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Physical, Chemical, And Therapeutic Applications of Silver Nanoparticles: A Review

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Abstract

Since their physical, chemical and therapeutic properties of noble nanometal deviate markedly from those at bulk scale, silver nanoparticles (AgNPs) have become promising nano-substances. At the nanoscale, silver displays high surface reactivity, strongly plasmonic properties and modulable bio-, electro- and optical properties, thereby finding several applications in biomedicine and technology. The physical properties of AgNPs are reviewed in a well-documented science encompassing size- and shape-controlled effects, crystallinity, as surface plasmon resonance (SPR) and thermal and electrical conductivity. Moreover, the chemical properties of AgNPs (ion release, redox activity, surface chemistry, and catalytic activity) and mechanisms linked to the generation of ROS are thoroughly addressed. Special attention is given to the therapeutic uses of AgNPs, such as antimicrobial, antiviral action and wound-healing activity especially those related to cancer treatment and drug-delivery. Issues concerning the toxicity, biocompatibility, environmental impact and clinical transfer to human are also discussed. Accordingly, this review focuses on the recent progression of AgNP studies and summarizes prospective for



designing safe, effective, and clinically viable silver nanoparticle-related therapeutic systems.

Keywords: Surface Plasmon Resonance, Silver Nanoparticles

Introduction

Over the past decade, silver nanoparticles (AgNPs) have gained prominence as one of the most flexible and highly investigated sets of nanomaterials because of their remarkable physicochemical properties and wide range of medical applications. Objectives and potential uses due to their unique properties Silver nanoparticles (AgNPs) are defined as particles made of silver at least in one dimension less than 100 nm, displaying physical and chemical characteristics considerably different from those of the bulk counterpart: high surface-to-volume ratio, increased reactivity and characteristic optical effects such as surface plasmon resonance that explain some of its applications. The unique properties of these classes, on the other hand, have accelerated their utilization in antimicrobial coatings to current drug delivery systems (Bruna et al., 2021; Sati et al., 2025).

The increasing attention AgNPs have been receiving from scientists comes in part from its unique physicochemical properties. With nanoscale sizes these particles have high surface-to-volume ratio that make it possible for strong interaction with biomolecules, improved catalytic activity and remarkable optical effects which are used in diagnostics and imaging (ACS Omega, 2028; MDPI Nanomaterials (Sati et al., 2025). For instance, localized surface plasmon resonance or LSPR. The phenomenon of the conduction electrons on the nanoparticle being driven by incident light to oscillate as a result resulting in fluctuations in local temperature and electric field. is responsible for their (appended) high performance in biosensing and bioimaging application while attracting prospectus link between material science with biomedical diagnostic. The size, shape and surface functionalization can be controlled by different synthesis methods such as physical, chemical or green (biological) approaches which increase the flexibility in the functionality of AgNPs according to a given application. (Unser et al., 2015).

In the group of physical and chemical synthesis, techniques like evaporation-condensation, laser ablation, chemical reduction and polyol methods persist as a basis. Although physical methods can produce nanoparticles of a relatively narrow size distribution, they tend to require more energy and costly apparatus. Chemical CuAAC can be more scaleable but often

requires toxic reagents or stringent cleaning steps to render the conjugate biocompatible. Recently, alternative greener methods using plant extracts as reductants have been developed because of their lower environmental footprint and reduced cellular toxicity. These versatile synthesis approaches are essential to determine the physicochemical properties of the nanostructures as well as their toxicological behavior and biological functionality (Sati et al., 2025).

The promising usage of AgNPs for therapeutic purposes is an area of current interest. Throughout history, silver has been highly regarded for its antibiotic properties and disinfectant power, beginning with the ancient Greeks and Romans who stored liquids in silver coated vessels to ensure purity. At the nano level, these antimicrobial properties are amplified and could be due to the fact that AgNPs can contact with microorganisms' membranes directly and produce ROS or release silver ions, causing damage on targets cell essential processes in pathogens (Bruna et al., 2021; Frontiers Pharmacol, 2024). These effects are responsible for their efficacy as antibacterial, antifungal and antiviral agents, making AgNPs ideal candidates in the fight against antibiotic-resistant infections – an increasingly urgent facet of present-day medicine (Bruna et al., 2021; Jangid et al., 2024).

