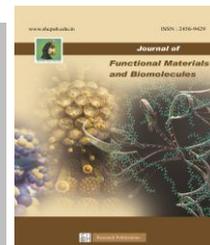




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SILVER NANOPARTICLES (Ag NPs): COMPREHENSIVE INSIGHTS INTO BIO/SYNTHESIS, AND MULTIFACETED APPLICATIONS

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Abstract

Silver nanoparticles (AgNPs) are widely recognized for their unique optical, electronic, and antibacterial properties, enabling their use in biosensing, photonics, electronics, drug delivery, and antimicrobial treatments. Green chemistry-based biological synthesis methods offer an eco-friendly alternative to traditional chemical techniques. Among metallic nanoparticles (NPs) and metal oxides, those derived from plant extracts exhibit notable medicinal properties. Due to their exceptional stability and low chemical reactivity, AgNPs are particularly well-suited for various biological applications. AgNPs can be synthesized through chemical, physical, or biological methods, each with distinct benefits and challenges. Chemical and physical approaches often involve complex purification, reactive reagents, and high energy demands, while biological methods, though slower, provide sustainable solutions. This review emphasizes the importance of selecting appropriate synthesis methods to optimize the characteristics and functionality of silver NPs. It consolidates research spanning the past two decades, including the most recent findings from 2024. A comprehensive electronic search of databases such as PubMed, Scopus, Science Direct, Cochrane, and Google Scholar was conducted to provide an up-to-date overview of advances in the synthesis and applications of silver nanoparticles.

Keywords: Silver nanoparticles, MCF-7 cells, Anti-viral and Anti-cancer agents.

1. Introduction

The growing interest in nanotechnology among researchers in recent years is unsurprising, given the remarkable advancements in the field. Nanotechnology is inherently versatile, finding applications across various disciplines, including electronics, sensors, optics, mechanics, catalysis, chemistry, cosmetics, pharmaceuticals, medicine and biomedical sciences, food technology, and environmental science. Differences in chemical composition, morphology, size, and controlled dispersity lead to variations in the properties of nanoparticles (NPs). These differences often arise from the synthesis process, which is influenced by various factors. Modern nanoparticle production emphasizes not only achieving nanoscale dimensions but also ensuring that the synthesis process is straightforward, cost-effective, environmentally friendly, and customizable for specific applications [1]. Silver nanoparticles typically range in size from 1 to 100 nm. Silver nanoparticles (AgNPs), known for their unique optical, electronic, and

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antibacterial properties, have found wide-spread use in various applications, including biosensing, photonics, electronics, and antimicrobial treatments,10 among others. In recent years, the increasing integration density of electronic components has driven a growing demand for precise control over the thickness and width of printed electronic circuits, considering the spacing between them [2].

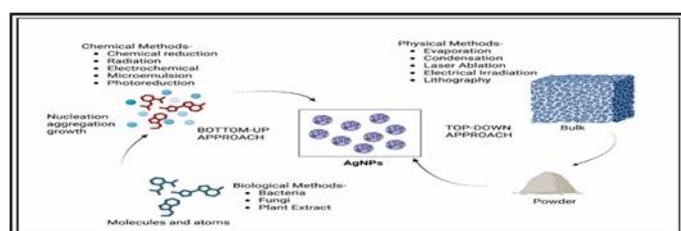


Fig 1. AgNP synthesis using a top-down and a bottom-up approach.

Currently, various methods have been developed for synthesising silver nanoparticles (AgNPs), including chemical, physical, photochemical, and biological approaches. Each method has its advantages and limitations, with common challenges such as cost, scalability, particle size, and size distribution [3]. Physical and photochemical methods often require high temperatures, vacuum conditions, and expensive equipment [16,17]. Among these, chemical methods are the most widely used for AgNP production due to their simplicity and efficiency. These methods are well-suited for producing pure, well-defined nanoparticles under mild and straightforward conditions. In chemical synthesis, AgNPs are typically prepared by reducing silver ions in water or organic solvents, resulting in colloidal dispersions with varying particle sizes. The growing demand for silver nanoparticles (AgNPs) necessitates a sufficient

and efficient supply, making their synthesis a crucial focus in nanoscience [4].

2. Experimental

AgNPs were synthesized using different techniques, such as physical, chemical, and biological means. Synthesis typically involves reducing silver ions (Ag^+) to metallic silver (Ag), which is followed by nucleation and growth processes that determine the shape, size, and morphology of the nanoparticles. The synthesis method used may also impart different properties to the nanoparticles [6].

2.1. Physical Methods

Metal Nanoparticles like AgNPs can be synthesised from bulk materials with the application of External forces. These external forces can be conventional Processes like crushing, grinding, and milling, or advanced Processes like arc discharge, laser abrasion, or vapor Condensation [7]. The so-formed AgNPs are of uniform size and exhibit more or less uniform morphological properties and High purity. The size of these nanoparticles can range from 10 to 100 nm.

