Review

Transformation of Biowaste for Medical Applications: Incorporation of Biologically Derived Silver Nanoparticles as Antimicrobial Coating

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Abstract: Nanobiotechnology has undoubtedly influenced major breakthroughs in medical sciences. Application of nanosized materials has made it possible for researchers to investigate a broad spectrum of treatments for diseases with minimally invasive procedures. Silver nanoparticles (AgNPs) have been a subject of investigation for numerous applications in agriculture, water treatment, biosensors, textiles, and the food industry as well as in the medical field, mainly due to their antimicrobial properties and nanoparticle nature. In general, AgNPs are known for their superior physical, chemical, and biological properties. The properties of AgNPs differ based on their methods of synthesis and to date, the biological method has been preferred because it is rapid, nontoxic, and can produce well-defined size and morphology under optimized conditions. Nevertheless, the common issue concerning biological or biobased production is its sustainability. Researchers have employed various strategies in addressing this shortcoming, such as recently testing agricultural biowastes such as fruit peels for the synthesis of AgNPs. The use of biowastes is definitely cost-effective and eco-friendly; moreover, it has been reported that the reduction process is simple and rapid with reasonably high yield. This review aims to address the developments in using fruit- and vegetable-based biowastes for biologically producing AgNPs to be applied as antimicrobial coatings in biomedical applications.

Keywords: silver nanoparticles; nanobiotechnology; biowaste; biomedical; antimicrobial coating

1. Introduction

Silver nanoparticles (AgNPs) have received great attention for diverse applications in nanobiotechnology research [1]. Generally, silver nanoparticles are smaller than 100 nm with 20–15,000 silver atoms [2]. Owning to their chemical stability; thermal, optical, and catalytic properties; and high conductivity, silver nanoparticles have garnered increasing attention [3]. In addition, free release of silver ions from the silver nanoparticles under certain conditions induces cell death of mammalian cells or microbial cells, meaning silver nanoparticles are broad-spectrum antimicrobial agents. Therefore, AgNPs have also become the most widely used sterilizing nanomaterials in various products, including food storage bags, refrigerator surfaces, and personal care products, as well as their use...
in drug delivery, biosensors, food technology, molecular tagging, textile manufacturing, antimicrobial coatings, anticancer agents, wound dressings, and cosmetic products [4].

AgNPs are unique in terms of their physical, chemical, and biological properties. Therefore, these nanoparticles have been exploited for various purposes. Various methods have been employed in the synthesis of AgNPs. Nevertheless, the conventional physical and chemical methods adapted in the synthesis of AgNPs seem to be very expensive and hazardous. However, biological preparation of AgNPs overcomes these limitations as it seems to be simple, rapid, nontoxic, dependable, green, and can produce well-defined size and morphology under optimized conditions. Further, biological synthesis produces high yield, solubility, and stability [5]. The synthesis of AgNPs involves top-down and bottom-up approaches: in the bottom-up approach, nanoparticles are synthesized using chemical and biological methods involving the self-assembly of atoms that grow into nanoparticles; meanwhile in the top-down approach, bulk materials are broken down into fine particles by size reduction.

In biological or biobased production, the important issue to be addressed is sustainability. This involves the type of resources used for the production of AgNPs, the reduction process, and the size and yield of AgNPs. The biological or green synthesis, as it is often referred to, utilises various biological systems such as bacteria, fungi, and plant extracts and small biomolecules such as vitamins and amino acids [6]. The use of fruit wastes is generally new and has been proposed as a good secondary resource for producing AgNPs [7,8]. Transformation of biowastes into value-added products is another way of effectively managing waste and achieving circular economy [9].

The current review discusses the biological synthesis of AgNPs using biowastes and the antimicrobial properties of AgNPs and their application in antimicrobial coatings. The review also looks into the research gaps on the applications of AgNPs and general health; for example, evaluation of possible risks such as genotoxicity, carcinogenicity, and toxicokinetics of AgNPs as individual compounds or when they are present as composites. Besides, it is important to consider any inevitable use of hazardous materials even during green synthesis and its effects on terms of usage and environmental safety. Nevertheless, progressing research on and the advancement of AgNPs emphasizes the prospective outlook of AgNP-related applications and opportunities to address the gaps and limitations.

2. Silver Nanoparticles (AgNPs)

Medical research, including AgNP-related research, has intensified due to the 2019 coronavirus disease (COVID-19), with total global cases still on the rise daily. AgNPs harbour antiviral attributes and have been reported to inhibit severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is still spreading due to the lack of effective antiviral measures [10]. Furthermore, the recent upsurge in AgNP-related research and the third Sustainable Development Goal, set by the United Nations to support the research and development of medicines against diseases and protect public health, also advocate the need for a summary of the existing literature and advancements in the field of medical AgNP research. The recent progress in medical AgNP research includes the development of antibiotics, drug delivery methods, hydrogels, wound dressings, nanocomposites, antioxidants, and antitumour, anticancer, antifungal, and antiparasitic agents, as well as the green synthesis of AgNPs [11–19]. Recent AgNP research related to nanocomposite formulation, tissue engineering, and the green synthesis of AgNPs has been relatively abundant.

Other AgNP-related progress has been observed to further elucidate the additional advancements of AgNP research. Reports have disclosed the use of plant extracts in AgNP synthesis for antimicrobial, antitumour, and anticancer drugs, wound healing, cytotoxicity, and water purification, albeit being significantly emphasised in the medical fields as antimicrobial coatings [15–17]. Table 1 shows the latest AgNP usages investigated in 2020, whereby most of the applications were apparently related to the medical industry as antimicrobial coatings, although the trends may have been partially encouraged by the current pandemic and third Sustainable Development Goal. Besides that, another progress
in AgNP production worth noting is the advancement of AgNP composite properties using the bimetallic approach, which allows the adjustment of compositional percentage for application-specific composite properties [18–20]. Bimetallic studies have the potential to further develop nanocomposite research since this method has demonstrated enhanced outcomes, such as an improved antibacterial effectivity in Cu–AgNPs compared to sole Cu- or AgNPs [19]. In addition, AgNPs have also been involved in the design of several recent patents due to their attractive characteristics (Table 2).

**Table 1.** Applications related to silver nanoparticles that have recently been investigated in multiple industries; a brief summary to illustrate the recent trends and advancements in the research of silver nanoparticle applications.

| Industry   | Application                        | Properties                                             | References |
|------------|------------------------------------|--------------------------------------------------------|------------|
| Medical    | Scaffold                           | Cyto-compatible and antibacterial scaffold              | [21]       |
|            | Aerogel                            | Antibacterial aerogel                                   | [22]       |
|            | Endodontics                        | Antibacterial Gutta-percha                              | [23]       |
|            | Dental acrylic resin               | Antimicrobial and biocompatible resin                   | [24–26]   |
|            | Ocular therapeutics                | Antiangiogenic and antibacterial therapeutic nanoparticle| [27]       |
|            | Urinary catheters                  | Antibiofilm urinary catheter                            | [28]       |
|            | Medical dressing                   | Wound-healing cotton fabric                             | [29]       |
|            | Supercapacitor andelectrochemical sensing | High electrochemical capacity in 3D-printed microfluidic device | [30] |
| Electronics| Optoelectronic applications        | Enhanced optical transmittance                         | [31]       |
|            | Sensing and biosensing             | Stable and rapid photo-optical sensor                   | [32,33]   |
|            | Paper coating                      | Extends food shelf-life                                 | [34]       |
| Packaging  | Film                               | Antioxidant and antibacterial film                      | [35]       |
| Surface coating | Ceramic glaze                  | Antibacterial ceramic surface                           | [36]       |
| Remediation| Dye degradation                    | Catalytic ability on dye                                | [31,37]   |

**Table 2.** Recent patents related to silver nanoparticles.

| Application                          | Patent Title                                                                 | Patent ID       | References |
|--------------------------------------|-----------------------------------------------------------------------------|-----------------|------------|
| Antimicrobial agent for wound healing| Composition comprising amino acid polymers and a bioactive agent and method of preparing thereof | US20200368176A1 | [38]       |
| Scaffold                             | Coating scaffolds                                                           | AU2020250274A1 | [39]       |
| Electromagnetic shielding agent      | Microcellular foamed HIPS electromagnetic shielding material and preparation method and application thereof | CN111961305A    | [40]       |
| Slow-release antibacterial agent     | Preparation method of nano-silver slow-release antibacterial agent           | CN111973794A    | [41]       |
| Biocidal agent                       | Mobile device for cleaning and disinfecting room air that can be operated using a temperature difference | DE202020105700U1| [42]       |
| Antioxidative agent                  | Skin cleanser                                                               | AU2020227091A1 | [43]       |
| Antimicrobial agent                  | Synthetic fiber with semi-permanent antibacterial and anti-fungal properties and uses thereof | KR102163245B1  | [44]       |
| Antimicrobial coating                | A system that provides local cooling to the brain and spinal cord            | JP2020171791A  | [45]       |
| Reducing agent in biopolymer microgel| Method of reducing an organic pollutant in contaminated water               | US10793648B1   | [46]       |
| Slow-release bactericidal agent      | Medicine for treating ant bite and its medicine applying plaster             | CN111671844A   | [47]       |
| Colorimetric sensing of trypsin      | Trypsin detection film, preparation method and application thereof and trypsin detection kit | CN111808916A   | [48]       |

HIPS: high impact polystyrene.
The desirable traits of AgNPs have been reflected by the intensive and comprehensive research of the nanoparticles’ potential as an antimicrobial coating. AgNPs have been recurrently credited for their biocidal (i.e., viricidal, fungicidal, bactericidal, parasiticidal, mosquitocidal), theranostic, thermoplasmonic, antiplasmodial, catalytic, electrochemical, magnetic, optical, surface-enhanced Raman scattering, large surface-area-to-volume ratio, spatial confining, surface energy, high specific surface, and chemically stable properties [14,15,49–56]. The mentioned qualities of AgNPs have amplified their use in various applications, especially in the medical and electronic industries. For example, electrically conductive and small (1–100 nm) AgNPs can traverse nuclear and cellular membranes to trigger higher cytotoxicity with fewer implications than other drugs on the market [16]. Furthermore, AgNPs also allow versatile modification in terms of morphology and composite adjustments for desired applications [12,50]. The efficacy, toxicity, or production costs of AgNPs can be adjusted by exploiting a variety of accessible hybrid materials (e.g., silver/biopolymer nanocomposites), as well as forming them into spherical, diamond, octagonal, or thin-sheet forms [57–59]. For example, polymers embed nanoparticles and control nucleation while AgNPs augment the nanocomposite’s performance [60,61]. In brief, the properties of AgNPs have been broadly recognised, hence driving further research and development of this material.

Although AgNP investigation is relatively focused on surfaces and medicine, the research and development of AgNPs in the sensorics field for analytical and medical equipment are comparable. AgNPs have been investigated for target biosensors of DNA or cancer, surface-enhanced Raman scattering, molecular imaging of cancer cells, enhanced X-ray contrast, photothermal ablation of tumours, colorimetric sensing of heavy metals and ammonia for water purification, signal enhancers, and biological assays [62–69]. Biological assays can comprise considerable data requiring high-throughput screening technologies and AgNP compound semiconductors for biotagging. Other than their application in sensorics, the electrochemical and conductive traits of AgNPs enable their function as a power source or conductor. For example, AgNPs have been employed in power engineering, enhanced energy storage of batteries, intercalation material of electrical batteries, silver/polyaniline composites of microelectronic devices, and conductive inks [50,61,70,71].