Apart from their use as antimicrobial agents AgNPs received attention in anticancer and other therapeutic applications. Various investigations have been conducted to determine their ability to induce cytotoxic effects on tumor cells based on oxidative stress and apoptosis under certain doses, thus proposing AgNPs as a targeted therapy of cancer, alone or in combination with other therapies to achieve therapeutic improvements (Sati et al., 2025). Furthermore, the application of AgNPs in wound healing is under investigation where they might be able to manage infection and inflammation states; as a result enhance tissue regeneration (Frontiers in Pharmacology, 2024). The incorporation of them in dental materials and medical-device coatings illustrates the broadening application of AgNPs in clinical therapeutics (Maruri-Casas et al., 2025).

The exponential emergence of work on AgNPs is an affirmation not only to their potential applications, but also to current hurdles encountered, more especially in safety and environmental perspectives. Although numerous research papers highlight its attractive biological activity, the cytotoxicity, biodistribution and chronic side effects need to be systemically investigated. Results indicate that particle size, surface functionalization and dosage determine the uptake in cells and systemic response which require standardized assessment schemes to ensure safe translation from laboratory into medical applications (Sati et al., 2025). In addition, the regulatory environment for nanomaterial-based



therapeutics is changing as they are becoming more widely used; therefore, thorough toxicological and ecotoxicological analysis of these compounds should be included in any risk assessment (Eker et al., 2024).

Herein, we describe physical and chemical methods for the synthesis of silver NPs and summarize their basic physicochemical properties together with an analysis on therapeutic uses in present-day biomedical disciplines. By building on recent progress, especially exploiting developments after 2015, we place the current state-of-the-art AgNP technologies into perspective; discuss active fields of innovation; and consider remaining hurdles along with emerging research opportunities.

Physical properties of silver nanoparticles

Silver nanoparticles (AgNPs) have a physical behaviour which is unique, in comparison to those exhibited by bulk silver, and form the basis for their widespread applications in chemistry, technology, and biomedicine. These properties are highly size-dependent, nanostructure-, surface- and atomic morphology-specific and they all affect the optical behavior of the catalysts, their stability low and their interaction with the surrounding environment (Bruna et al., 2021; Sati et al., 2025).

Particle size, usually within the range of 1–100 nm, is one of the most important physical properties of AgNPs. At such a size scale, the quantum size effects become pronounced and electronic structure and surface energy are changed from bulk materials. Particle size reduction results in a huge amount of surface area generated (surface/volume ratio), which contributes to the increase of reactivity surface and aggregation behaviors (Khan et al., 2019). Size is also a crucial determinant of optical absorption, catalytic activity, and biological performance of nanoparticles, which makes it an important characteristic in the design of application-specific NPs. State-of-the-art methods to determine size distribution and polydispersity, which are crucial for reproducibility and functionality, include transmission electron microscopy (TEM) and dynamic light scattering (DLS), respectively; see also ref 1 (Abbas et al., 2024).

The shape, or morphology of silver nanoparticles closely related to size includes spheres, rods, triangles and cubes of structures. Shape has a strong influence on the physical and optical properties, most notably SPR. For example, triangular or rod-shaped AgNPs frequently show several SPR peaks and enhanced electromagnetic field confinement relative to that of spherical particles (Bruna et al., 2021). The shape of AuNPs is highly

appealing for use in sensing, imaging and photothermal therapy. Synthesis parameters such as type of reducing agents, stabilizers, temperature and the time of reaction play a key role in morphology (Sati et al., 2025).

