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Modern Approaches to Silver Nanoparticle Synthesis and Their Functional Roles

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Abstract

Silver nanoparticles (AgNPs) have quickly become one of the most widely studied nanomaterials because of their unique physicochemical properties and the vast application space they occupy. In this review paper, we present a comprehensive literature assessment of current synthesis methods for AgNPs, particularly how differing material precursors influence nanoparticle properties and functional performance. Traditional synthesis approaches (chemical and physical) are specific and provide excellent control over size and shape, but are subject to environmental and human health concerns while (green) synthesis approaches using extracts from plants, as well as microorganisms and enzymes, are more sustainable and biocompatible but have issues around reproducibility.

We highlight the role of material precursors (especially plant-based systems) on producing stable AgNPs with bioactive surface coatings, and assess functional applications - in four broad areas being antibacterial, antioxidant, biomedical, and environmental. We discuss the mechanism of activity for AgNPs, including membrane disruption, generation of reactive oxygen species (ROS), and catalytic degradation of environmental pollutants. While the functional advantages of AgNPs are clear, we note concerns around AgNP toxicity (in particular related to bioaccumulation and persistence in ecosystems).

To manage these risks, the review emphasizes the necessity of safe-by-design strategies, surface functionalization strategies, and strong regulatory frameworks. Ultimately, AgNPs will advance if safety and sustainability are balanced with innovation. The review helps advance these efforts by bringing together contemporary studies and considering future pathways of research and applications.

Keywords: Silver nanoparticles, green synthesis, Chemical reduction, Antibacterial activity, Nanotoxicology, Biomedical applications, Plant-based precursors, Nanotechnology

1. Introduction

Silver nanoparticles (AgNPs) have gained considerable interest globally in recent years based on their unique physicochemical properties and many uses. Their nanoscale, large surface to volume ratio, and biological system interactions facilitate their presence in biomedical, environmental, food, and material science (Raza *et al.*, 2024) [13]. As such, there has been a flare of research and application in the accomplishment of different methods to synthesize AgNPs and control the particle size, shape, dispersity, and surface chemistry-all of which influence their reactivity and bioactivity (Kumar *et al.*, 2023) [28].

Although there are physical and chemical methods of synthesis, they are often associated with toxicity issues, hazardous waste, and limited scalability. The use of greener approaches to the synthesis of AgNPs, relying primarily on plant extracts, microbial cultures, and biopolymers as harmless and sustainable reduce and stabilizing agents, is becoming more common (Shahzadi *et al.*, 2023) [53]. Green synthesis approaches are gaining acceptance and are especially valuable when used in areas of health engineering and environmental remediation.

However, AgNPs have been associated with cytotoxicity, oxidative stress, and environmental ecotoxicity, despite their potential. Bioaccumulation in critical organs and detrimental impacts on environmental organisms expected an evolution towards comprehensive toxicological studies (Zehra and Khan, 2020) [29]. With research on AgNPs growing,

advancements in synthesis that are safe, standardized, and in reasonable-scale production with minimal environmental impact, could not be timelier (Fatima and Ahmad, 2023) [19].
The review aims to discuss the current synthesis methods, with an emphasis on green and hybrid methods. Furthermore, it aims to objectively evaluates the functional roles of AgNPs in antibacterial, antioxidant, biomedical, and environmental applications, of Advances development in toxicity studies and regulatory thoughts for responsible development of silver nanoparticles.

2. Modern Synthesis Strategies of Silver Nanoparticles

The synthesis method used for silver nanoparticles (AgNPs) has a significant impact on their size, shape, dispersion stability, and surface characteristics that all affect their activities in many applications, including drug delivery, antimicrobial efficacy, catalysis, and environmental remediation (Khan *et al*., 2023) [28]. As the demand for biocompatible and sustainable nanomaterials rises, researchers are transitioning away from traditional chemical syntheses to environmentally benign green synthesis approaches (Yousef *et al*., 2022) [31]. At the same time, although each synthesis method (chemical, physical, and biological) has a distinct set of advantages and disadvantages that are determined by its application and intended particle properties, these methods can be equally beneficial in producing AgNPs with useful characteristics.