Furthermore, AgNPs can also function as catalysts in biochemical and chemical reactions [65,72]. AgNPs have been reported to catalyse the oxidation of methanol to formaldehyde, ethylene to ethylene oxide, the reduction of 4-nitrophenol into 4-aminophenol, and the degradation of acridine orange and methylene blue dyes [72,73]. Additionally, AgNPs have also shown potential applications in the agricultural field. The mentioned nanoparticles can enhance plant growth while affecting the root length, shoot length, biomass, and seedling germination [74]. Accordingly, mixed reactions were observed with different plant species, age, nanoparticle concentration, and treatment duration [74–79]. Existing literature has upheld the attraction to AgNPs of multiple industries, especially surfaces and medicine. However, several routes regarding the biocidal mechanisms and chronic implications of AgNPs on living organisms are yet to be clarified. Consequently, thorough research is necessary to confront critical issues, such as the interaction of AgNPs with the biological system and natural environment.

3. Production of AgNPs

Generally, there are two approaches involved in the synthesis of silver nanoparticles: either the “top-down” approach or the “bottom-up” approach (Figure 1), which are commonly achieved using physical, chemical, and biological methods. In the bottom-up approach, nanoparticles can be synthesized using chemical and biological methods involving the self-assembly of atoms into new nuclei, which grow into a nanoscale particle. Conversely, in the top-down approach, suitable bulk material is broken down into fine particles by size reduction with various lithographic techniques, grinding, milling, sputtering, and thermal/laser ablations [80]. In the bottom-up approach, chemical reduction is the most common scheme for the synthesis of silver nanoparticles [81,82]. Different
organic and inorganic reducing agents, such as sodium borohydride (NaBH$_4$), sodium citrate, ascorbate, elemental hydrogen, Tollens reagent, N,N-dimethyl formamide (DMF), and poly (ethylene glycol) block copolymers are used for the reduction of silver ions (Ag+) in aqueous or nonaqueous solutions [80,83–87].

Figure 1. The approaches in silver nanoparticle synthesis involve bottom-up and top-down approaches.

The physical and chemical methods can produce well-defined AgNPs, but they have certain limitations in terms of expensive equipment usage, high energy consumption, and operation conditions, for instance, high temperature and pressure [88]. Chemical and physical methods are often costly and generate toxic byproducts; these methods involve the utilization of hazardous chemicals such as sodium borohydride (NaBH$_4$) as a reducing agent, which has an adverse effect on health due to the absorption of harmful chemicals on its surface. This has brought about the development of biological synthesis, which has been recognized as an inexpensive and eco-friendly process. Biosynthesis of nanoparticles through biological approaches offers an alternative to conventional chemical and physical methods [80]. This process includes the utilization of microorganisms, plant extracts, or agricultural biowaste, which offers a green solution with limited usage of toxic chemicals [83]. It has been noted that synthesized AgNPs can have a synergic relationship with the antibiotic levofloxacin, increasing the total antimicrobial properties against Gram-positive and Gram-negative pathogens [89], as well as exerting cytotoxic effects on different cancerous and normal cell lines. In addition, AgNPs are highly efficient due to a high surface-area-to-volume ratio, which can easily disrupt and penetrate bacterial cells when compared to silver ions alone [1].

Biological Approach of Nanoparticle Synthesis

In the green synthesis of AgNPs, plant constituents, including proteins, enzymes, and carbohydrates, are used together with AgNO$_3$ to formulate nanoparticles that can easily interact with targeted biomolecules [90]. The bioactive components in plants act as reducing agents to facilitate the reduction of metallic ions to nanoparticles [91]. Several studies have reported that the biological synthesis of nanoparticles has gathered much attention due to the high-yield production of AgNPs. Furthermore, this biological approach is green, cost-effective, and biocompatible without the use of toxic chemicals. Moreover, in the biological synthesis of AgNP, it is relatively simpler to control the size, shape, and distribution of nanoparticles by optimizing several parameters, including the synthesis methods, quantity of precursors, temperature, pH, and quantity of reducing and stabilizing
agents [92]. The biological synthesis of AgNPs utilises various biological systems, such as bacteria, fungi, and plant extracts, and small biomolecules such as vitamins and amino acids [6]. In this green chemistry approach, several bacteria including *Pseudomonas stutzeri AG259*, *Lactobacillus* strains, *Bacillus licheniformis*, *Escherichia coli* (*E. coli*), *Brevibacterium casei*, fungi including *Fusarium oxysporum*, and plant extracts including *Allophylus cobbe*, *Artemisia princeps*, and *Typha angustifolia* were utilized [93].

Biowaste is also among the various biological systems that can be used to biologically synthesise AgNPs. The consumption of biowastes to produce AgNPs employs a simple, safe, eco-friendly, cost-effective, waste-to-wealth, and circular bioeconomy approach [94–96]. The prominent categories of biowastes used to biologically synthesise AgNPs are forestry, industrial, and agricultural wastes (Figure 2) [95–98]. Different types of biowastes, such as forest biomass, paper industry waste, sugar industry waste, spent coffee grounds, husks, as well as vegetable and fruit peels, have been broadly researched for the production of AgNPs (Table 3). Existing literature has shown a focus of research attention on AgNP synthesis using fruit pericarp, likely due to the ease of access, relatively lower cost, and abundance of this waste type. Biowastes are sustainable renewable energy sources, hence the management and utilization of biowastes can help to alleviate the global energy consumption demand [9]. Biowaste-derived AgNPs are thus not only of low economic value but also environmentally and economically sustainable [94]. The efforts in the biological conversion of waste to a valuable product, AgNPs, not only reduce waste generation and AgNP production costs, but also help to shift the economy from a cradle-to-grave to a cradle-to-cradle concept [9]. Therefore, the biosynthesis of AgNPs from biowastes is considered to reinforce the valuable utilization of biomass for the synthesis of metal nanoparticles. Consequently, the major advantage of biological synthesis is the elimination of toxic chemicals, and the use of biological molecules for the synthesis of AgNPs is profoundly eco-friendly and pollution-free.

![Pie chart](image.png)

**Figure 2.** A pie chart visualizing the general dominance of prominent biowastes in the field of silver nanoparticle (AgNP) synthesis.
Table 3. The various biowastes used in the green biological synthesis of silver nanoparticles.

| Source                        | Size of the Nanoparticle | Inhibited Microbes          | Application                                                                 | References |
|-------------------------------|--------------------------|-----------------------------|-----------------------------------------------------------------------------|------------|
| **Musa** (banana peels)       | 50 nm                    | *S. aureus*                 | Possess good antimicrobial activity against foodborne microorganisms        | [99]       |
|                               |                          | *B. subtilis*               |                                                                             |            |
|                               |                          | *P. aeruginosa*             |                                                                             |            |
|                               |                          | *E. coli*                   |                                                                             |            |
|                               |                          | *C. albicans*               |                                                                             |            |
| **Punica granatum** (pomegranate peels) | 10–30 nm                |                             | Potential application in the biomedical field                                | [7]        |
| **Citrus x sinensis** (orange peels) | 10 nm                   |                             | Prospective method of citrus canker control using orange waste              | [8]        |
| **Citrus grandis** (pomelo)   | 20–30 nm                 |                             | These nanoparticles can be used as a reducing agent                         | [100]      |
| **Citrus limetta** (Mosambi peels) | 9–46 nm                  | *E. coli*                   | Viable resource for antioxidant extraction; anticancer properties            | [80]       |
|                               |                          | *S. aureus*                 |                                                                             |            |
| **Vitis** (grapes), **Carica papaya** (papaya) | 50 nm                   | *B. subtilis*               | Active food packaging                                                        | [101]      |
|                               |                          | *S. aureus*                 |                                                                             |            |
|                               |                          | *E. coli*                   |                                                                             |            |
|                               |                          | *P. aeruginosa*             |                                                                             |            |
| **Ananas comosus** (pineapple) | 9 nm                     | *E. faecium*                | Reducing and stabilizing agent                                               | [102]      |
|                               |                          | *L. monocytogenes*          |                                                                             |            |
|                               |                          | *B. cereus*                 |                                                                             |            |
|                               |                          | *S. aureus*                 |                                                                             |            |
| **Citrus maxima** (pomelo)    | 2.5–5.7 nm               |                             | Useful in extracellular synthesis of silver nanoparticles                     | [105]      |
| **Punica granatum** (pomegranate) | 74.9 nm (pomegranate)      |                             | Antimicrobial and wound healing                                              | [106]      |
|                               |                          |                             |                                                                             |            |
| **Vitis vinifera L.** (grape pomace), **Citrus x sinensis** (orange peels) | 90 nm (grape pomace)   | *E. coli*                   | Reduced silver ions acting as capping agents, and also shows highest antiviral activity | [107]      |
|                               |                          | *S. aureus*                 |                                                                             |            |
|                               |                          | *P. arginosa*               |                                                                             |            |
| **Citrus x sinensis** (orange peels) | 96 nm (orange)            |                             | Paves the way for future studies on AgNP toxicity                            | [108]      |
|                               |                          |                             |                                                                             |            |
| **Punica granatum** (Saudi pomegranate fruit) | 34–50 nm                 | *S. aureus*                 | An ideal prerequisite for efficient drug delivery                            | [88]       |
|                               |                          | *S. typhi*                  |                                                                             |            |
|                               |                          | *P. aeruginosa*             |                                                                             |            |
|                               |                          | *E. coli*                   |                                                                             |            |
|                               |                          | *S. epidermidis*            |                                                                             |            |
|                               |                          | *K. pneumoniae*             |                                                                             |            |
| **Eucalyptus camaldulensis** (river red gum bark) **Rhododendron ponticum** (common rhododendron leaf waste) | 468.7 nm                    | *L. innocua*                 | Commercial skincare formulations                                              | [109]      |
|                               |                          | *B. subtilis*               |                                                                             |            |
|                               |                          | *E. aerogenes*              | Antibacterial ointment; textile or fabric                                    | [94]       |
|                               |                          | *E. coli*                   |                                                                             |            |
| **Spent coffee grounds**      | 34.6–54.2 nm             |                             | Water treatment applications                                                 | [95]       |
Table 3. Cont.

| Source                                      | Size of the Nanoparticle | Inhibited Microbes                  | Application                                      | References |
|---------------------------------------------|--------------------------|-------------------------------------|--------------------------------------------------|------------|
| Eucalyptus sp. (prehydrolysis waste liquor of wood) | 20 nm                    | P. aeruginosa S. aureus E. coli C. oxytosporum P. chrysogenum C. albicans A. niger | Biomedical applications | [96]       |
| *Poa annua* (annual meadow grass leaf)       | 36.66 nm                 | -                                   | Potential drug carrier and therapeutic            | [97]       |
| Saccharum sp. (sugar cane bagasse)           | 6–36 nm                  | E. coli P. aeruginosa S. aureus     | Bactericidal applications without AgCl formation | [98]       |
| Allium cepa L. (red onion peels)             | 14 nm                    | -                                   | Medical and agricultural applications             | [110]      |
| Nipa fruticans (waste husks of Nipa palm)    | 10–15 nm                 | B. cereus                           | General range of AgNP-related applications       | [111]      |
| Physalis peruviana L. (outer accrescent fruiting calyx of Cape gooseberry) | 25–55 nm                 | E. coli S. typhimurium              | Antibacterial material, coating, cosmeceutical, and biomedical applications | [112]      |
| Cocos nucifera L. (outer shell fibre of coconut) | -                       | E. coli E. faecium P. acnes L. monocytogenes C. albicans S. aureus E. coli B. cereus | Biomedical, food, and pharmaceutical applications | [113]      |
| Citrullus lanatus (rinds of watermelon)      | 20–260 nm                | S. typhimurium                      | Agricultural, biomedical, cosmeceutical, and pharmaceutical applications | [114]      |
| Solanum tuberosum (potato peels)             | 20–40 nm                 | -                                   | General range of AgNP-related applications       | [115]      |
| Oryza sativa japonica (rice husks)           | <47.90 nm                | -                                   | General range of AgNP-related applications       | [116]      |

4. Antimicrobial Properties of AgNPs

In the context of antibacterial purposes, silver metal has been a favoured material even 2000 years ago, and especially starting from 19th-century civilizations [117]. The studies of silver as a material that exhibits antimicrobial properties have also gained increasing attention and extensive experimentation among researchers, owing to its range of bactericidal attributes, potencies, low level of toxicity, and numerous utilizations as a sanitizer [118]. Silver nanoparticles (AgNPs) especially have prevailed in showing positive results in inhibiting the bacterial growth of a variety of Gram-negative and Gram-positive bacteria [119]. As many as 650+ microbes that are known to be affected by the antimicrobial activity of silver-based compounds have been recorded [80,120].