An intriguing physical property of AgNPs is the localized surface plasmon resonance (LSPR). The LSPR results from its collective oscillation of conduction electrons on the nanoparticle surface under incident light irradiation. This phenomenon induces a strong absorption band in the visible region that for spherical AgNPs is commonly situated between 400 and 450 nm, but it depends on the size of the particles, their shape, and also on the dielectric medium (Eker et al., 2024). They have high optical absorption and scattering due to their LSPR, which can be used for various applications such as imaging agents, diagnostic tools and optical biosensors. Such an SPR peak for the induced changes in environment or aggregation of nanoparticles gives a shift that can detect sensitive biomolecular interactions (Loiseau et al., 2019).

One other important physical property of the silver nanoparticles is crystalline shapes. Most AgNPs have FCC lattices in common with bulk silver. XRD pattern of the sample portrays typical crystalline nature and gives sharp & diffraction peaks at (111), (200), (220) and yield (311) planes of FCC structure which confirmed that the prepared 2.2 XRD analysis have also been supported for FCC structure. Crystallinity affects mechanical integrity, thermal behavior and electron transport properties that are beneficial for both catalytic and electronic applications. Greater crystallinities are usually related to enhanced stability and are responsible for better optical performance as well (Khan et al., 2019).

AgNPs is characterized by the surface becomes larger than that of bulk state, leading to specific physical features. High surface energy is good for the strong interaction between encapsulated particle and molecules/solvents/biopolymer. This is a vital issue for the adsorption performance and catalytic activities of NP, while it may cause NPs to be aggregated when they are not well stabilized. In order to redress this issue, surface coatings and capping agents are often employed to modulate the interface charge and steric effects for achieving colloidal stability and at the same time without disturbing native physical attributes (Bruna et al., 2021).

Thermal and electrical conductivities are other important physical properties. Bulk silver is well known for its high conductivity; however, nanoscale silver shows size-dependent features owing to enhanced electron scattering at the grain boundaries and surfaces. Such an effect is favored for AgNPs,



although they maintain relatively high conductivity and can be employed in a range of applications, such as printed electronics, conductive ink, flexible electronic devices. The thermal stability, while compromised to a certain extent on the nanoscale, is still sufficient for many industrial and biomedical applications when suitably synthesized nanoparticles are stabilized (Sati et al., 2025).

In short, the physical properties of silver nanoparticles such as size, shape, optical properties (transparency), crystallinity, surface area and conduction are all intimately connected to one another and highly variable. All these attributes ultimately contribute to the functional behaviour of AgNPs for various applications. A deep knowledge of such physical properties is therefore required for rational nanoparticle design and to exploit their functionality in therapeutic, diagnostic and technological applications.

Chemical Properties of Silver Nanoparticles

The physicochemical properties of AgNPs are important, as they strongly determine the reactivity, stability and bioavailability or toxicity of AgNPs and thus influence potential therapeutic and industrial applications. In contrast to bulk silver, the AgNPs show improved chemical activity owing to their nanometre size, higher surface energy and rich active sites. These properties control crucial phenomena, e.g., ion liberation, redox activity, surface functionalization and biological and environmental matrix interactions (Marambio-Jones & Hoek, 2010; Raza et al., 2016).

One of the most significant material characteristics of AgNPs is their capacity to release silver ions (Ag^+). Ion release is considered as one of the main reasons responsible for the biological action (antimicrobial, therapeutic) of AgNPs. It is well known that rate and extent of Ag^+ release depends on several parameters such as particle size, surface capping, pH, temperature and the presence of oxidizing compound. Even smaller particles may have higher ion dissolution at more rapid rates since they possess a larger surface area to volume ratio, with an increased number of silver atoms contributing to the oxidatively exposed state. This controlled ion-release distinguishes AgNPs from coarse silver salt powders and further enables maintaining biocidal efficacy during extended contacts (Ivask et al., 2014).

Another feature of chemical property is the redox behavior of Ag NP. Upon exposure to oxygen compounds or aqueous phase, the AgNPs are rapidly oxidized on their surface leading to formation of a layer of silver oxide that could control reactivity and stability

résultats. This oxidation can have the potential to generate electron transfer Rxns and ROS formation including super oxide radicals (O_2^-) and hydrogen peroxide as observed in hypermetabolism which is a physiological situation. Such redox reactions epitomize the antimicrobial and anticancer activities of AgNPs, although they also lead to oxidative stress as well as toxicity on host tissues (Raza et al., 2016).

