and copper metabolism. *Mol. Aspects Med.* **2005**, *26*, 313–327. [[CrossRef](#)]

231. Chatterjee, A.K.; Chakraborty, R.; Basu, T. Mechanism of antibacterial activity of copper nanoparticles. *Nanotechnology* **2014**, *25*, 135101. [CrossRef]
232. Rattanukul, S.; Oguma, K. Analysis of Hydroxyl Radicals and Inactivation Mechanisms of Bacteriophage MS2 in Response to a Simultaneous Application of UV and Chlorine. *Environ. Sci. Technol.* **2017**, *51*, 455–462. [CrossRef]
233. Dealba-Montero, I.; Guajardo-Pacheco, J.; Morales-Sánchez, E.; Araujo-Martínez, R.; Loredó-Becerra, G.M.; Martínez-Castañón, G.A.; Ruiz, F.; Jasso, M.E.C. Antimicrobial Properties of Copper Nanoparticles and Amino Acid Chelated Copper Nanoparticles Produced by Using a Soya Extract. *Bioinorg. Chem. Appl.* **2017**, *2017*, 1–6. [CrossRef]
234. Ready, T. FDA Clears First Antiviral Surgical Mask. Available online: <https://www.medscape.com/viewarticle/745801> (accessed on 17 February 2022).
235. Mitovski, A.; Grekulović, V.; Štrbac, N.; Jovanović, S.M.; Božinović, K.; Zdravković, M. Antimicrobial properties of copper and its alloys through the prism of the current SARS CoV-2 pandemic. *Mater. Prot.* **2021**, *62*, 297–303. [CrossRef]
236. Luque, P.A.; Garrafa-Gálvez, H.E.; Nava, O.; Olivás, A.; Martínez-Rosas, M.E.; Vilchis-Nestor, A.R.; Villegas-Fuentes, A.; Chinchillas-Chinchillas, M.J. Efficient sunlight and UV photocatalytic degradation of Methyl Orange, Methylene Blue and Rhodamine B, using Citrus × paradisi synthesized SnO₂ semiconductor nanoparticles. *Ceram. Int.* **2021**, *47*, 23861–23874. [CrossRef]
237. Matussin, S.; Harunsani, M.H.; Tan, A.L.; Khan, M.M. Plant-Extract-Mediated SnO₂ Nanoparticles: Synthesis and Applications. *ACS Sustain. Chem. Eng.* **2020**, *8*, 3040–3054. [CrossRef]
238. Hodek, J.; Zajícová, V.; Lovetinská-Šlamborová, I.; Štibor, I.; Müllerová, J.; Weber, J. Protective hybrid coating containing silver, copper and zinc cations effective against human immunodeficiency virus and other enveloped viruses. *BMC Microbiol.* **2016**, *16*, 56. [CrossRef] [PubMed]
239. Naahidi, S.; Jafari, M.; Edalat, F.; Raymond, K.; Khademhosseini, A.; Chen, P. Biocompatibility of engineered nanoparticles for drug delivery. *J. Control. Release* **2013**, *166*, 182–194. [CrossRef]
240. Zamay, G.S.; Zamay, T.N.; Lukyanenko, K.A.; Kichkailo, A.S. Aptamers increase biocompatibility and reduce the toxicity of magnetic nanoparticles used in biomedicine. *Biomedicines* **2020**, *8*, 59. [CrossRef]
241. Yuan, P.; Ding, X.; Yang, Y.Y.; Xu, Q.H. Metal Nanoparticles for Diagnosis and Therapy of Bacterial Infection. *Adv. Healthc. Mater.* **2018**, *7*, 1701392. [CrossRef] [PubMed]
242. Schärfl, W. Current directions in core-shell nanoparticle design. *Nanoscale* **2010**, *2*, 829–843. [CrossRef] [PubMed]
243. Sanità, G.; Carrese, B.; Lamberti, A. Nanoparticle Surface Functionalization: How to Improve Biocompatibility and Cellular Internalization. *Front. Mol. Biosci.* **2020**, *7*, 381. [CrossRef]
244. Fierascu, I.; Fierascu, I.C.; Dinu-Pirvu, C.E.; Fierascu, R.C.; Anuta, V.; Velescu, B.S.; Jinga, M.; Jinga, V. A short overview of recent developments on antimicrobial coatings based on phytosynthesized metal nanoparticles. *Coatings* **2019**, *9*, 787. [CrossRef]
245. Li, J.; Sun, Q.; Sun, Y.; Chen, B.; Wu, X.; Le, T. Improvement of banana postharvest quality using a novel soybean protein isolate/cinnamaldehyde/zinc oxide bionanocomposite coating strategy. *Sci. Hortic.* **2019**, *258*, 108786. [CrossRef]