The usage of AgNPs has its own precedence of having lower reactivity compared to silver ions, making this material greatly applicable for medical and restorative purposes [121–123]. Out of the wide range of possible implementations of AgNPs in these fields, numerous research and development projects have been extensively deployed towards their auspicious utilization in wound dressings, tissue scaffolds, and protective clothing use, among others [124–126]. Furthermore, licensing bodies such as the FDA and EPA of the USA, the SIAA of Japan, the Korea Testing and Research for Chemical Indus-
try, and the FITI Testing & Research Institute of Korea have granted the development of numerous products containing or associated with AgNPs [127]. This demonstrates how AgNPs efficacy as antimicrobial material has been taken advantage of in being implemented domestically and clinically [120].

4.1. Mechanism of Action of AgNPs as Antimicrobial Agent

As a type of metal, AgNPs possess an oligodynamic effect, which is related to the biocidal effects of metals, particularly heavy metals, that may potentially take place in low concentrations of that particular material [118]. There are some important facets regarding the particular antimicrobial features of AgNPs and their innate physical and chemical attributes, which sustain their nanoscale size, enhance their rapid distribution, and avoid accretum [128]. The large surface areas of AgNPs are the important feature of their enhanced oligodynamic effect in their capability to cohere with bacterial plasma membranes, their aptitude for cell perforation, to induce synthesis of reactive oxygen species (ROS) and free radicals, and to function as signal transduction pathway modulators of microorganisms [129]. In addition, the distinctions in AgNPs’ physicochemical traits, such as size [130], morphology [131], oxidation and dissolution states [132], and charges and coating of surfaces [133,134], have great impact on their antimicrobial activity [135,136].

4.2. Antibacterial Effects of AgNPs

Silver nanoparticles are becoming a hot topic among those in the scientific domain due to their wide range of bactericidal and fungicidal qualities. The effect of microbial inhibition can even affect both Gram-positive and Gram-negative bacteria, with high antibacterial activity. Currently, the mechanism of actions of AgNPs as antimicrobial agents consist of four main actions [118,123]:

1. Adherence onto the cell membrane of microorganisms.
2. Perforation of cells by AgNPs, interrupting cell molecules and causing intracellular destruction.
3. Effecting toxicity of microbial cells through the synthesis of ROS that stimulates cell oxidative stress.
4. Obstruction of cell signal transduction pathways.

In a condition where AgNPs are introduced to any microorganism, the positive charge of silver ions prompted from the oxidation of AgNPs will be attracted towards the negatively charged cell membrane of microbes due to the electrostatic effect, causing the nanoparticles to fasten to the cell wall or membrane [137]. The changes in the shape of cell membrane are permanent and irreparable when AgNPs are completely attached to the plasma membrane of the microorganism, which can cause impairment of the lipid bilayer and permeability of the plasma membrane and thus ability to enclose its content of cytoplasm and nucleoplasm [138]. The modifications in the morphology of the cell can result in affecting the cell’s capability to separate the cell from the surrounding interstitial fluid. As an example, formation of silver ions by the nanoparticles will reorient the movement of potassium ions (K+) from the inside and outside of the cell, which can impede the mobilization activity of essential materials of the cell [118]. Moreover, increment of membrane permeability may induce the depletion or discharge of intracellular contents including cytoplasm, ions, adenosine triphosphate (ATP), and proteins, which can engender the formation of a ghost cell of a microbe. Excretion of all essential materials out of the microorganism through membrane leakages, leaving behind an empty microbial cell envelope, is known as the ghost cell effect [139]. A study by Vazquez-Munoz et al. proved that the coherence of the plasma membrane of Gram-negative bacteria (E. coli and Salmonella typhirium) was disrupted by AgNPs’ bactericidal activity through the action of membrane depolarization and destabilization, which was observed via transmission electron microscopic (TEM) images. Figure 3 shows the mechanism of AgNPs’ adhesion to the cell membrane [140].
Figure 3. The mechanism of action of AgNPs affected through cell binding via the mechanism of AgNPs’ adhesion to the cell membrane.

Besides the mechanism of binding onto the surface of the membrane, AgNPs can also pierce through the microbes and cause disturbance of crucial biomolecules and cellular activity [118]. There are water-filled channels known as porins located in the extracellular membrane of Gram-negative bacteria (e.g., *E. coli*), which can be a passageway for AgNPs to invade the intracellular environment. Following successful AgNP invasion, they will begin to cohere with biomolecules and cellular structures, including proteins, DNA, lipids, and mitochondria, that can deteriorate the inner composition of the bacteria. In addition, the free-roaming silver ions discharged from AgNPs will cohere with negatively charged proteins, resulting in modifications of protein composition and ultimately protein degeneration [118]. There is a study that demonstrated the inhibition activity of AgNPs by hindering the respiratory chain dehydrogenase through the metamorphosis of a number of enzymes, such as glycerol-3-phosphate dehydrogenase into dihydroxyacetone, in a Gram-positive bacterium (*S. aureus*), which concluded with the obstruction of the bacteria’s normal growth and metabolic activity [141]. AgNPs can also trigger DNA denaturation and impede the cellular growth of bacteria when in contact with bacterial DNA [142]. Additionally, the stability of DNA composition can be lessened through AgNP–DNA interactions due to the occurrence of electrostatic repulsion between these two because of their similar polar charge [143]. Moreover, detachment of double-stranded DNA into single strands through a hybridization process may occur due to interfaces between silver ions and DNA, causing dissociation of H-bonds in DNA strands [144]. The simplified mechanism is illustrated in Figure 4.

Reactive oxygen species (ROS), a type of cellular oxidative stress of microorganisms, is another course of action affected by AgNPs’ inhibiting activity [145]. AgNPs can cause an increment of cell oxidative stress due to the nanoparticles’ capability of generating ROS and free radicals [118]. The potential of nanoparticles to prompt lipid destruction, perforation of biomolecules, and also programmed cell death are things to look into as it suggests the occurrence and generation of intercellular ROS inside the cells is one of the biggest factors to determine the toxicity of AgNPs [146]. Su et al. reported that treatment with clay and AgNPs could enhance the bactericidal properties towards *S. aureus, P. aeruginosa,* and *Streptococcus pyogenes,* causing a declination of membrane integrity in response to the formation of ROS, followed by cell death [147]. There is another study that proposed that the antibacterial activity due to ROS generation is dependent on the size of AgNPs, where nanoparticles with a concentration of 10 mg/L resulted in higher levels of ROS production in *Azotobacter vinelandii* and *Nitrosononas europaea* compared to 50 mg/L of AgNPs [148]. The method of ROS formation in bacterial cells induced by AgNPs is shown in Figure 5.
Figure 4. The mechanism of action of AgNPs affected through membrane penetration assisted by electrostatic repulsion and hybridization.

Figure 5. The mechanism of action of AgNPs affected through the formation of reactive oxygen species (ROS).

The mechanism of action involving pathway signaling is influenced by the phosphorylation and dephosphorylation cascade of important enzymes or protein contents that is required for growth of bacteria and cellular activity [118]. The distinctive physicochemical traits of AgNPs may bring about the potential for another mechanism of bacterial inhibition through functionality of these nanoparticles as modulators of cell signal transduction [149]. A study had experimented on the capability of gold–silver nanoparticles to effectuate bacterial cell apoptosis through destruction of the bacterial actin cytoskeletal network [126]. The study also discovered that the cytoskeletal actin MreB (an actin homologue), which has a crucial responsibility in the modulation of local cell shapes and survivability, was experiencing changes in morphology, causing an increase of membrane liquidity and thus mediating cell destruction. Figure 6 shows the mechanism of action of bacterial inhibition through pathway signaling modification.
Figure 6. The mechanism of action of AgNPs effected through the inhibition of signal transduction [117].

Different strains will experience different mechanisms of action of nanoparticles’ antibacterial activities. Table 4 lists the microbial inhibition studies of AgNPs, including their mechanism of action.

Table 4. The antimicrobial activities of AgNPs [118,123].

| Bacterial Strains | Size of AgNPs | Mechanism of Antimicrobial Activity | Reference |
|-------------------|---------------|-------------------------------------|-----------|
| **Gram-positive** |               |                                     |           |
| Multidrug-resistant *Staphylococcus aureus* (MMC-20) | 18 ± 3 nm | Obstruction of membrane due to ROS formation | [150] |
| *Staphylococcus aureus* ATCC25923 | 3.91 nm/2.29 nm/1.59 nm | Obstruction of membrane due to ROS formation | [151] |
| *Staphylococcus aureus* | <100 nm | Oxidative stress caused by modification of kynurenine protein | [152] |
| *Bacillus subtilis* | <100 nm | Modification of kynurenine protein-mediated kynurenine pathways that inhibited growth | [152] |
| *Listeria monocytogenes* | 23 ± 2 nm | Increase in ROS levels | [153] |
| *Clostridium diphtheria* | 28.42 nm | Cell wall hostility, denaturation of proteins | [154] |
| **Gram-negative** |               |                                     |           |
| *Escherichia coli* | <100 nm | Oxidative stress caused by modification of kynurenine protein | [155] |
| *Escherichia coli* AB1157 | 8.3 ± 1.9 nm | Destruction of DNA | [156] |
| *Escherichia coli* ATCC25922 | 3.91 nm/2.29 nm/1.59 nm | Obstruction of membrane due to increased ROS formation | [151] |
| *Pseudomonas aeruginosa* | 45 nm | Binding of AgNPs to cell wall and synthesis of ROS | [157] |
| *Klebsiella pneumoniae* | <100 nm | Modification of kynurenine protein-mediated kynurenine pathways that inhibited growth | [152] |
| *Proteus sp.* | 38 nm | Estrangement of cell membrane and hindered DNA replication | [155] |
| *Vibrio cholera* | <50 nm | Impeded metabolic pathways | [158] |
| *Salmonella thyphii* | 2–23 nm | Cell wall rupture | [159] |
5. Applications of AgNPs in Antimicrobial Coatings

AgNPs have been investigated for a multitude of applications due to their qualities. The existing commercial products that employ the use of AgNPs include surfaces, textiles, food containers, nutrient supplements, cosmetics, packaging materials, electronics, domestic appliances, water and air disinfectants, as well as medical and laboratory instruments [11,160] (Figure 7). Furthermore, AgNP research and development has also contributed to the surfaces, medical, electronic, remediation, sanitation, catalyst, and agricultural industries, as well as analytical and medical equipment. Existing literature has shown relatively abundant publications of AgNPs in the industrial fields of surfaces and medicine. The properties of AgNPs (e.g., biocidal, superhydrophobic, thermal conductive) have advocated its use as a sheet or layer to improve apparel, footwear, paint, wound dressings, cosmetics, appliances, packaging, and plastics applications [161]. For example, biocidal AgNPs allow the production of antimicrobial paints and sterile wound dressings for accelerated wound healing, which incites the option of future AgNP deployment in odourless fabrics for sensitive skin [44]. In addition, silver/polymer composites allow applications that require high thermal conductivity, such as electronic packaging, encapsulations, light-based sensors, and satellite devices [50].