2.1.1. Ball Milling Method

In this method, the milling balls and metal materials are placed in a specific mass ratio, and a Gaseous medium, like air or any inert gas, is supplied into the Container that agitates the mixture. The critical factors, such as Milling time, rotational speed, type of metal particles, and inert Medium used, significantly affect the morphology and properties of the nanoparticles. An increase in particle size results in to decrease in surface energy, which results in the agglomeration of the particles, whereas the temperature impacts

the diffusivity and phase characteristics. Khayati and Jan-ghorban co-workers synthesized Nanostructured silver with a crystallite size of 28 nm and internal strain of 0.44% via mechanochemical reduction of Ag₂O using graphite in a high-Energy ball mill [8].

2.2. Chemical Methods

Several chemical methods are employed for synthesizing silver nanoparticles (AgNPs), with Chemical reduction being the most widely used. This method utilizes organic or inorganic reducing agents to produce silver Nanoparticles in a single-step process, resulting in the Characteristic color of the silver solution. This phenomenon occurs due to the free electrons present on the metal's surface in the conduction band, interacting with positively charged Nuclei. Over time, stable silver clusters form, confirming the Successful synthesis of AgNPs. The microemulsion technique is another approach with extensive applications in chemical and biological fields. It is favoured for its unique properties, including ultralow interfacial tension, large interfacial area, Thermodynamic stability, and the ability to solubilize immiscible liquids. Microwave-assisted synthesis, on the other hand, involves the reduction of silver nanoparticles using variable-rate microwave radiation, offering an efficient Alternative to traditional heating methods [9].

2.2.1. Chemical reduction

Chemical reduction is a well-established method for synthesizing silver nanoparticles (AgNPs), relying on two primary components: a reducing Agent and a silver source. Various reagents serve as reducing agents, with sodium

borohydride being one of the most commonly used due to its strong and rapid reducing capabilities. The coreduction approach, which combines agents Such as sodium borohydride and trisodium citrate, hydrazine Hydrate and sodium citrate, or borohydride and citrate, has also been employed for AgNP synthesis. For instance, Agnihotri et al. demonstrated the use of sodium borohydride as a primary reductant and trisodium citrate as both a Secondary reductant and a stabilizing agent. This method Allowed precise control over nucleation and growth kinetics, yielding silver nanoparticles with average sizes of 5, 7, 10, 15, 20, 30, 50, 63, 85, and 100 nm. These nanoparticles exhibited High yield and uniform size distribution (monodispersity). The addition of a stabilizing agent plays a crucial role in maintaining the nanoparticles in a dispersed state and can also influence their crystal structure. Besides the commonly observed spherical nanoparticles protective agents enable the formation of alternative morphologies, such as rhomboidal structures and nanosheets. Silver nitrate, a widely used silver source in these processes, is favoured for its chemical stability, affordability, and availability compared to other silver salts, making it an ideal supplier of silver ions for nanoparticle synthesis. Figure 2 represents the coreduction method for the synthesis of AgNPs.

2.2.2. Microemulsion techniques

Microemulsion techniques involve synthesizing AgNPs by utilizing a surfactant to mix two immiscible liquids, such as oil and water or water and supercritical CO₂, along with a combination of oil, one or more surfactants, and water. This approach enables the production of uni-

form AgNPs with precise size control. The synthesis of AgNPs in two-phase aqueous-organic systems relies on the spatial separation of reactants, such as the silver precursor and the reducing agent, in two immiscible phases. "Ready-to-use" surfactants, which can be anionic, cationic, zwitterionic, or non-ionic, include bis(2-ethylhexyl) sulfosuccinate, lauryl sodium sulfate, sodium dodecylbenzenesulfonate (anionic); cetyltrimethylammonium bromide (CTAB) and poly-vinylpyrrolidone (PVP) (cationic); and Triton X-100 (nonionic). The choice of surfactant depends on the experimental requirements and reaction conditions. Various surfactants or microemulsion systems used in the synthesis process can yield AgNPs with unique sizes or morphologies. 10 The interaction rate between metal precursors and reducing agents is determined by the interface between the two phases and the efficiency of inter-phase transport, which is facilitated by ammonium salts. The stabilization of silver clusters at the interface is achieved through the transfer of nonpolar stabilizer molecules from the aqueous phase to the organic medium by the interphase transporter.

A study by Hak et al. focuses on the eco-friendly, cost-effective synthesis of silver nanoparticles (AgNPs) for targeted breast cancer therapy. Neural network optimization was employed to correlate formulation parameters with particle size. AgNPs were incorporated into microemulsions, demonstrating controlled drug release, enhanced bioavailability, and strong anticancer activity against MCF-7 cells. In-vivo results confirmed reduced

tumour growth, showcasing AgNPs' therapeutic potential [11].