It has been suggested that surface chemistry and functionalization are influent factors in dictating AgNPs chemical features. Because of high surface energy, colloidal AgNPs tend to agglomerate without capping agents or modifying agents. (eg Polymers (Polyvinyl pyrrolidone), surfactants, thiol compounds and as stabilizers biomolecules e.g. proteins or polysaccharides. This surface coating not only imparts colloidal stability, but also tunes chemical reactivity and solubility/biological interactions. Moreover, surface functionalization with targeting ligands or bioactive entities provides exquisite chemical control over AgNPs for their drug delivery, diagnostics and site-specific therapeutics (Sharma et al., 2014).

Another important issue is related to the interaction of AgNPs with biomolecules. AgNPs are able to complex with proteins, nucleic acids, and lipids mainly through electrostatic interaction, hydrogen bonding and silver atoms' coordination bonding with the functional groups containing nitrogen or sulfur. These interactions often generate what are termed as "protein corona" when nanoparticles encounter the biological fluid. The corona composition is significantly altering the chemical nature of AgNPs which consequently affect their cellular uptake, in vivo biodistribution and toxicity. Such interactions are critical in predicting the in vivo biocompatibility and/or hazardousness of nanoparticles (Ivask et al., 2014).

Apart from that, AgNPs are also efficient and excellent chemical catalysts for redox- as well as electron-transfer reactions. They are good catalytic materials with effective surface states, which can support chemical reactions, for example decomposition of organic dyes and other pollutants in environment. This catalytic activity causes the antimicrobial effect through ROS generation and cellular redox homeostasis disruption, indirectly in biomedical environments. Nevertheless, unregulated catalysts of oxidative damage can bring overcatalyzation (Sharma et al., 2014), indicating that conditioned surface chemistry is crucial.

Stability is another major concern. In potentially more interferent-rich conditions (e.g., biological fluids or wastewaters), AgNPs are also likely to agglomerate, possibly sulfide and chlorinate. Sulfur containing ligands can be coalesced with AgNPs and generate silver sulfide, which itself reduces ion



release as well as its biological effects. Like bicarbonate, chloride ions are also able to influence NP dissolution and surface charge. These chemical changes demonstrate the dynamic nature of AgNPs and stress the need to carry out a thorough chemical analysis in real applications (Marambio-Jones & Hoek, 2010).

Overall, the chemical properties of AgNPs including ion release, redox activity, surface modification/reaction with biomacromolecules, catalytic performance and stability are critical to these NPs functions. These properties are closely interrelated and respond sensitively to various environmental influences, therefore the chemical manipulation of AgNPs is critical for its successful and safe use. Because a good understanding of AgNP chemistry is therefore essential for optimization for therapeutic effect and minimization of undesirable systemic effects.

Therapeutic properties of silver nanoparticles

Silver nanoparticles (AgNPs) have attracted great attention in biomedicine because of their broad-spectrum therapeutic potential derived from physicochemical reactivity, small size and biological compatibility. AgNPs have superior therapeutics as compared to conventional silver salts through controlled ion release, increased surface contact and multifunctional action modes. This characteristic has led them to be regarded as possible in the antimicrobial therapy, wound healing, cancer treatment or anti-inflammatory (Durán et al., 2016).

The antibacterial activity of AgNPs is the most extensively reported therapeutic role. AgNPs are potent bactericidal agents and have demonstrated broad spectrum activity against gram-positive and -negative bacteria, even including multi-drug resistant microbes. It is reported that the bactericidal and/or fungicidal action of essential oils derives from different mechanisms, such as disruption of microbial cell wall or membranes, ROS (reactive oxygen species) production, inhibition of thiol containing enzymes and DNA synthesis (Yin et al., 2020). The mechanisms of action are multiple, which lowers the likelihood of microbial resistance developing, then AgNPs may be a promising alternative or complement to conventional antibiotics. In addition, AgNPs also possess the antifungal and anti-viral activities and therefore their therapeutic potential is extended (Galdiero et al., 2011). Wound healing and repair of tissue is a second important therapeutic application for AgNPs. Silver nanoparticles (AgNP) based dressing is one of the most commonly utilized in clinics for its dual activities, preventing