The prospects of AgNPs as an accommodating surface have also promoted its application as a coating in the field of medicine. The previously mentioned qualities of AgNPs have fostered its application as antimicrobial medical coatings in scaffolds, skin recipient and donor sites, wound dressings, clinical fabrics, cancer therapy, protein detection, antibiofilm catheters, hydro- or aerogels, and gene or drug delivery. The diverse applications of AgNPs in medical coatings demonstrate the prominence of the AgNPs’ superior antimicrobial trait. For example, biocidal fabrics are essential clinical accessories since microbial pathogens can survive on laundered clothes for up to 3 months, posing infection risks to surgical wounds, bedding, or patient clothing. Moreover, infections contracted post-injury

Figure 7. The various applications of AgNPs.
or surgery can be fatal. Besides that, AgNPs have also shown to inhibit cancer cell lines, multidrug-resistant bacterial strains, plus the herpes simplex virus type 1 (HSV-1) and influenza A virus subtype H1N1 [162–165]. In addition, therapeutic gel comprising AgNPs has shown potential to accelerate wound healing without scarring. Also, AgNP-based antimicrobial coatings have been applied in the sanitation sector for various public and domestic-use surfaces including wood, glass, and polystyrene. In conclusion, AgNPs possess immense potential as a coating enhancer for various industries, although they are remarkably valuable in the medical field due to their biocidal feature.

6. Future Outlook and Conclusions

The properties of AgNPs have been widely acknowledged, thus propelling the research and development of this material. The main advantages of biomediated AgNPs are their nontoxic and eco-friendly production route and properties, which reduce undesirable negative implications on human health [90]. The biologically mediated AgNP synthesis is thus safer for medical applications and essential antimicrobial coatings that are required in clinical settings. The biological synthesis of AgNPs has also been reported to be rapid and of high yield. Moreover, unlike physical and chemical methods, the biomediated synthesis of AgNPs does not require expensive equipment, high pressure, high temperature, or chemical additives (e.g., stabilizers) [80–87]. However, although the chemical synthesis of AgNP generates relatively uniform structures, the capability to produce homogenous surfaces and crystallographic structures is a current and major challenge for the biological synthesis of AgNPs. The inconsistent composition of biowaste in each batch can cause yield fluctuations and problems with standardized quality demands of the AgNP-based final product [91]. Furthermore, the availability of biowaste for large-scale continuous manufacturing and the feasibility (e.g., costs) of biowaste refining remains questionable.

Nevertheless, the existing and projected gaps of AgNP research should be identified concurrently to better protect public health in the direction of the third Sustainable Development Goal (Figure 8). The potential harm of loosely attached or detached nanoparticles’ entry into the biological system is still being validated. The main target organs (e.g., liver, spleen, gastrointestinal tract, lung) likely to be exposed to nanoparticles after intravenous administration should be monitored, as the mononuclear phagocytic system may also recognise these nanoparticles as foreign agents and then remove them from the circulation system [166]. Additionally, past research has been focused on the fine manipulation of the crystallinity, shape, size, and stability of AgNPs to achieve various physicochemical characteristics. Although green biological synthesis methods at present are mostly preferred over chemical and physical techniques (e.g., photochemical, electrochemical, thermal, radiation, lithographic, and laser ablation processes) to tailor nanoparticle qualities toward specific applications, any inevitable use of hazardous materials during the synthesis or structuring of AgNPs should not be overlooked in terms of usage and environmental safety [167–170]. Other gaps in AgNP research should also be pinpointed to attain more comprehensive insight in this field. Currently, limited information is available on the possible risks of AgNP exposure or lack thereof. Other knowledge gaps within AgNP research include the genotoxicity, carcinogenicity, and toxicokinetics of AgNPs as individual compounds and composites in a wide range of forms and intensities [11,171,172]. Nevertheless, as a final point, AgNP advancements continue to move forward despite the limitations and gaps confronted in this field, thus emphasising the prospective outlook of AgNP-related applications.
In conclusion, AgNP nanocomposite research has been extensively reported on and developed over the past decade. The present review reports the industrial use of AgNPs, especially in the field of medicine, chiefly due to their antimicrobial properties. Along with other attractive properties of AgNPs, research and development involving the utilisation of this material have been increasing, particularly in 2019 and 2020. Our review reveals the diverse applications of AgNP that include but are not limited to medical antimicrobial coatings. The possibility of composition and chemical modifications to achieve desirable properties and functionalities has been and is still being explored as a high-potential research area. Moreover, several studies have accentuated the need to better understand the environmental and biological impacts of AgNPs. Substantial reductions in environmental implications can be obtained with the appropriate waste management strategies of AgNP development prior to further commercialization. Furthermore, future research is also expected to focus on cost-effective processes and more sustainable materials. In addition, efforts are also observed in AgNP development for the large industrial scale of the material sciences and manufacturing fields.

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References

1. Eskin, N.A.M.; Robinson, D.S. Food Shelf Life Stability; CRC Press: Boca Raton, FL, USA, 2000.
2. Keat, C.L.; Aziz, A.; Eid, A.M.; Elmarzugi, N.A. Biosynthesis of nanoparticles and silver nanoparticles. Bioreour. Bioprocess. 2015, 2, 47. [CrossRef]
3. Vega-Baudrit, J.; Gamboa, S.M.; Rojas, E.R.; Martinez, V.V. Synthesis and characterization of silver nanoparticles and their application as an antibacterial agent. Int. J. Biosens. Bioelectron. 2019, 5, 166–173. [CrossRef]
4. Firdhouse, M.J.; Lalitha, P. Biosynthesis of silver nanoparticles and its applications. J. Nanotechnol. 2015, 2015, 47. [CrossRef]
5. Castillo-Henriquez, L.; Alfaro-Aguilar, K.; Ugalde-Alvarez, J.; Vega-Fernandez, L.; Montes de Oca-Vasquez, G.; Vega-Baudrit, J.R. Green synthesis of gold and silver nanoparticles from plant extracts and their possible applications as antimicrobial agents in the agricultural area. Nanomaterials 2020, 10, 1763. [CrossRef] [PubMed]
6. Zhang, X.F.; Liu, Z.G.; Shen, W.; Gurunathan, S. Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. Int. J. Mol. Sci. 2016, 17, 1534. [CrossRef]
7. Nasiriboroumand, M.; Montazer, M.; Barani, H. Preparation and characterization of biocompatible silver nanoparticles using pomegranate peel extract. J. Photochem. Photobiol. B Biol. 2018, 179, 98–104. [CrossRef]
8. Barros, C.H.N.; Cruz, G.C.F.; Mayrink, W.; Tasic, L. Bio-based synthesis of silver nanoparticles from orange waste: Effects of distinct biomolecule coatings on size, morphology, and antimicrobial activity. Nanotechnol. Sci. Appl. 2018, 11, 1–14. [CrossRef]
9. Kee, S.H.; Chiongson, J.B.V.; Saludes, J.P.; Vigneswari, S.; Ramakrishna, S.; Bhubalan, K. Bioconversion of agro-industry sourced biowaste into biomaterials via microbial factories—A viable domain of circular economy. Environ. Pollut. 2021, 271, 116311. [CrossRef]
10. Jeremiah, S.S.; Miyakawa, K.; Morita, H.; Yamaoka, Y.; Ryo, A. Potent antiviral effect of silver nanoparticles on SARS-CoV-2. Biochem. Biophys. Res. Commun. 2020, 533, 195–200. [CrossRef] [PubMed]
11. Volkova, N.A.; Yukhta, M.S.; Pavlovich, E.V.; Golts, A.N. Change in functional state of bone marrow-derived mesenchymal stem cells after incubation with silver nanoparticles. In Nanophotonics, Nanooptics, Nanobiotechnology, and Their Applications; Fesenko, O., Yatsenko, L., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 273–282.
12. Nadtoka, O.; Kutsevol, N.; Linnik, O.; Nikiforov, M. Nanocomposite hydrogels containing silver nanoparticles as materials for wound dressings. In Nanophotonics, Nanooptics, Nanobiotechnology, and Their Applications; Fesenko, O., Yatsenko, L., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 375–387.
13. Pylypchuk, I.V.; Mukha, I.P.; Vityuk, N.V.; Szczepaniowicz, K.; Storozhuk, L.P.; Eremenko, A.M.; Warszyński, P.; Gorbyk, P.P. Tryptophan-stabilized plasmonic Fe3O4/Ag nanoparticles. In Nanophotonics, Nanooptics, Nanobiotechnology, and Their Applications; Fesenko, O., Yatsenko, L., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 417–430.
14. Sundar, A.; Arunachalam, S.; Jayavel, S.; Muthulakshmi, L. Encapsulation of amphotericin B into quercetin based silver nanoparticles: Preparation, characterization and preliminary investigation of antiparasitic activity. In Proceedings of the International Conference on Nanomedicine (ICON–2019); Rajan, M., Anand, K., Chuturgoon, A., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 63–71.
15. Ganesan, S.; Mehalingam, P.; Selvam, G.S. Green synthesis of silver nanoparticles from de-oiled rhizomes of Curcuma longa L. and its biomedical potential. In Proceedings of the International Conference on Nanomedicine (ICON–2019); Rajan, M., Anand, K., Chuturgoon, A., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 94–106.
16. Soneya, S.; Reddy, N.V.; Saritha, K.V.; Kotakadi, V.S.; Vijaya, T. Phytosynthesis of silver nanoparticles using Rynchosia lecomei wirt & arm leaf extract: Characterization and in vitro assessment of antimicrobial, antioxidant and anticancer activities. In Proceedings of the International Conference on Nanomedicine (ICON–2019); Rajan, M., Anand, K., Chuturgoon, A., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 120–140.
17. Asswini, R.; Meimozhi, S.; Tamilmozhi, R.; Kowsalya, M.; Murugesan, S. Green synthesis of silver nanoparticles using Ledebouria revoluta bulb extract and its biological activity. In Proceedings of the International Conference on Nanomedicine (ICON–2019); Rajan, M., Anand, K., Chuturgoon, A., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 1–10.
18. Banik, M.; Patra, M.; Dutta, D.; Mukherjee, R.; Basu, T. A simple robust method of synthesis of copper-silver core shell nanoparticle: Evaluation of its structural and chemical properties with anticancer potency. Nanotechnology 2018, 29, 325102. [CrossRef] [PubMed]
19. Edis, Z.; Bloukh, S.H.; Ashames, A.; Ibrahim, M. Copper-based nanoparticles, their chemistry and antibacterial properties: A review. In Chemistry for a Clean and Healthy Planet; Ramasami, P., Bhowon, M.G., Laulloo, S.J., Wah, H.L.K., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 401–428.
20. Khare, P.; Sharma, A.; Verma, N. Synthesis of phenolic precursor-based porous carbon beads in situ dispersed with copper-silver bimetal nanoparticles for antibacterial applications. J. Colloid Interface Sci. 2014, 418, 216–224. [CrossRef] [PubMed]
21. Takamiya, A.S.; Monteiro, D.R.; Gorup, L.F.; Silva, E.A.; Camargo, E.R.; Gomes-Filho, J.E.; Oliveira, S.H.P.; Barbosa, D.B. Biocompatible silver nanoparticles incorporated in acrylic resin for dental application inhibit Candida albicans biofilm. Mater. Sci. Eng. C 2021, 118, 111341. [CrossRef]
22. Nguyen, D.D.; Luo, L.-J.; Lai, J.-Y. Toward understanding the purely geometric effects of silver nanoparticles on potential application as ocular therapeutics via treatment of bacterial keratitis. Mater. Sci. Eng. C 2021, 119, 111497. [CrossRef] [PubMed]
23. Mohan, A.; Dipallini, S.; Lata, S.; Mohanty, S.; Pradhan, P.K.; Patel, P.; Makkar, H.; Verma, S.K. Oxidative stress induced antimicrobial efficacy of chitosan and silver nanoparticles coated Gutta-percha for endodontic applications. Mater. Today Chem. 2020, 17, 100299. [CrossRef]