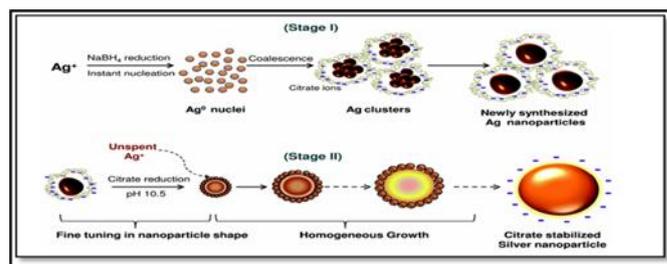


Fig 2. Schematic representation of size-controlled silver nanoparticles synthesized employing the co-reduction approach.

2.2.3. Polymers and Polysaccharides

Silver nanoparticles (AgNPs) can be synthesized using water as an eco-friendly solvent, with polysaccharides serving as capping and reducing agents. Starch can act as a capping agent, while D-glucose functioned as the reducing agent in the production of starch-AgNPs under mild heating. The weak interaction between starch and AgNPs makes this bond reversible at elevated temperatures, resulting in the separation of AgNPs. Common polymers used as reducing agents for AgNP synthesis include poly(vinyl alcohol) (PVA), polyethylene glycol (PEG), polyacrylamide, and biopolymers like chitosan. PEG-coated AgNPs have demonstrated high stability in saline solutions, while carboxyl-coated lipoic acid particles are suitable for bioconjugation applications. A study by Singh et al. explores the synthesis of silver nanoparticles (AgNPs) using gum acacia and tragacanth gum, followed by their incorporation into hydrogels for drug delivery applications. Cefoperazone-loaded hydrogels exhibited pH-responsive sustained re-release and antimicrobial activity

against *E. coli*, *P. aeruginosa*, and *S. aureus*. Characterisation confirmed AgNPs' uniform distribution, crystalline structure, and polymer integration [12]. The hydrogels demonstrated antioxidant properties, blood compatibility, mucoadhesion, and a non-Fickian drug diffusion mechanism, making them promising drug delivery carriers (figure 3). Another study by Sarkar et al. explores the green synthesis of silver nanoparticles (AgNPs) using bacterial cell wall polysaccharides (CPS3) isolated from *Chryseobacterium geo-carposphaerae* DD3, sourced from textile industry dye effluent. CPS3-stabilised AgNPs showed significant photo-catalytic activity, effectively degrading azo dyes such as Congo red, methyl red, and malachite green, demonstrating their potential in bioremediation applications.

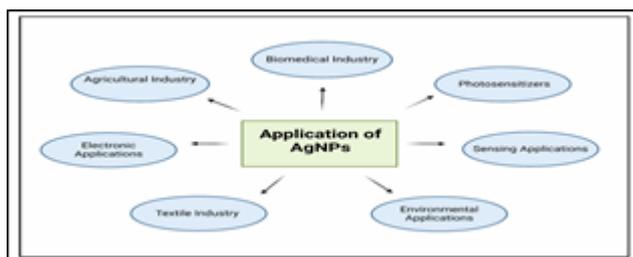


Fig 3: Biological methods for AgNP synthesis.

AgNP-polymer nanocomposites. AgNP-polymer nanocomposites are synthesized using various methods tailored to their specific applications. For tissue engineering, water-soluble polymers such as poly (vinyl alcohol) (PVA), poly-ethylene glycol (PEG), and poly (acrylic acid) (PAA) are frequently employed to create hydrogels. These hydrogels are formed through freeze-thaw cycles, which induce phase separation into polymer-rich and polymer-poor regions, yielding a porous structure [13]. Repeated

freeze-thawing increases cross-linking and enhances swelling capacity. AgNP-polymer composite hydrogels can be prepared either by incorporating pre-formed AgNPs into the polymer matrix or generating AgNPs in situ. The latter involves dissolving a metal salt in the polymer solution, reducing it with sodium borohydride, and performing freeze-thawing cycles. For antimicrobial fabrics, the dip-coating method is commonly employed. This involves immersing fabrics in a silver salt solution followed by chemical reduction. UV or microwave radiation may be used to accelerate the reaction and control AgNP size on fabric fibers. Plasma treatment to polyamide 6,6 (PA 6,6) fabrics, followed by coating with colloidal AgNPs of various sizes. The plasma treatment introduced oxygen species on the fibers, facilitating ionic and covalent interactions between the oxygen groups and AgNPs, thereby improving nanoparticle deposition. (RF) plasma to etch polyester fibers, enhancing the binding efficiency of colloidal AgNPs and boosting the antibacterial performance of polyester nanocomposites. Babaahmadi and Montazer240 demonstrated a one-step in situ synthesis of AgNPs on polyamide (nylon) fabrics by reducing silver nitrate with stannous chloride (SnCl_2) using CTAB as a stabilizer. The prepared AgNPs using the $[\text{Ag}(\text{NH}_3)_2]^+$ complex with PVP as a reducing and stabilizing agent under UV irradiation. These nanoparticles were then deposited onto nylon fabric using a dip-pad technique. In another study, Montazer et al. directly reduced the $[\text{Ag}(\text{NH}_3)_2]^+$ complex with polyamide functional groups, avoiding external reductants. Here, the nitrogen atoms in

the polyamide chains stabilized the AgNPs through coordination with silver ions. Plasma treatment can enhance AgNP deposition on fabrics by introducing active functional groups on the fibers [14].