246. La, D.D.; Nguyen-Tri, P.; Le, K.H.; Nguyen, P.T.M.; Nguyen, M.D.B.; Vo, A.T.K.; Nguyen, M.T.H.; Chang, S.W.; Tran, L.D.; Chung, W.J.; et al. Effects of antibacterial ZnO nanoparticles on the performance of a chitosan/gum arabic edible coating for post-harvest banana preservation. *Prog. Org. Coat.* **2021**, *151*, 106057. [CrossRef]
247. Lavinia, M.; Hibaturrahman, S.N.; Harinata, H.; Wardana, A.A. Antimicrobial activity and application of nanocomposite coating from chitosan and ZnO nanoparticle to inhibit microbial growth on fresh-cut papaya. *Food Res.* **2020**, *4*, 307–311. [CrossRef]
248. Koushesh Saba, M.; Amini, R. Nano-ZnO/carboxymethyl cellulose-based active coating impact on ready-to-use pomegranate during cold storage. *Food Chem.* **2017**, *232*, 721–726. [CrossRef] [PubMed]
249. Saekow, M.; Naradisorn, M.; Tongdeesoontorn, W.; Hamauzu, Y. Effect of carboxymethyl cellulose coating containing ZnO-nanoparticles for prolonging shelf life of persimmon and tomato fruit. *J. Food Sci. Agric. Technol.* **2019**, *5*, 41–48.
250. Le, K.H.; Nguyen, M.D.B.; Tran, L.D.; Nguyen Thi, H.P.; Van Tran, C.; Van Tran, K.; Nguyen Thi, H.P.; Dinh Thi, N.; Yoon, Y.S.; Nguyen, D.D.; et al. A novel antimicrobial ZnO nanoparticles-added polysaccharide edible coating for the preservation of postharvest avocado under ambient conditions. *Prog. Org. Coat.* **2021**, *158*, 106339. [CrossRef]
251. Joshy, K.S.; Jose, J.; Li, T.; Thomas, M.; Shankregowda, A.M.; Sreekumaran, S.; Kalarikkal, N.; Thomas, S. Application of novel zinc oxide reinforced xanthan gum hybrid system for edible coatings. *Int. J. Biol. Macromol.* **2020**, *151*, 806–813. [CrossRef]
252. Arroyo, B.J.; Bezerra, A.C.; Oliveira, L.L.; Arroyo, S.J.; de Melo, E.A.; Santos, A.M.P. Antimicrobial active edible coating of alginate and chitosan add ZnO nanoparticles applied in guavas (*Psidium guajava* L.). *Food Chem.* **2020**, *309*, 125566. [CrossRef]
253. Chi, H.; Song, S.; Luo, M.; Zhang, C.; Li, W.; Li, L.; Qin, Y. Effect of PLA nanocomposite films containing bergamot essential oil, TiO₂ nanoparticles, and Ag nanoparticles on shelf life of mangoes. *Sci. Hortic.* **2019**, *249*, 192–198. [CrossRef]
254. An, J.; Zhang, M.; Wang, S.; Tang, J. Physical, chemical and microbiological changes in stored green asparagus spears as affected by coating of silver nanoparticles-PVP. *LWT Food Sci. Technol.* **2008**, *41*, 1100–1107. [CrossRef]
255. Kanikireddy, V.; Varaprasad, K.; Rani, M.S.; Venkataswamy, P.; Mohan Reddy, B.J.; Vithal, M. Biosynthesis of CMC-Guar gum-Ag₀ nanocomposites for inactivation of food pathogenic microbes and its effect on the shelf life of strawberries. *Carbohydr. Polym.* **2020**, *236*, 116053. [CrossRef]
256. Kanikireddy, V.; Kanny, K.; Padma, Y.; Velchuri, R.; Ravi, G.; Jagan Mohan Reddy, B.; Vithal, M. Development of alginate-gum acacia-Ag₀ nanocomposites via green process for inactivation of foodborne bacteria and impact on shelf life of black grapes (*Vitis vinifera*). *J. Appl. Polym. Sci.* **2019**, *136*, 47331. [CrossRef]

257. Youssef, A.M.; Assem, F.M.; Abdel-Aziz, M.E.; Elaaser, M.; Ibrahim, O.A.; Mahmoud, M.; Abd El-Salam, M.H. Development of bionanocomposite materials and its use in coating of Ras cheese. *Food Chem.* **2019**, *270*, 467–475. [[CrossRef](#)] [[PubMed](#)]