24. Sofi, H.S.; Akram, T.; Shabir, N.; Vasita, R.; Jadhav, A.H.; Sheikh, F.A. Regenerated cellulose nanofibers from cellulose acetate: Incorporating hydroxyapatite (HAp) and silver (Ag) nanoparticles (NPs), as a scaffold for tissue engineering applications. Mater. Sci. Eng. C 2021, 118, 115147. [CrossRef]

25. Barot, T.; Rawtani, D.; Kulkarni, P. Physicochemical and biological assessment of silver nanoparticles immobilized Halloysite nanotubes-based resin composite for dental applications. Heligyn 2020, 6, e03601. [CrossRef]

26. Rodrigues, M.C.; Rolim, W.R.; Viana, M.M.; Rodrigues Souza, T.; Gonçalves, F.; Tanaka, C.J.; Bueno-Silva, B.; Seabra, A.B. Biogenic synthesis and antimicrobial activity of silica-coated silver nanoparticles for esthetic dental applications. J. Dent. 2020, 96, 103327. [CrossRef]

27. Hosseini, H.; Zirakjou, A.; Goodarzi, V.; Mousavi, S.M.; Khonakdar, H.A.; Zamanlui, S. Lightweight aerogels based on bacterial cellulose/silver nanoparticles/polyaniline with tuning morphology of polyaniline and application in soft tissue engineering. Int. J. Biol. Macromol. 2020, 152, 57–67. [CrossRef]

28. LewisOscar, F.; Nithya, C.; Vismaya, S.; Arunkumar, M.; Pugazhendhi, A.; Nguyen-Tri, P.; Alharbi, S.A.; Alharbi, N.S.; Thajuddin, N. In vitro analysis of green fabricated silver nanoparticles (AgNPs) against Pseudomonas aeruginosa PA14 biofilm formation, their application on urinary catheter. Prog. Org. Coat. 2021, 151, 106058. [CrossRef]

29. Maghima, M.; Alharbi, S.A. Green synthesis of silver nanoparticles from Curcuma longa L. and coating on the cotton fabrics for antimicrobial applications and wound healing activity. J. Photochem. Photobiol. B 2020, 204, 111806. [CrossRef]

30. Salve, M.; Mandal, A.; Amreen, K.; Pattnaik, P.K.; Goel, S. Greenly synthesized silver nanoparticles for supercapacitor and electrochemical sensing applications in a 3D printed microfluidic platform. Microchem. J. 2020, 157, 104973. [CrossRef]

31. Qayyum, H.; Ahmed, W.; Hussain, S.; Khan, G.A.; Rehman, Z.U.; Ullah, S.; Rahman, T.U.; Dogar, A.H. Laser synthesis and its application in photocatalytic dye degradation activity. Environ. Technol. Innov. 2021, 252, 117156. [CrossRef]

32. Rajesh, K.; Sakthivel, P.; Santhanam, A.; Venugobal, J. Incorporation of silver ion on structural and optical characteristics of CeO2 nanoparticles: White LED applications. Optik 2020, 216, 164800. [CrossRef]

33. Munir, T.; Mahmood, A.; Imran, M.; Sohail, A.; Fakhar-e-Alam, M.; Sharif, M.; Masood, T.; Baiwa, S.Z.; Shafiq, F.; Latif, S. Quantitative analysis of glucose by using (PVP and MA) capped silver nanoparticles for biosensing applications. Physica B Condens. Matter. 2021, 602, 412564. [CrossRef]

34. He, Y.; Li, H.; Fei, X.; Peng, L. Carboxymethyl cellulose/cellulose nanocrystals immobilized silver nanoparticles as an effective coating to improve barrier and antibacterial properties of paper for food packaging applications. Carbohydr. Polym. 2021, 252, 117156. [CrossRef]

35. Affes, S.; Maalej, H.; Aranaz, I.; Kchaou, H.; Acosta, N.; Nasri, M. Controlled size green synthesis of bioactive silver nanoparticles assisted by chitosan and its derivatives and their application in biofilm preparation. Carbohydr. Polym. 2020, 236, 116063. [CrossRef] [PubMed]

36. Gol, F.; Aygun, A.; Seyrankaya, A.; Gur, T.; Yenikaya, C.; Sen, F. Green synthesis and characterization of Camellia sinensis mediated silver nanoparticles for antibacterial ceramic applications. Mater. Chem. Phys. 2020, 250, 123037. [CrossRef]

37. Rajkumar, R.; Ezhumalai, G.; Gnanadesigan, M. A green approach for the synthesis of silver nanoparticles by Chlorella vulgaris and its application in photocatalytic dye degradation activity. Environ. Technol. Innov. 2021, 21, 101282. [CrossRef]

38. Tawil, N.; Katsarava, R.; Tugushi, D.; Beridze, V. Composition comprising Amino acid Polymers and a Bioactive Agent and Method of Preparing Thereof. U.S. Patent No. US20200368176A1, 26 November 2020.

39. Jongpaiboonkit, L.; Williams, L.; Murphy, S.V.S. Coating Scaffolds. Australian Patent No. AU2020520274A1, 11 May 2020.

40. Jiang, G.; Zou, J.; Qin, P. Microcellular foamed HIPS Electromagnetic Shielding Material and Preparation Method and Application thereof. Chinese Patent No. CN111973794A, 24 November 2020.

41. Li, Y.; Sun, M.; Zhong, Y.; Huang, Y.; Zhang, H.; Tang, H. Preparation Method of Nano-Silver Slow-Release Antibacterial Agent. Chinese Patent No. CN111973794A, 24 November 2020.

42. Munch, E. Mobile Device for Cleaning and Disinfecting Room Air That Can be Operated Using a Temperature Difference. German Patent No. DE202020105700U1, 16 October 2020.

43. Sedic, L. Skin Cleanser (09-24-2020). Australian Patent No. AU2020227091A1, 24 September 2020.

44. Song, C. Synthetic Fiber with Semi-Permanent Antibacterial and Anti-Fungal Properties and Uses Thereof. Korean Patent No. KR102163245B1, 8 October 2020.

45. Base, A. A System that Provides Local Cooling to the Brain and Spinal Cord. Japanese Patent No. JP2020171791A, 22 October 2020.

46. Kamal, T.; Abdullah, M.; Asiri, S.B.K. Method of Reducing an Organic Pollutant in Contaminated Water. U.S. Patent No. US10793684B1, 6 October 2020.

47. Wang, Z. Medicine for Treating ant Bite and Its Medicine Applying Plaster. Chinese Patent No. CN111671844A, 18 September 2020.

48. Zhang, S.; Duan, X. Trypsin Detection film, Preparation Method and Application Thereof and Trypsin Detection Kit. Chinese Patent No. CN111808196A, 23 October 2020.
49. Nikolopoulou, S.G.; Boukos, N.; Sakellis, E.; Efthimiadou, E.K. Synthesis of biocompatible silver nanoparticles by a modified polyol method for theranostic applications: Studies on red blood cells, internalization ability and antibacterial activity. J. Inorg. Biochem. 2020, 211, 111177. [CrossRef]

50. Sadasivuni, K.K.; Rattan, S.; Waseem, S.; Bramhe, S.K.; Kondawar, S.B.; Ghosh, S.; Das, A.P.; Chakraborty, P.K.; Adhikari, J.; Saha, P.; et al. Silver nanoparticles and its polymer nanocomposites—Synthesis, optimization, biomedical usage, and its various applications. In Polymer Nanocomposites in Biomedical Engineering; Sadasivuni, K.K., Ponnamma, D., Rajan, M., Ahmed, B., Al-Maadeed, M.A.S.A., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 331–373.

51. Mishra, V.K.; Husen, A.; Rahman, Q.I.; Iqbal, M.; Sohrab, S.S.; Yassin, M.O. Plant-based fabrication of silver nanoparticles and their application. In Nanomaterials and Plant Potential; Husen, A., Iqbal, M., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 135–175.

52. Adekoya, J.A.; Oggunniran, K.O.; Siyanbola, T.O.; Dare, E.O.; Revaprasadu, N. Band structure, morphology, functionality, and size-dependent properties of metal nanoparticles. In Noble and Precious Metals-Properties, Nanoscale Effects and Applications; IntechOpen: London, UK, 2018; pp. 15–42.

53. Govindarajan, M.; Rajeswary, M.; Veerakumar, K.; Muthukumaran, U.; Hoti, S.L.; Benelli, G. Green synthesis and characterization of silver nanoparticles fabricated using Anisomeles indica: Mosquitocidal potential against malaria, dengue and Japanese encephalitis vectors. Exp. Parasitol. 2016, 161, 40–47. [CrossRef] [PubMed]

54. Manukyan, A.; Gyulasaryan, H.; Ginoyan, A.; Kaniukov, E.; Petrov, A.; Yakimchuk, D.; Shashov, S.; Nurijanyan, M.; Mirzakhanyan, A. Structural, morphological and magnetic properties of nickel-carbon nanocomposites prepared by solid-phase pyrolysis of Ni phthalocyanine. Fundam. Appl. Nano Electromagn. 2016, 1, 273–290.