3. Results and Discussion

3.1. Environmental Applications

Electrochemical Sensors for Detection of Heavy Metal Ions in Water Matrices. Electrochemical sensors are gaining attention for detecting heavy metal ions such as Cu (II) and Pb (II) due to their environmental and health impacts. A novel Ag@MOF nanocomposite was synthesised via the reflux method and coated onto ITO glass, showing exceptional sensitivity and reproducibility. The Ag@MOF/ITO electrode detected Cu (II) and Pb (II) ions at trace levels with LODs of 0.68 and 0.64 μM , respectively, through complexation with hydroxyl groups, demonstrating its potential as an effective sensor. Ece et al., developed a cost-effective, eco-friendly electrochemical sensor for Hg^{2+} detection using herbal silver nanoparticles (AgNPs) and folic acid (FA) on pencil graphite electrodes. It offered excellent selectivity for Hg^{2+} over other metal ions, required no electrode regeneration, and also enabled rapid, sensitive detection in tap water, demonstrating potential for environmental monitoring while promoting sustainability [15].

A green silver nanoparticle-based sensor for detecting Hg (II) ions in water. Silver nanoparticles were synthesized via a microwave reactor from *Agaricus bisporus* which showed excellent optical and electrochemical properties.

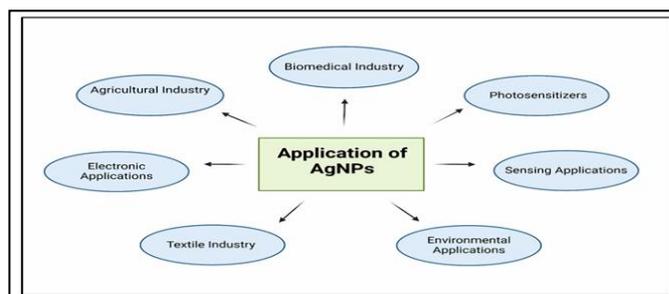


Fig 4. Applications of AgNPs

The sensor achieved a detection limit of 2.1×10^{-6} M using differential pulse voltammetry and demonstrated high selectivity for Hg (II) ions. This eco-friendly approach was validated with water samples, highlighting its potential for environmental monitoring. However, this was not the same in the case of unmodified silver nanoparticles (AgNP-MD), which were synthesised using *Mi-mosa diplotricha* leaf extract, serving as a reducing and stabilizing agent. The 13.88 nm nanoparticles functioned as optical and electrochemical Hg^{2+} sensors, achieving a 1.46 μM detection limit via DPV and 102–106% recovery in water samples. Characterisation of AgNP-MD also degraded hazardous dyes, demonstrating eco-friendly multifunctionality for toxic metal detection and environmental sustainability. Another example is Calixar--functionalized silver nanoparticles (ThC-AgNPs) selectively detect Hg^{2+} (LOD: 0.5 nM by UV-vis, 10 nM by amperometry) and Hg^0 in aqueous and vapor phases. Detection involves Hg^{2+} -induced calixarene displacement, forming Ag-Hg amalgams and nanoparticle assemblies [1–5]. These nanoparticles show high sensitivity, no interference from other ions, and have been applied to real samples for

detecting Hg^{2+} in water and Hg^0 in soil. Similarly, the detection of mercury ions ($\text{Hg}(\text{II})$), a hazardous environmental pollutant, was achieved using microwave-assisted silver nanoparticles (AgNPs) synthesized with *Curcuma longa* rhizome (CLR) extract. The curcuminoids in CLR act as reducing and stabilizing agents, enhancing the sensitivity and selectivity of AgNPs for $\text{Hg}(\text{II})$ detection. Electrochemical methods, including CV and DPV, demonstrated low detection limits (6.5 nM), with applications validated in real water samples. The single-pot synthesis of carboxymethylcellulose-protected silver nanoparticles (CMC@AgNPs) was synthesized by Meenakshi et al., for electrochemical detection of Hg^{2+} in water. Using aniline as a reducing agent, CMC@AgNPs were synthesized under reflux and room temperature conditions, and characterized by UV-vis, FT-IR, and SEM. The modified electrode, CMC@AgNPs/GCE, exhibited enhanced electrochemical properties for Hg^{2+} detection, with a detection limit of 0.19 nM and a linear range of [5–75] μM , showing high sensitivity for low-concentration water samples. Likewise, a highly sensitive electrochemical sensor for detecting ultratrace levels of Hg^{2+} in water has been developed using a silver nanoparticle-modified glassy carbon electrode (AgNP-GCE). This method, based on linear sweep voltametry, offers a linear range from 100 pM to 10 nM Hg^{2+} with a detection limit of 28 pM. It is suitable for routine environmental monitoring and drinking water quality assessment, aligning with the US EPA guidelines for inorganic mercury in drinking water