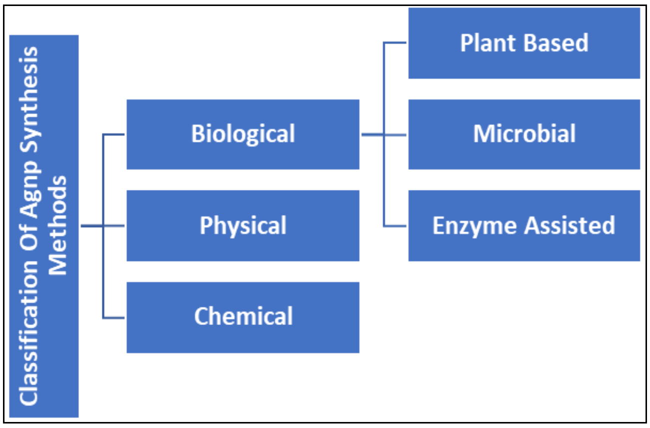

Fig 1: Classification of silver nanoparticle (AgNP) synthesis methods. Diagram created by the author, adapted from the classification framework described by Kumar *et al*. (2020) [30].

2.1 Chemical Synthesis

Chemical synthesis remains the most developed route for the production of AgNPs as they can be produced on large scale and afford the most ability to control particle morphology. In these methods, silver ions (Ag^+) derived from a source, commonly silver nitrate ($AgNO_3$), can be reduced and produced as metallic silver (Ag^0) using reducing agents (e.g., sodium borohydride ($NaBH_4$), hydrazine, or ascorbic acid) (Rahman *et al*., 2021) [46]. In a redox reaction, the reductant donates electrons to silver ions and subsequently nucleation (formation of a new particle) and growth (incremental addition of atoms to existing particles) steps occur in which atoms aggregate into a nanostructure (Vijayakumar *et al*., 2020) [33].
A pivotal characteristic of these reactions is the need for capping/stabilization agents (e.g., polyvinylpyrrolidone (PVP), citrate, polyethylene glycol (PEG), dextran) wherein the capping agents positively adsorb at the surface of the nanostructures so that additional aggregation is inhibited and an electrostatic or steric stabilizing action can occur (Alharbi *et al*., 2022) [6]. Furthermore, the reduction reaction also depends on the pH and temperature of the media, and both have a significant effect on rates of the reduction and uniformity of the final particles. For narrow size distributions, alkaline pH and moderate heating (60–90 °C) is preferred (Das *et al*., 2019) [15].
Chemical synthesis provides excellent control of parameters such as shape (spherical, cubic, triangular) and size, normally in the range of 5–50 nm, which is advantageous for precision-based applications, including biosensing and conductive materials (Jain *et al*., 2022) [24]. However, chemical synthesis procedures often involve toxic chemicals and toxic by-products that can be hazardous to human health and the environment, particularly in biomedical and food-contact settings (Singh *et al*., 2023) [60].
Research continues to endeavor more optimal chemical synthesis protocols using less toxic; or bio-based chemicals, chemical–biological hybrid methods, and microfluidic platforms to reduce reagent usage and improve reproducibility (Kandiah *et al*., 2023) [27].