55. Yuan, Z.; Zhao, Y.; Yang, W.; Hu, Y.; Cai, K.; Liu, P.; Ding, H. Fabrication of antibacterial surface via UV-inducing dopamine polymerization combined with co-deposition Ag nanoparticles. Mater. Lett. 2016, 183, 85–89. [CrossRef]

56. You, C.; Han, C.; Wang, X.; Zheng, Y.; Li, Q.; Hu, X.; Sun, H. The progress of silver nanoparticles in the antibacterial mechanism, clinical application and cytotoxicity. Mol. Biol. Rep. 2012, 39, 9193–9201. [CrossRef]

57. Relinque, J.J.; de León, A.S.; Hernández-Saz, J.; García-Romero, M.G.; Navas-Martos, F.J.; Morales-Cid, G.; Molina, S.I. Development of surface-coated polylactic acid/polylactidealkanoate (PLA/PHA) nanocomposites. Polymers 2019, 11, 400. [CrossRef]

58. Mukheem, A.; Muthosamy, K.; Manickam, S.; Sudesh, K.; Shahabuddin, S.; Saidur, S.; Akbar, N.; Sridewi, N. Fabrication and characterization of an electropositive SPH/graphene silver nanocomposite scaffold for antibacterial applications. Materials 2018, 11, 1673. [CrossRef]

59. Temgire, M.K.; Joshi, S.S. Optical and structural properties of silver nanoparticles. Radiat. Phys. Chem. 2003, 71, 1039–1044. [CrossRef]

60. Castro-Mayorga, J.L.; Martín, J.M.; Ocio, M.J.; Ocío, M.J.; Sánchez, G. Silver-based antibacterial and viricide biomaterials: Usage and potential in antimicrobial packaging. In Antimicrobial Food Packaging; Elsevier: Amsterdam, The Netherlands, 2016; pp. 407–416.

61. Li, Y.; Fu, Z.-Y.; Su, B.-L. Hierarchically structured porous materials for energy conversion and storage. Adv. Funct. Mater. 2012, 22, 4634–4667. [CrossRef]

62. Qiu, R.; Cha, H.G.; Noh, H.B.; Shim, Y.B.; Zhang, X.L.; Qiao, R.; Zhang, D.; Kim, Y.I.; Pal, U.; Kang, Y.S. Preparation of dendritic polymer-coated polyelectrolyte multilayers on polymer nanocomposites. J. Phys. Chem. C 2009, 113, 15891–15896. [CrossRef]

63. Jain, P.; Pradeep, T. Potential of silver nanoparticle-coated polyelectrolyte foam as an antibacterial water filter. Biotechnol. Bioeng. 2005, 90, 59–63. [CrossRef] [PubMed]

64. Farkhri, N.; Abbasian, S.; Moshadi, A.; Nikkhah, M. Mechanism of adsorption of single and double stranded DNA on gold and silver nanoparticles: Investigating some important parameters in bio-sensing applications. Colloids Surf. B Biointerfaces 2016, 148, 657–664. [CrossRef] [PubMed]

65. Li, S.; Li, D.; Zhang, Q.-Y.; Tang, X. Surface enhanced Raman scattering substrate with high-density spots fabricated by depositing Ag film on TiO₂-catalyzed Ag nanoparticles. J. Alloys Compd. 2016, 689, 439–445. [CrossRef]

66. Iravani, S.; Korbekandi, H.; Mirmohammadi, S.; Zolfaghari, B. Synthesis of silver nanoparticles: Chemical, physical and biological methods. Res. Pharm. Sci. 2014, 9, 385.

67. Zhang, Y.; Huang, R.; Zhu, X.; Wang, L.; Wu, C. Synthesis, properties, and optical applications of noble metal nanoparticle-biomolecule conjugates. Chin. Sci. Bull. 2012, 57, 238–246. [CrossRef]

68. Lee, K.S.; El-Sayed, M.A. Gold and silver nanoparticles in sensing and imaging: Sensitivity of plasmon response to size, shape, and metal composition. J. Phys. Chem. B 2006, 110, 19220–19225. [CrossRef]

69. Penn, S.G.; He, L.; Natan, M.J. Nanoparticles for bioanalysis. Curr. Opin. Chem. Biol. 2003, 7, 609–615. [CrossRef]

70. Plowman, B.J.; Jones, L.A.; Bhargava, S.K. Building with bubbles: The formation of high surface area honeycomb-like films via hydrogen bubble templated electrodeposition. Chem. Commun. 2015, 51, 4331–4346. [CrossRef] [PubMed]

71. Wang, T.; Kaempgen, M.; Nopphawan, P.; Wee, G.; Mhaiasalkar, S.; Srinivasan, M. Silver nanoparticle-decorated carbon nanotubes as bifunctional gas-diffusion electrodes for zinc-air batteries. J. Power Sourc. 2010, 195, 4350–4355. [CrossRef]

72. Edison, T.N.J.I.; Athchudan, R.; Kamal, C.; Lee, Y.R. Caulerpa racemosa: A marine green alga for eco-friendly synthesis of silver nanoparticles and its catalytic degradation of methylene blue. Bioprocess Biosyst. Eng. 2016, 39, 1401–1408. [CrossRef] [PubMed]

73. Kumar, B.; Smita, K.; Cumbal, L.; Debut, A. Ficus carica (fig) fruit mediated green synthesis of silver nanoparticles and its antioxidant activity: A comparison of thermal and ultrasonication approach. BioNanoScience 2016, 6, 15–21. [CrossRef]
74. Vinković, T.; Novák, O.; Strnad, M.; Goessler, W.; Jurašin, D.D.; Paradiković, N.; Vrček, I.V. Cytokinin response in pepper plants (Capsicum annuum L.) exposed to silver nanoparticles. *Environ. Res.* 2017, 156, 10–18.

75. Siddiqui, K.S.; Husen, A. Plant response to engineered metal oxide nanoparticles. *Nano Res. Lett.* 2017, 12, 92. [CrossRef] [PubMed]

76. Cvjetko, P.; Milošić, A.; Domijan, A.M.; Vrček, I.V.; Tolić, S.; Stanić, P.P.; Letofsky-Papst, I.; Tkalec, M.; Balen, B. Toxicity of silver ions and differently coated silver nanoparticles in Allium cepa roots. *Ecotoxicol. Environ. Saf.* 2017, 137, 18–28. [CrossRef]

77. Rui, M.; Ma, C.; Tang, X.; Yang, J.; Jiang, F.; Pan, Y.; Xiang, Z.; Hao, Y.; Rui, Y.; Cao, W.; et al. Phytotoxicity of silver nanoparticles to peanut (Arachis hypogaea L.): Physiological responses and food safety. *ACS Sustain. Chem. Eng.* 2017, 5, 6557–6567. [CrossRef]

78. Huang, T.; Sui, M.; Yan, X.; Zhang, X.; Yuan, Z. Anti-algae efficacy of silver nanoparticles to *Microcystis aeruginosa* and *Chlorella vulgaris*: New insights from proteomic and physiological analyses. *Sci. Total Environ.* 2016, 572, 1213–1221. [CrossRef]

79. Ahmed, S.; Ahmad, M.; Swami, B.L.; Ikram, S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *J. Adv. Res.* 2016, 7, 17–28. [CrossRef] [PubMed]

80. Ali, A.; Ahmed, S. Recent advances in edible polymer based hydrogels as a sustainable alternative to conventional polymers. *J. Agric. Food Chem.* 2018, 66, 6940–6967. [CrossRef] [PubMed]

81. Amini, M.; Yousefi-Massumabad, H.; Younesi, H.; Abayr, H.; Bahramifar, N. Production of the polyhydroxyalkanoate biopolymer by *Cupriavidus necator* using beer brewery wastewater containing maltose as a primary carbon source. *J. Environ. Chem. Eng.* 2020, 8, 103588. [CrossRef]

82. Amudo, D.A.V.; Helmann, G.A.B.; Detoni, A.M.; de Carvalho, S.L.C.; de Aguiar, C.M.; Martin, C.A.; Tiuman, T.S.; Cottica, S.M. Antioxidant and cytotoxic effects of silver nanoparticles synthesized using *Punica granatum* peel extract. *Antioxidant and cytotoxicity effects of synthesized silver nanoparticles from *Punica granatum* peel extract. Nanoscale Res. Lett.* 2018, 13, 315. [CrossRef]

83. Annu, A.S.; Kaur, G.; Sharma, P.; Singh, S.; Ikram, S. Fruit waste (peel) as bio-reductant to synthesize silver nanoparticles with antimicrobial, antioxidant and cytotoxic activities. *J. Appl. Biomed.* 2018, 16, 221–231. [CrossRef]

84. Ahvenainen, R. New approaches in improving the shelf life of minimally processed fruit and vegetables. *Trends Food Sci. Technol.* 1996, 7, 179–187. [CrossRef]

85. Alhendi, A.S.; Choudhary, R. Current practices in bread packaging and possibility of improving bread shelf life by nanotechnology. *Mater. Sci.* 2013, 3, 55–60.

86. Alsalhi, M.S.; Devanesan, S.; Alfuraydi, A.A.; Vishnubalaji, R.; Munusamy, M.A.; Murugan, K.; Nicoletti, M.; Benelli, G. Green synthesis of silver nanoparticles using *Pimpinella anisum* seeds: Antimicrobial activity and cytotoxicity on human neonatal skin stomal cells and colon cancer cells. *Int. J. Environ. Chem.* 2011, 11, 4439–4449. [CrossRef]

87. Amado, D.A.V.; Helmann, G.A.B.; Detoni, A.M.; de Carvalho, S.L.C.; de Aguilar, C.M.; Martin, C.A.; Tuuman, T.S.; Cottica, S.M. Antioxidant and antibacterial activity and preliminary toxicity analysis of four varieties of avocado (*Persea americana* Mill.). *Braz. J. Food Technol.* 2019, 22. [CrossRef]

88. Devanesan, S.; Alsalhi, M.S.; Balaji, R.V.; Ranjitsingh, A.J.A.; Ahamed, A.; Alfuraydi, A.A.; Alqatani, F.Y.; Abeamizy, F.S.; Othman, A.H. Antimicrobial and cytotoxicity effects of synthesized silver nanoparticles from *Punica granatum* peel extract. *Nanoscale Res. Lett.* 2018, 13, 315. [CrossRef]

89. Vu, B.; Chen, M.; Crawford, R.J.; Ivanova, E.P. Bacterial extracellular polysaccharides involved in biofilm formation. *Molecules* 2009, 14, 2535–2554. [CrossRef] [PubMed]

90. Rui, M.; Ma, C.; Tang, X.; Yang, J.; Jiang, F.; Pan, Y.; Xiang, Z.; Hao, Y.; Rui, Y.; Cao, W.; et al. Phytotoxicity of silver nanoparticles to peanut (Arachis hypogaea L.): Physiological responses and food safety. *ACS Sustain. Chem. Eng.* 2017, 5, 6557–6567. [CrossRef] [PubMed]
99. He, Y.; Du, Z.; Ma, S.; Cheng, S.; Jiang, S.; Liu, Y.; Li, D.; Huang, H.; Zhang, K.; Zheng, X. Biosynthesis, antibacterial activity and anticancer effects against prostate cancer (PC-3) cells of silver nanoparticles using dimocarpus longan peel extract. Nanoscale Res. Lett. 2016, 11, 300. [CrossRef] [PubMed]

100. Jalani, N.S.; Michell, W.; Lin, W.E.; Hanari, S.Z.; Hashim, U.; Abdullah, R. Biosynthesis of silver nanoparticles using Citrus grandis peel extract. Malays. J. Anal. Sci. 2018, 22, 676–683.