(10 nM). Smruti et al., work focused on the synthesis of bioinspired Ag@PtNPs core-shell nanoparticles using *Psidium guajava* leaf extract and microwave irradiation for electrocatalytic Pb (II) sensing. These nanoparticles were integrated onto graphite electrodes, enhancing the sensor's sensitivity by 4.5–20.2 times compared to individual AgNPs and PtNPs. The sensor exhibited excellent selectivity for Pb (II) detection in complex water matrices with a low detection limit (0.8 nM), demonstrating the potential for environmental monitoring of heavy metal ions. Here, a noteworthy advancement is the development of a polyrutin/silver nanoparticle (AgNP) modified glassy carbon electrode (GCE) via a one-step electrodeposition/polymerisation [16].

3.2. Biomedical Applications. Silver nanoparticle

(AgNP) based materials have emerged as transformative solutions in biomedical applications, offering effective anti-bacterial properties and the ability to mitigate infections. Several commercially available products employ Ag NP technology for clinical purposes. For example, Acticoat, developed by Smith & Nephew, Inc. (London, UK), functions as a wound dressing that utilizes nanocrystalline silver to combat over 150 pathogens with broad-spectrum bactericidal efficacy. Similarly, PolyMem Silver by Ferris Mfg. Corp. (Texas, USA) features nanocrystalline silver particles embedded within the dressing, enhancing its antibacterial capabilities. In catheter systems, the Silverline Ventricular Drainage Catheter by Spiegelberg GmbH & Co. KG

(Hamburg, Germany) incorporates a specialized silver additive to prevent microbial colonisation on its surface. 1–5 Drug delivery devices, such as the ON-Q SilverSoaker catheter from Halyard Health, Inc.(Georgia, USA), utilize silver nanoparticle coatings to inhibit biofilm formation and reduce infection risks. Additionally, the Agento I.C. silver-coated endotracheal tube by C.R. Bard Inc. (New Jersey, USA) employs a hydrophilic polymer coating infused with silver particles, significantly lowering the incidence of ventilator-associated pneumonia. Collectively, these Ag NP-based innovations demonstrate their potential to enhance patient care and infection control in medical applications [17].

3.2.1 Antiviral Agents

Silver nanoparticles (AgNPs) have shown significant promise as antiviral agents due to their ability to interact with viral particles and inhibit their replication. The antiviral properties of AgNPs are attributed to their surface characteristics, which enable them to bind to viral membranes and disrupt the viral structure. Studies have shown that AgNPs can effectively neutralize a wide range of viruses, including influenza and herpes simplex virus, by damaging viral proteins and preventing entry into host cells. However, further research on the safe application of AgNPs in vivo is necessary. Figure 5 gives a schematic representation for AgNPs having antiviral actions. The AP/PP compost's demonstrate remarkable potential as Antiviral agents, with the ability to inactivate SARS-CoV-2 and other pathogens via contact-mediated oxidation. These Materials

leverage the generation of hydroxyl radicals ($\bullet\text{OH}$) and superoxide anions ($\bullet\text{O}_2^-$) to disrupt microbial membranes and viral structures [18].

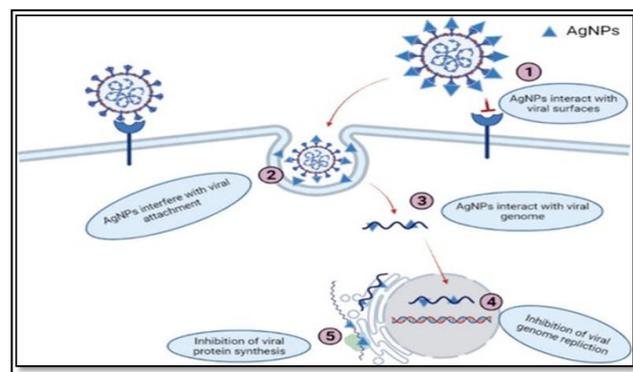


Fig 5. Possible mechanism for AgNPs as antiviral agents.