258. Kaewklin, P.; Siripatrawan, U.; Suwanagul, A.; Lee, Y.S. Active packaging from chitosan-titanium dioxide nanocomposite film for prolonging storage life of tomato fruit. *Int. J. Biol. Macromol.* **2018**, *112*, 523–529. [[CrossRef](#)] [[PubMed](#)]
259. Vizzini, P.; Beltrame, E.; Zanet, V.; Vidic, J.; Manzano, M. Development and evaluation of qpcr detection method and zn-go/alginate active packaging for controlling listeria monocytogenes contamination in cold-smoked salmon. *Foods* **2020**, *9*, 1353. [[CrossRef](#)] [[PubMed](#)]
260. Lin, B.; Luo, Y.; Teng, Z.; Zhang, B.; Zhou, B.; Wang, Q. Development of silver/titanium dioxide/chitosan adipate nanocomposite as an antibacterial coating for fruit storage. *LWT* **2015**, *63*, 1206–1213. [[CrossRef](#)]
261. Xing, Y.; Li, W.; Wang, Q.; Li, X.; Xu, Q.; Guo, X.; Bi, X.; Liu, X.; Shui, Y.; Lin, H.; et al. Antimicrobial nanoparticles incorporated in edible coatings and films for the preservation of fruits and vegetables. *Molecules* **2019**, *24*, 1695. [[CrossRef](#)] [[PubMed](#)]
262. Zambrano-Zaragoza, M.L.; González-Reza, R.; Mendoza-Muñoz, N.; Miranda-Linares, V.; Bernal-Couoh, T.F.; Mendoza-Elvira, S.; Quintanar-Guerrero, D. Nanosystems in edible coatings: A novel strategy for food preservation. *Int. J. Mol. Sci.* **2018**, *19*, 705. [[CrossRef](#)] [[PubMed](#)]
263. Ojha, P.K.; Kar, S.; Roy, K.; Leszczynski, J. Toward comprehension of multiple human cells uptake of engineered nano metal oxides: Quantitative inter cell line uptake specificity (QICLUS) modeling. *Nanotoxicology* **2019**, *13*, 14–34. [[CrossRef](#)] [[PubMed](#)]
264. Chang, H.J.; Choi, S.W.; Ko, S.; Chun, H.S. Effect of Particle Size of Zinc Oxides on Cytotoxicity and Cell Permeability. in Caco-2 Cells Research Note. *J. Food Sci. Nutr.* **2011**, *16*, 174–178. [[CrossRef](#)]
265. EFSA Food Contact Materials, Enzymes and Processing Aids | EFSA. *EFSA J.* **2013**, *11*, 3155.
266. Qari, S.H.; Alrefaei, A.F.; Ashoor, A.B.; Soliman, M.H. Genotoxicity and Carcinogenicity of Medicinal Herbs and Their Nanoparticles. *Nutraceuticals* **2021**, *1*, 31–41. [[CrossRef](#)]
267. Tan, C.; Xie, J.; Zhang, X.; Cai, J.; Xia, S. Polysaccharide-based nanoparticles by chitosan and gum arabic polyelectrolyte complexation as carriers for curcumin. *Food Hydrocoll.* **2016**, *57*, 236–245. [[CrossRef](#)]
268. Pandey, S.; De Klerk, C.; Kim, J.; Kang, M.; Fosso-Kankeu, E. Eco friendly approach for synthesis, characterization and biological activities of milk protein stabilized silver nanoparticles. *Polymers* **2020**, *12*, 1418. [[CrossRef](#)]
269. Gnanasekar, S.; Murugaraj, J.; Dhivyabharathi, B.; Krishnamoorthy, V.; Jha, P.K.; Seetharaman, P.; Vilwanathan, R.; Sivaperumal, S. Antibacterial and cytotoxicity effects of biogenic palladium nanoparticles synthesized using fruit extract of *Couroupita guianensis* Aubl. *J. Appl. Biomed.* **2018**, *16*, 59–65. [[CrossRef](#)]
270. Li, X.; Cheung, P.C.K. Application of natural β -glucans as biocompatible functional nanomaterials. *Food Sci. Hum. Wellness* **2019**, *8*, 315–319. [[CrossRef](#)]
271. Serban, M.A. Translational biomaterials—The journey from the bench to the market—Think “product”. *Curr. Opin. Biotechnol.* **2016**, *40*, 31–34. [[CrossRef](#)] [[PubMed](#)]
272. Querido, M.M.; Aguiar, L.; Neves, P.; Pereira, C.C.; Teixeira, J.P. Self-disinfecting surfaces and infection control. *Colloids Surf. B Biointerfaces* **2019**, *178*, 8–21. [[CrossRef](#)]