infection and healing tissue. AgNPs are also able to control inflammatory response, diminish the microbial burden and increase keratinocyte and fibroblast migration, promoting the closure of wound (Balaure et al., 2025). Their application to hydrogels, nanofibers, and polymeric scaffolds has greatly enhanced the effectiveness of wound care treatment, especially in chronic wounds and burn injuries where infection management is key (Wei et al., 2015).

AgNPs were also shown to possess strong anti-cancer activity. Many in vitro and in vivo studies have shown that AgNPs may cause selective cytotoxicity toward cancer cells, whereas normal cells might be less in need of toxic levels exposure. Its major anticancer action involves increasing of oxidative stress, disrupted mitochondrial function and DNA damage, with a consequent activation of the apoptotic pathways. AgNPs are likely to potentiate the effectiveness of chemotherapeutic drugs when used in combination therapy, indicating their potential application as sensitizers or delivery enhancers in oncology (Gurunathan et al., 2018).

Another potential therapeutic attribute related with the application of AgNPs is their anti-inflammatory and immunomodulatory effect. When used at suitable concentrations, ANPs can also suppress the overreaction of immune system through reducing pro-inflammatory cytokines and controlling inflammatory cells attacking. This feature proves to be especially advantageous in the skin repairing process as well as inflammatory dermatoses. But the immunological impacts of AgNPs are dose and size dependent, thus accurate monitoring of its therapeutic dosage is important to prevent improper activation or suppression on immune system (Singh et al., 2022).

AgNPs could also be potential drug delivery and therapeutic carrier systems. Due to their high surface area, they can be conjugated with drugs, biomolecules and targeting ligands effectively for site-directed delivery or controlled release. Surface-modified AgNPs have been studied to be applicable for antimicrobial agents, anticancer drugs and bioactive compounds in order to increase the efficiency of therapy with lower systemic toxicity. Moreover, their direct antimicrobial activity makes them possessing dual therapeutic function upon being used as delivery platforms (Wei et al., 2015).

Biocompatibility and safety of AgNPs are still challenges in spite to their therapeutic advantages. The effectiveness is strongly related to particle size, surface treatment, dose and exposure time. AgNPs can be tolerated at low levels, but they will cause cytotoxicity, oxidative stress and organ related toxic in saturation level. Therefore, stringent safety and in vivo investigation are



required for their clinical translation (Yin et al., 2020). Silver NPs have been widely investigated for a variety of therapeutic applications other than cancer treatment (such as antimicrobial, wound healing, anticancer, anti-inflammatory and drug delivery). Due to the small size and tunable properties, such systems are good candidates as useful platforms in contemporary medicine. However, the therapeutic and safety compromise remains an issue to be resolved and further study is indicated on modified preparations for clinical trials.

Conclusion

The insatiable curiosity of researchers looking for handmade silver particles (Ag-NPs); the unique physical, chemical, and therapeutic properties are exerting a large impact on whole fields such as clinical medicine to public health and public sanitation. The ability to tune all of these parameters--size, shape, and surface chemistries--gives these nanoscaled materials novel optical properties, controlled reactivities, and optimized biological interactions. In terms of therapeutics, AgNPs were strongly anti-bacterial, wound healers, and cancer fighters. They also served as a small delivery vehicle for drugs; they were dynamite addressing the most difficult problems of antimicrobials resistance, tissue engineering and so on. It costs money to treat these more serious health problems. There are already many potentials uses for silver nano-materials, but even then, there are potentials for toxicity, and the long-term environmental effects remain uncertain. Because it will be used in several different forms requires standardized synthesis procedures, an integrated safety assessment of these compounds, and research aimed at translating those findings into clinical tools for use in humans. In conclusion, AgNPs present a huge potential as multitasking agents for latest bio-medical and technological applications.

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