The bioactive compounds in these extracts, when incorporated into AgNPs, enhance antiviral efficacy through interactions with viral proteins, disrupting replication. Such bionanocomposites show great promise for future therapeutic strategies, though further research is required to assess their safety and efficacy in vivo. AgNPs interact with viral membranes, damaging them and preventing entry into host cells. While promising, challenges like toxicity, biocompatibility, and understanding their precise mechanisms of action need further investigation before clinical application. Advances in nano-medicine continue to highlight AgNPs as a promising tool in antiviral therapy. Silver nanoparticles (AgNPs) demonstrate promising antiviral activity, particularly against the influenza A virus, by inhibiting replication and preventing viral spread. Studies reveal that AgNPs exhibit minimal cytotoxicity at effective

concentrations, making them safe for potential therapeutic use. Coating AgNPs with natural resins further enhances their antiviral efficacy, positioning them as a viable postinfection virostatic agent. These findings highlight AgNPs' potential in combating viral infections with reduced side effects, offering an innovative approach to influenza treatment [19].

Nanoparticles are extensively being used as photosensitizers in various applications, particularly in photodynamic therapy (PDT), photovoltaics, and photocatalysis. They have the property of absorbing light and transferring the energy to generate reactive species like singlet oxygen, which are used in various chemical and biochemical processes. Silver nanoparticles have strong plasmonic properties and are often used in imaging and anti-bacterial applications. In a study by Malá et al., antimicrobial photodynamic inactivation (aPDI) using the photosensitizer TMPyP and silver nanoparticles (AgNPs) demonstrated a synergistic antibacterial effect against methicillin-resistant *Staphylococcus aureus* 4591 (MRSA) and extended-spectrum beta-lactamases-producing *Klebsiella pneumoniae* 2486 (ESBL-KP) [20]. In another study by Tabaika et al., silver nanoparticles (AgNPs) were used with red and blue LEDs utilizing its photodynamic effect to generate reactive oxygen species (ROS) to target *Candida albicans* biofilms. Blue light with AgNPs achieved 94.68% inactivation in 10 min due to high energy, while red light reached 90.98%.

3.2.2 Anticancer Agents

Venkatadari et al. highlight the potential of silver nanoparticles (AgNPs) synthesized using synergistic aqueous extracts of *Curcuma longa* and *Zingiber officinale* as promising anticancer agents. These AgNPs, characterized by various analytical techniques, demonstrated effective cytotoxicity against human colon carcinoma (HT-29) cells. The MTT assay confirmed their anticancer potential, with an IC₅₀ value of 150.8 µg/mL. The involvement of carboxyl and amine groups in AgNP synthesis underscores their functional role in nanoparticle formation. Similarly, the biosynthesized silver nanoparticles (AgNPs) from *Aspergillus terreus* exhibited significant anticancer activity, particularly in the MCF-7 breast cancer cell line. Their spherical shape, small size (~25 nm), and negative zeta potential contribute to their potential for targeted drug delivery, overcoming barriers in conventional therapies. The plasmonic properties of AgNPs offer prospects for theranostic applications, combining both cancer diagnosis and treatment [21]. However, further clinical trials and preclinical studies are essential to assess toxicity and optimize their pharmacological use in cancer therapy. The eco-friendly synthesis of nanoparticles, such as silver nanoparticles (dAgNps) derived from *Detarium microcarpum* leaves, has also shown significant promise in cancer treatment. The phytochemicals present in the plant, including polyphenols and flavonoids, contribute to the reduction of silver ions and enhance the nanoparticles' anticancer activity. dAgNps

demonstrated potent cytotoxic effects against pancreatic (PANC-1) and cervical (HeLa) cancer cells, with IC50 values of 84 $\mu\text{g}/\text{mL}$ and 31.5 $\mu\text{g}/\text{mL}$, respectively, highlighting their potential as candidates for cancer therapy.¹⁹¹ Silver nano-particles (AgNPs) synthesized from *Fagonia indica* exhibit significant anticancer properties, making them a promising candidate for future cancer therapies [22].

The biosynthesized AgNPs, characterized by a size range of 10–60 nm, display concentration-dependent cytotoxicity against MCF-7 cells, as demonstrated by MTT assay (IC50 of 12.35 $\mu\text{g}/\text{mL}$). AgNPs induce apoptosis through activation of caspases, nuclear condensation, and increased membrane permeability. Additionally, AgNPs generate reactive oxygen species, modulating oxidative stress, and further enhancing their anticancer potential. Ikram et al., work highlights the potential of *Fagonia indica*-mediated AgNPs in cancer treatment development.¹⁹² Similarly, biologically synthesized silver nanoparticles (AgNPs) have shown great potential as anti-cancer agents. The green synthesis using *Rhizopus stolonifer* provides a cost-effective, environmentally friendly alternative to traditional methods. These nanoparticles, characterized by UV-visible absorption at 422 nm and sizes ranging from 5 to 50 nm, exhibit significant anticancer efficacy against HT-29 (colon cancer) and EAC cells. The findings underscore their potential for future cancer therapy and drug delivery applications, highlighting the importance of green chemistry in biomedical research