101. Kowsalya, E.; MosaChristas, K.; Balashanmugam, P.; Rani, J.C. Biocompatible silver nanoparticles/poly (vinyl alcohol) electrospun nanofibers for potential antimicrobial food packaging applications. Food Packag. Shelf Life 2019, 21, 100379.

102. Kokila, T.; Ramesh, P.S.; Geetha, D. Biosynthesis of silver nanoparticles from Cavendish banana peel extract and its antibacterial and free radical scavenging assay: A novel biological approach. Appl. Nanosci. 2015, 5, 911–920. [CrossRef]

103. Ahmad, N.; Sharma, S.; Rai, R. Rapid green synthesis of silver and gold nanoparticles using peels of Punica granatum. Adv. Mater. Lett. 2012, 3, 376–380. [CrossRef]

104. Das, G.; Patra, J.K.; Debnath, T.; Ansari, A.; Shin, H.S. Investigation of antioxidant, antibacterial, anti-diabetic, and cytotoxicity potential of silver nanoparticles synthesized using the outer peel extract of Ananas comosus (L.). PlOS ONE 2019, 14. [CrossRef] [PubMed]

105. Sarvamangala, D.; Kondala, K.; Murthy, U.S.N.; Rao, B.N.; Sharma, G.V.R.; Satyanarayana, R. Biogenic synthesis of AGNP’s using Pomelo fruit—characterization and antimicrobial activity against gram +Ve and gram –Ve bacteria. Int. J. Pharm. Sci. Res. Rev. 2013, 19, 30–35.

106. Vinay, C.H.; Goudanavar, P.; Acharya, A. Development and characterization of pomegranate and orange fruit peel extract based silver nanoparticles. J. Mammoth Meth. Inst. Heal. Sci. 2018, 4, 72–85. [CrossRef]

107. Soto, K.M.; Quezada-Cervantes, C.T.; Hernández-Iturriaga, M.; Luna-Bárencnas, G.; Vazquez-Duhalt, R.; Mendoza, S. Fruit peels waste for the green synthesis of silver nanoparticles with antimicrobial activity against foodborne pathogens. LWT 2019, 103, 293–300. [CrossRef]

108. Kahrilas, G.A.; Wally, L.M.; Fredrick, S.J.; Hiskey, M.; Prieto, A.L.; Owens, J.E. Microwave-assisted green synthesis of silver nanoparticles using orange peel extract. ACS Sustain. Chem. Eng. 2014, 2, 367–376. [CrossRef]

109. Radwan, R.A.; El-Sherif, Y.A.; Salama, M.M. A novel biochemical study of anti-ageing potential of Eucalyptus camaldulensis bark waste standardized extract and silver nanoparticles. Colloids Surf. B Biointerfaces 2020, 191, 111004. [CrossRef]

110. Abdullah, H.S.T.S.H.; Asseri, S.N.A.R.M.; Mohamad, W.N.K.W.; Kan, S.Y.; Azmi, A.A.; Julius, F.S.Y.; Chia, P.W. Green synthesis, characterization and applications of silver nanoparticle mediated by the aqueous extract of red onion peel. Environ. Pollut. 2021, 271. [CrossRef]

111. Doan, V.D.; Phung, M.T.; Nguyen, T.L.H.; Mai, T.C.; Nguyen, T.D. Noble metallic nanoparticles from waste Nypa fruticans fruit husk: Biosynthesis, characterization, antibacterial activity and recyclable catalysis. Arab. J. Chem. 2020, 13, 7490–7503. [CrossRef]

112. Patra, J.K.; Das, G.; Kumar, A.; Ansari, A.Z.; Kim, H.; Shin, H.S. Photo-mediated biosynthesis of silver nanoparticles using the non-edible accreent fruiting calyx of Physalis peruviana L. Fruits and investigation of its radical scavenging potential and cytotoxicity activities. J. Photochem. Photobiol. B Biol. 2018, 188, 116–125. [CrossRef] [PubMed]

113. Das, G.; Shin, H.S.; Kumar, A.; Vishnuprasad, C.N.; Patra, J.K. Photo-mediated optimized synthesis of silver nanoparticles using the extracts of outer shell fibre of Cocos nucifera L. fruit and detection of its antioxidant, cytotoxicity and antibacterial potential. Saudi J. Biol. Sci. 2020, 28, 980–987. [CrossRef] [PubMed]

114. Patra, J.K.; Das, G.; Baek, K.H. Phyto-mediated biosynthesis of silver nanoparticles using the rind extract of watermelon (Citrus lanatus) under photo-catalyzed condition and investigation of its antibacterial, anticandidal and antioxidant efficacy. J. Photochem. Photobiol. B Biol. 2016, 161, 200–210. [CrossRef] [PubMed]

115. Pirathiba, S.; Dayananda, B.S. Potato peel waste as reductant for the biogenesis of gold and silver ultrafine particles. Mater. Today Proc. 2021. [CrossRef]

116. Liu, Y.S.; Chang, Y.C.; Chen, H.H. Silver nanoparticle biosynthesis by using phenolic acids in rice husk extract as reducing agents and dispersants. J. Food Drug Anal. 2018, 26, 649–656. [CrossRef] [PubMed]

117. Prabhu, S.; Poulouse, E.K. Silver nanoparticles: Mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. Int. Nano Lett. 2012, 2, 32. [CrossRef]

118. Salleh, A.; Naomi, R.; Utami, N.D.; Mohammad, A.W.; Mahmoudi, E.; Mustafa, N.; Fauzi, M.B. The potential of silver nanoparticles for antiviral and antibacterial applications: A mechanism of action. Nanomaterials 2020, 10, 1566. [CrossRef]

119. Mambiro-Jones, C.; Hoek, E.M. 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]

120. Barkat, M.A.; Beg, S.; Naim, M.; Pootoo, F.H.; Singh, S.P.; Ahmad, F.J. Current progress in synthesis, characterization and applications of silver nanoparticles: Precepts and prospects. Recent Pat. Anti Infect. Drug Disc. 2018, 13, 53–69. [CrossRef]

121. Kim, J.Y.; Kim, S.E.; Kim, J.E.; Lee, J.C.; Yoon, J.Y. The biocidal activity of nano-sized silver particles comparing with silver ion. J. Korean Soc. Environ. Eng. 2005, 27, 771–776.

122. Chen, X.; Schluesener, H.J. Nanosilver: A nanoproduct in medical application. Toxicol. Lett. 2008, 176, 1–12. [CrossRef]

123. Dakal, T.C.; Kumar, A.; Majumdar, R.S.; Yadav, V. Mechanistic basis of antimicrobial actions of silver nanoparticles. Front. Microbiol. 2016, 7, 1831. [CrossRef]

124. Mokhena, T.C.; Luyt, A.S. Electrospun alginate nanofibres impregnated with silver nanoparticles: Preparation, morphology and antibacterial properties. Carbohydr. Polym. 2017, 165, 304–312. [CrossRef]
125. Gudikandula, K.; Vadapally, P.; Singara Chary, M.A. Biogenic synthesis of silver nanoparticles from white rot fungi: Their characterization and antibacterial studies. *OpenNano* 2017, 2, 64–78. [CrossRef]

126. Jena, P.; Bhattacharya, M.; Bhattacharjee, G.; Satpathi, B.; Mukerjee, P.; Senapati, D.; Srinivasan, R. Bimetallic gold–silver nanoparticles mediate bacterial killing by disrupting the actin cytoskeleton MreB. *Nanoscale* 2020, 12, 3731–3749. [CrossRef]

127. Veeraputhiran, V. Bio-catalytic synthesis of silver nanoparticles. *Int. J. Chem. Tech. Res.* 2013, 5, 255–262.

128. Guan, Q.; Xia, C.; Li, W. Bio-friendly controllable synthesis of silver nanoparticles and their enhanced antibacterial property. *Catal. Today* 2019, 327, 196–202. [CrossRef]

129. Prasher, P.; Singh, M.; Mudila, H. Oligodynamic effect of silver nanoparticles: A review. *Biomass Science* 2018, 8, 951–962. [CrossRef]

130. Lee, J.H.; Lim, J.M.; Velmurugan, P.; Park, Y.J.; Park, Y.J.; Bang, K.S.; Oh, B.T. Photobiologic-mediated fabrication of silver nanoparticles with antibacterial activity. *J. Photochem. Photobiol. B Biol.* 2016, 162, 93–99. [CrossRef]

131. Ghiută, I.; Cristea, D.; Croitoru, C.; Kost, J.; Wenkert, R.; Vyrides, I.; Anayiotos, A.; Munteanu, D. Characterization and antimicrobial activity of silver nanoparticles, biosynthesized using *Bacillus* species. *Appl. Surf. Sci.* 2018, 438, 66–73. [CrossRef]

132. Amoobaghiaie, R.; Saer, M.R.; Azizi, M. Synthesis, characterization and biocompatibility of silver nanoparticles synthesized from *Nigella sativa* leaf extract in comparison with chemical silver nanoparticles. *Ecotoxicol. Environ. Saf.* 2015, 120, 400–408. [CrossRef]

133. Zhou, Y.; Hu, K.; Guo, Z.; Fang, K.; Wang, X.; Yang, F.; Gu, N. PLLA microcapsules combined with silver nanoparticles and chlorhexidine acetate showing improved antibacterial effect. *Mater. Sci. Eng. C* 2017, 78, 349–353. [CrossRef]

134. Zhang, L.; Wu, L.; Mi, Y.; Si, Y. Silver nanoparticles induced cell apoptosis, membrane damage of *Escherichia coli* and *somonas europaea* via generation of reactive oxygen species. *Biomaterials* 2019, 3311–3327. [CrossRef] [PubMed]

135. Zheng, K.; Setyawati, M.I.; Leong, D.T.; Xie, Y. Antimicrobial silver nanomaterials. *Coord. Chem. Rev.* 2018, 357, 1–17. [CrossRef]

136. Koduru, J.R.; Kailasa, S.K.; Bhamore, J.R.; Kim, K.H.; Dutta, T.; Vellingiri, K. Phytochemical-assisted synthetic approaches for silver nanoparticles antimicrobial applications: A review. *Adv. Colloid Interface Sci.* 2018, 256, 326–339. [CrossRef]

137. Choi, O.; Yu, C.P.; Esteban Fernández, G.; Hu, Z. Interactions of nanosilver with *Escherichia coli* cells in planktonic and biofilm cultures. *Water Res.* 2010, 44, 6095–6103. [CrossRef]

138. Abdalla, S.I.; Katas, H.; Chan, J.Y.; Ganasan, P.; Azmi, F.; Busra, M.F.M. Antimicrobial activity of multifaceted lactoferrin or graphene oxide functionalized silver nanocomposites biosynthesized using mushroom waste and chitosan. *RSC Adv.* 2020, 10, 4969–4983. [CrossRef]

139. Zheng, K.; Setyawati, M.I.; Leong, D.T.; Xie, Y. Antimicrobial silver nanomaterials. *Coord. Chem. Rev.* 2018, 357, 1–17. [CrossRef]

140. Vazquez-Muñoz, R.; Meza-Villéczas, A.; Fournier, P.G.J.; Soria-Castro, E.; Juarez-Moreno, K.; Gallego-Hernández, A.L.; Bogdanchikova, N.; Vazquez-Duhalt, R.; Huerta-Saquero, A. Enhancement of antibiotics antimicrobial activity due to the silver nanoparticles impact on the cell membrane. *PLoS ONE* 2019, 14, 1–18. [CrossRef]