[23]. Silver nanoparticles (AgNPs) have gained significant attention as potential anticancer agents due to their cytotoxic effects on cancer cells. In Sabah's work, AgNPs synthesized via pulsed laser ablation exhibited a cytotoxic effect on cancer cells at a concentration of 80 $\mu\text{g}/\text{mL}$, as demonstrated by the MTT assay. These nano-particles show promise as effective agents in cancer therapy, offering selective toxicity toward cancer cells while minimizing damage to healthy cells, such as red blood cells. One study investigates the uptake mechanisms and toxicological effects of silver nanoparticles (Ag-NPs) on cells. Ag-NPs are primarily internalized via endocytosis, involving clathrin-mediated processes and macropinocytosis. Exocytosis, a key process for expelling nanoparticles, was slow and time-dependent, suggesting long-term retention within cells and potential chronic toxicity. The upregulation of metallothioneins (MT) and heme oxygenase-1 (HO-1) indicates oxidative stress response. Ag-NPs, accumulating in the nucleus, may cause genotoxicity, DNA damage, and chromosomal aberrations. Additionally, Ag-NP exposure disrupts calcium homeostasis, leading to mitochondrial dysfunction, ATP depletion, and apoptosis. Cytoskeletal injury, linked to calcium fluctuations, inhibits cell division, further contributing to the toxic effects of Ag-NPs.

3.2.3. Antibacterial Agents

The green synthesis of silver nanoparticles (AgNPs) is also gaining attention for its sustainability and effectiveness as an antibacterial agent. Plant-based synthesis

methods offer a safer, eco-friendly alternative to traditional chemical approaches, utilizing plant extracts to enhance biocompatibility and reduce toxicity.

Agnihotri et al. Synthesized silver nanoparticles (AgNPs) in sizes ranging from 5 to 100 nm and found that AgNPs smaller than 10 nm demonstrated superior antibacterial activity against *E. coli* compared to larger nanoparticles.

3.2.4. As Antifungal Agents

To further enhance the biomedical potential of silver oxide nanoparticles, exploring their antifungal activity is crucial, as fungal infections contribute significantly to global morbidity and mortality. While the current study reports the antibacterial properties of silver-chitosan nanocomposites, future investigations could focus on assessing their antifungal efficacy, especially against resistant fungal strains, by modifying nanoparticle size, surface charge, or biopolymer interactions. This could pave the way for broader therapeutic applications in treating fungal infections, alongside bacterial ones.

4. Conclusions

Silver nanoparticles (NPs) have gained immense popularity due to their unique physical, chemical, and biological properties, influenced by size, shape, and synthesis methods. Their small size and large surface area enhance antimicrobial activity, optical properties, and electrical conductivity, making them ideal for diverse applications like bioimaging, wound healing, drug delivery, and sensor technologies. Smaller silver NPs show increased cellular accumulation and bactericidal efficacy, while larger particles are preferred in specific

applications, such as wound healing, to control tissue penetration. Surface charge and functionalization play critical roles in enhancing cellular interactions and targeting, enabling applications in drug delivery and imaging. Modified surfaces improve bioavailability, specificity, and system stability while mitigating aggregation risks. These characteristics make silver NPs highly versatile and suitable for use in diagnostics, therapeutic delivery, and biosensing. Localised surface plasmon resonance (LSPR) further augments their efficacy in imaging and sensing applications. Synthesis methods significantly influence the properties and applications of silver NPs. While chemical and physical methods offer scalability, they often involve high energy consumption and complex purification. In contrast, biological approaches, especially green synthesis using plant extracts, provide eco-friendly, cost-effective, and biocompatible alternatives. These methods are highlighted for their ability to produce bioactive NPs efficiently. However, optimization is required to enhance scalability and industrial applicability. Toxicity concerns remain a critical challenge, given the widespread potential applications in food packaging, medicine, and dental fields. Research emphasizes the need for standardized toxicity evaluation methods and area-specific standards. Green synthesis methods are particularly valuable for reducing toxicity risks. Given the increasing threat of antimicrobial resistance, silver NPs are emerging as potential alternatives to conventional antimicrobials, with promising applications in disinfection and wound care

products. Continued research is essential to optimize their synthesis, minimize toxicity, and unlock their full potential across industries.

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References

- [1] Natsuki, J.; Natsuki, T.; Hashimoto, Y. A Review of Silver Nanoparticles: Synthesis Methods, Properties and Applications. *International Journal of Materials Science and Applications* 2015, 4,325–332.
- [2] Natsuki, J.; Hashimoto, Y. A Review of Silver Nanoparticles: Synthesis Methods, Properties and Applications. *International Journal of Materials Science and Applications* 2022, 4, 325–332.
- [3] Vu, K. B.; Phung, T. K.; Tran, T. T. T.; Mugemana, C.; Giang,H. N.; Nhi, T. L. P. Polystyrene Nanoparticles Prepared by Nanoprecipitation: A Recyclable Template for Fabricating Hollow Silica. *Journal of Industrial and Engineering Chemistry* 2021, 97, 307–315.
- [4] Rajapaksha, P.; Orrell-Trigg, R.; Shah, D.; Cheeseman, S.; Vu, K.B.; Ngo, S. T.; Murdoch, B. J.; Choudhury, N. R.; Yin, H.; Cozzolino,D.; et al. Broad Spectrum Antibacterial Zinc Oxide-Reduced Graphene Oxide Nanocomposite for Water Depollution. *Mater.Today Chem.* 2023, 27, 101242.
- [5] Doan, L.; Nguyen, L. T.; Nguyen, N. T. N. Modifying Superparamagnetic Iron Oxides Nanoparticles for Doxo-rubicin Delivery Carriers: A Review. *J. Nanopart. Res.* 2023, 25, 73.
- [6] Natsuki, J.; Natsuki, T.; Hashimoto, Y. A Review of Silver Nanoparticles: Synthesis Methods, Properties and Applications. *International Journal of Materials Science and Applications* 2015, 4,325–332.
- [7] Habouti, S.; Solterbeck, C.-H.; Es-Souni, M. Synthesis of Silver Nano-Fir-Twigs and Application to Single Molecules Detection. *J.Mater. Chem.* 2010, 20, 5215–5219.
- [8] Hu, X.; Chan, C. T. Photonic Crystals with Silver Nanowires as aNear-Infrared Superlens. *Appl. Phys. Lett.* 2004, 85, 1520–1522.
- [9] Alshehri, A. H.; Jakubowska, M.; Młozniak, A.; Horaczek, M.; Rudka, D.; Free, C.; Carey, J. D. Enhanced Electrical Conductivity of Silver Nanoparticles for High Frequency Electronic Applications. *ACS Appl. Mater. Interfaces* 2012, 4, 7007–7010.
- [10] Chen, G.; Lu, J.; Lam, C.; Yu, Y. A Novel Green Synthesis Approach for Polymer Nanocomposites Decorated with Silver Nanoparticles and Their Antibacterial Activity. *Analyst* 2014, 139, 5793–5799.
- [11] Natsuki, J.; Natsuki, T.; Hashimoto, Y. A Review of Silver Nanoparticles: Synthesis Methods, Properties

- and Applications. International Journal of Materials Science and Applications 2015, 4,325–332.
- [12] Abou El-Nour, K. M. M.; Eftaiha, A.; Al-Warthan, A.; Ammar, R. A. A. Synthesis and Applications of Silver Na-noparticles. Arabian Journal of Chemistry 2010, 3, 135–140.
- [13] Lee, H.-H.; Chou, K.-S.; Huang, K.-C. Inkjet Printing of Nanosized Silver Colloids. Nanotechnology 2005, 16, 2436.
- [14] Yaqoob, A. A.; Umar, K.; Ibrahim, M. N. M. Silver Na-noparticles: Various Methods of Synthesis, Size Affecting Factors and Their Potential Applications-a Review. Appl. Nanosci 2020, 10,1369–1378.
- [15] Zielinska, A.; Skwarek, E.; Zaleska, A.; Gazda, M.; Hupka, J. Preparation of Silver Nanoparticles with Controlled Particle Size. Procedia Chem. 2009, 1, 1560–1566.
- [16] Toisawa, K.; Hayashi, Y.; Takizawa, H. Synthesis of Highly Concentrated Ag Nanoparticles in a Heterogeneous Solid-Liquid System under Ultrasonic Irradiation. Mater. Trans 2010, 51, 1764–1768.
- [17] Natsuki, J.; Natsuki, T.; Hashimoto, Y. A Review of Silver Nanoparticles: Synthesis Methods, Properties and Applications. International Journal of Materials Science and Applications 2015, 4,325–332.
- [18] Gates, B. C. Supported Metal Clusters: Synthesis, Structure, and Catalysis. Chem. Rev. 1995, 95, 511–522.
- [19] Lee, H.-H.; Chou, K.-S.; Huang, K.-C. Inkjet Printing of Nanosized Silver Colloids. Nanotechnology 2005, 16, 2436.
- [20] Gates, B. C. Supported Metal Clusters: Synthesis, Structure, and Catalysis. Chem. Rev. 1995, 95, 511–522.
- [21] Medici, S.; Peana, M.; Nurchi, V. M.; Zoroddu, M. A. Medical Uses of Silver: History, Myths, and Scientific Evidence. J. Med. Chem. 2019, 62, 5923–5943.
- [22] Xu, L.; Wang, Y. Y.; Huang, J.; Chen, C. Y.; Wang, Z. X.; Xie, H. Silver Nanoparticles: Synthesis, Medical Applications and Biosafety. Theranostics 2020, 10, 8996–9031.
- [23] Bouafia, A.; Laouini, S. E.; Ahmed, A. S. A.; Soldatov, A. V.; Algarni, H.; Chong, K. F.; Ali, G. A. M. The Recent Progress on Silver Nanoparticles: Synthesis and Electronic Applications. Nanomaterials 2021, 11, 2318.