141. Koduru, J.R.; Kailasa, S.K.; Bhamore, J.R.; Kim, K.H.; Dutta, T.; Vellingiri, K. Phytochemical-assisted synthetic approaches for silver nanoparticles antimicrobial applications: A review. *Adv. Colloid Interface Sci.* 2018, 256, 326–339. [CrossRef]

142. Choi, O.; Yu, C.P.; Esteban Fernández, G.; Hu, Z. Interactions of nanosilver with *Escherichia coli* cells in planktonic and biofilm cultures. *Water Res.* 2010, 44, 6095–6103. [CrossRef]

143. Abdalla, S.I.; Katas, H.; Chan, J.Y.; Ganasan, P.; Azmi, F.; Busra, M.F.M. Antimicrobial activity of multifaceted lactoferrin or graphene oxide functionalized silver nanocomposites biosynthesized using mushroom waste and chitosan. *RSC Adv.* 2020, 10, 4969–4983. [CrossRef]

144. Wakshtak, R.B.K.; Pedahzur, R.; Avnir, D. Antibacterial activity of silver-killed bacteria: The “zombies” effect. *Sci. Rep.* 2015, 5, 1–5. [CrossRef]

145. Vazquez-Muñoz, R.; Meza-Villéczas, A.; Fournier, P.G.J.; Soria-Castro, E.; Juarez-Moreno, K.; Gallego-Hernández, A.L.; Bogdanchikova, N.; Vazquez-Duhalt, R.; Huerta-Saquero, A. Enhancement of antibiotics antimicrobial activity due to the silver nanoparticles impact on the cell membrane. *PLoS ONE* 2019, 14, 1–18. [CrossRef]

146. Katas, H.; Raja, M.A.G.; Lam, K.L. Characterization and development of chitosan nanoparticles as a stable drug delivery system for protein/siRNA. *Int. J. Biomater.* 2013, 2013. [CrossRef] [PubMed]

147. Hu, S.; Yi, T.; Huang, Z.; Liu, B.; Wang, J.; Yi, X.; Liu, J. Etching silver nanoparticles using DNA. *Mater. Horizons* 2019, 6, 155–159. [CrossRef]

148. Sadoon, A.A.; Khadka, P.; Freeland, J.; Gundampati, R.K.; Manso, R.H.; Ruiz, M.; Krishnamurthi, V.R.; Thallapuranam, S.K.; Chen, J.; Wang, Y. Silver ions caused faster diffusive dynamics of histone-like nucleoid-structuring proteins in live bacteria. *Appl. Environ. Microbiol.* 2020, 86. [CrossRef] [PubMed]

149. Siess, H.; Jones, D.P. Reactive oxygen species (ROS) as pleiotropic physiological signalling agents. *Nat. Rev. Mol. Cell Biol.* 2020, 21, 363–383. [CrossRef]

150. Qing, Y.; Cheng, L.; Li, R.; Liu, G.; Zhang, Y.; Tang, X.; Wang, J.; Liu, H.; Qin, Y. Potential antibacterial mechanism of silver nanoparticles and the optimization of orthopedic implants by advanced modification technologies. *Int. J. Nanomed.* 2018, 13, 3311–3327. [CrossRef]

151. Su, H.L.; Chou, C.C.; Hung, D.J.; Lin, S.H.; Pao, I.C.; Lin, J.H.; Huang, F.L.; Dong, R.X.; Lin, J.J. The disruption of bacterial membrane integrity through ROS generation induced by nanohybrids of silver and clay. *Biomaterials* 2009, 30, 5979–5987. [CrossRef] [PubMed]

152. Zhang, L.; Wu, L.; Mi, Y.; Si, Y. Silver nanoparticles induced cell apoptosis, membrane damage of *Azotobacter vinelandii* and *Nitrosomonas europaea* via generation of reactive oxygen species. *Bull. Environ. Contam. Toxicol.* 2019, 103, 181–186. [CrossRef] [PubMed]

153. Pramanik, S.; Chatterjee, S.; Saha, A.; Devi, P.S.; Suresh Kumar, G. Unraveling the interaction of silver nanoparticles with mammalian and bacterial DNA. *J. Phys. Chem. B* 2016, 120, 5313–5324. [CrossRef] [PubMed]

154. Das, B.; Dash, S.K.; Mandal, D.; Ghosh, T.; Chattopadhyay, S.; Tripathy, S.; Das, S.; Dey, S.K.; Das, D.; Roy, S. Green synthesized silver nanoparticles destroy multidrug resistant bacteria via reactive oxygen species mediated membrane damage. *Arab. J. Chem.* 2017, 10, 862–876. [CrossRef]

155. Ji, H.; Zhou, S.; Fu, Y.; Wang, Y.; Mi, J.; Lu, T.; Wang, X.; Lü, C. Size-controllable preparation and antibacterial mechanism of thermo-responsive copolymer-stabilized silver nanoparticles with high antimicrobial activity. *Mater. Sci. Eng. C* 2020, 110, 110735. [CrossRef]
Adeyemi, O.S.; Shittu, E.O.; Akpor, O.B.; Rotimi, D.; Batika, G.E.S. Silver nanoparticles restrict microbial growth by promoting oxidative stress and DNA damage. *EXCLI J.* 2020, 19, 492–500. [PubMed]

Belluco, S.; Losasso, C.; Patuzzi, I.; Rigo, L.; Confoconi, D.; Galloccchio, F.; Cibin, V.; Catellani, P.; Segato, S.; Ricci, A. Silver as antibacterial toward *Listeria monocytogenes*. *Front. Microbiol.* 2016, 7. [CrossRef]

Nalwade, A.R.; Jadhav, A.A. Biosynthesis of silver nanoparticles using leaf extract of *Datura alba* Nees and evaluation of their antibacterial activity. *Arch. Appl. Sci. Res.* 2013, 5, 45–49.

Ouda Sahar, M. Some nanoparticles effects on *Proteus* sp. and *Klebsiella* sp. Isolated from water. *Am. J. Infect. Dis. Microbiol.* 2014, 2, 4–10.

Radzig, M.A.; Nadtochenko, V.A.; Koksharova, O.A.; Kiwi, J.; Lipasova, V.A.; Khmel, I.A. Antibacterial effects of silver nanoparticles on gram-negative bacteria: Influence on the growth and biofilms formation, mechanisms of action. *Colloids Surf. B Biointerfaces* 2013, 102, 300–306. [CrossRef] [PubMed]

Kora, A.J.; Arunachalam, J. Assessment of antibacterial activity of silver nanoparticles on *Pseudomonas aeruginosa* and its mechanism of action. *World J. Microbiol. Biotechnol.* 2011, 27, 1209–1216. [CrossRef]

Salem, W.; Leitner, D.R.; Zingl, F.G.; Schratt, G.; Prassl, R.; Goessler, W.; Reidl, J.; Schild, S. Antibacterial activity of silver and zinc nanoparticles against *Vibrio cholerae* and enterotoxic *Escherichia coli*. *Int. J. Med. Microbiol.* 2015, 305, 85–95. [CrossRef] [PubMed]

Rajawat, S.; Qureshi, M.S. Comparative study on bactericidal effect of silver nanoparticles, synthesized using green technology, in combination with antibiotics on *Salmonella typhi*. *J. Biomater. Nanobiotechnol.* 2012, 3, 480–485. [CrossRef]

Faunce, T.; Watal, A. Nanosilver and global public health: International regulatory issues. *Nanomedicine* 2010, 5, 617–632. [CrossRef] [PubMed]

He, Z.; He, J.; Zhang, Z. Selective growth of metallic nanostructures on microstructured copper substrate in solution. *CrystEngComm* 2015, 17, 7262–7269. [CrossRef]

Ghodake, G.; Kim, M.; Sung, J.S.; Shinde, S.; Yang, J.; Hwang, K.; Kim, D.Y. Extracellular synthesis and characterization of silver nanoparticles—Antibacterial activity against multidrug-resistant bacterial strains. *Nanomaterials* 2020, 10, 360. [CrossRef] [PubMed]

Banerjee, P.P.; Bandyopadhyay, A.; Harsha, S.N.; Policegoudra, R.S.; Bhattacharya, S.; Karak, N.; Chattopadhyay, A. *Menella arvensis* (Linn.)-mediated green silver nanoparticles trigger caspase 9-dependent cell death in MCF7 and MDA-MB-231 cells. *Breast Cancer Targets Ther.* 2017, 9, 265–278. [CrossRef]

Gaikwad, S.; Ingle, A.; Gade, A.; Rai, M.; Falanga, A.; Incoronato, N.; Russo, L.; Galdiero, S.; Galdiero, M. Antiviral activity of mycosynthesized silver nanoparticles against herpes simplex virus and human parainfluenza virus type 3. *Int. J. Nanomed.* 2013, 8, 4303–4314.

Xiang, D.X.; Chen, Q.; Pang, L.; Zheng, C.L. Inhibitory effects of silver nanoparticles on H1N1 influenza A virus in vitro. *J. Virol. Methods* 2011, 1780, 137–142. [CrossRef] [PubMed]

Jong, W.H.; Van Der Ven, L.T.M.; Sleijfer, A.; Park, M.V.D.Z.; Jansen, E.H.J.M.; Van Loveren, H.; Vandebriel, R.J. Systemic and immunotoxicity of silver nanoparticles in an intravenous 28 days repeated dose toxicity study in rats. *Biomaterials* 2013, 34, 8333–8343. [CrossRef]

Maretti, L.; Billone, P.S.; Liu, Y.; Scaiano, J.C. Facile photochemical synthesis and characterization of highly fluorescent silver nanoparticles. *J. Am. Chem. Soc.* 2009, 131, 13972–13980. [CrossRef] [PubMed]

Navaladain, S.; Viswanathan, B.; Viswanath, R.P.; Varadarajan, T.K. Thermal decomposition as route for silver nanoparticles. *Nanoscale Res. Lett.* 2007, 2, 44–48. [CrossRef] [PubMed]

Chen, P.; Song, L.; Liu, Y.; Fang, Y.-E. Synthesis of silver nanoparticles by γ-ray irradiation in acetic water solution containing chitosan. *Radiat. Phys. Chem.* 2007, 76, 1165–1168. [CrossRef]

Jing, S.; Xing, S.; Yu, L.; Wu, Y.; Zhao, C. Synthesis and characterization of Ag/polyaniline core-shell nanocomposites based on silver nanoparticles colloid. *Mater. Lett.* 2007, 61, 2794–2797. [CrossRef]

Krystek, P.; Cirtiu, C.M.; Braakhuis, H.; Park, M.; Jong, W.H. Inductively coupled plasma-mass spectrometry in biodistribution studies of (engineered) nanoparticles. In *Encyclopedia of Analytical Chemistry*; Wiley: Hoboken, NJ, USA, 2019; pp. 1–23.

Wijnhoven, S.W.P.; Peijnenburg, W.J.G.M.; Herberts, C.A.; Hagens, W.I.; Oomen, A.G.; Heugens, E.H.W.; Roszek, B.; Bisschops, J.; Gosen, I.; Van De Meent, D.; et al. Nano-silver—A review of available data and knowledge gaps in human and environmental risk assessment. *Nanotoxicology* 2009, 3, 109–138. [CrossRef]