2.2 Physical Methods

Physical synthesis methods are techniques that require energy from external electrical and/or electromagnetic sources (e.g. laser ablation, UV irradiation, evaporation-condensation, microwave heating, and arc discharge) to produce silver nanoparticles (AgNPs). These processes do not need any chemicals for reducing and surfactant chemistries. Therefore, these methods may provide cleaner synthesis pathways with lower contamination (Singh *et al*., 2023) [60]. Physical methods can be energy-consuming, but they are useful in applications that require high purity, reproducibility, and precise control over morphology of the particles.
Laser ablation is one of the most widely used physical methods. Laser ablation is when a high energy laser is beamed onto a solid target made of silver placed below the surface of a liquid. The ablation and condensation of the material creates nanoparticles (Luo *et al*., 2022) [34]. The size and distribution of AgNPs can be adjusted by controlling laser pulse duration, wavelength, and energy, as well as the choice of liquid medium (Kalita *et al*., 2020) [26].
Another widely Synthesis notable method is that of UV irradiation. In UV irradiation, a solution of silver ions is irradiated by ultraviolet light, which reduces Ag^+ ions to produce AgNPs (Paul *et al*., 2021) [43]. With UV irradiation, there are no chemical reducing agents added in the synthesis pathway and AgNPs are prepared at room temperature with small and uniform morphology. However, prolonged irradiation time may produce aggregation or reshape the AgNPs.
The evaporation–condensation procedure, generally performed in a tube furnace with an inert gas atmosphere, involves vaporizing metallic silver and allowing it to condense as nanoparticles on surfaces at lower temperatures. This approach can produce highly crystalline and size-controlled nanoparticles, but requires specialized high-temperature equipment and is not scalable (Basu *et al*.,

2021) [9].

Microwave-assisted synthesis is another newly emerging strategy. It can quickly provide uniform heating of the reaction mixture, which rapidly promotes nucleation and particle growth in some cases within 10 minutes. Despite being grouped as a type of chemical technique due to the use of solvents or mild reducing agents, microwave synthesis has shown to yield better energy efficiency, and provides shortened processing times when compared to conventional heating (Kumar *et al*., 2023) [30].

Physical methods are particularly relevant for the fields of sensing, photonics, and microelectronics since not using surfactants and having uniform narrow size distributions are important. The current drawbacks to physical methods are limited scalability, high operational costs and precision in operating the equipment which makes them impractical for routine or large-scale production (Al-Shehri *et al*., 2021) [7].

2.3 Green Synthesis (Biological Methods)

Also termed biological synthesis, green synthesis is an inexpensive and environmentally friendly alternative to physical and chemical methods that has emerged as an alternative. Green synthesis methods utilize natural sources such as plant extracts, fungi, bacteria, algae, or enzymes that serve as reducing and stabilizing agents. These biological systems contain a variety of natural materials that can effectively convert silver ions (Ag^+) into elemental silver (Ag^0) such as phytochemicals, amino acids, proteins, sugars, and organic acids to form stable nanoparticles (Gul *et al*., 2023) [21].

Plant-mediated synthesis is the most widely studied form of green synthesis due to its simplicity and abundance of natural resources. Extracts from leaves, roots, peels, and even seeds of various plants - such as *Moringa oleifera*, *Azadirachta indica*, *Citrus sinensis*, and *Camellia sinensis* - contain flavonoids, terpenoids, polyphenols, and other antioxidants capable of reducing silver ions (Shahzadi *et al*., 2023) [53]. The concentration of the extract, pH of the solution, and reaction time significantly affect the particle size and morphology.

Microbial synthesis, however, takes advantage of the naturally occurring biological systems of bacteria and fungi because they can make silver nanoparticles either extracellularly or intracellularly. Microorganisms secrete enzymes including nitrate reductase and proteins that may work to reduce Ag^+, while stabilizing and capping the particles, which enhances their stability and distribution (Rai *et al*., 2020) [47]. In many cases extracellular is preferred because it offers convenience for recovering the nanoparticle, and because precautions as to sterilization and growth conditions universally must be considered. Enzyme-mediated synthesis is another biocompatible route that uses purified enzymes (e.g., laccase, lipase and nitrate reductase) to directly reduce silver ions. Enzyme-mediated synthesis is slower and costlier than plant-based routes, but nanoparticle shape and biocompatibility can be highly controlled which is useful for drug delivery in targeting or biosensing (Farooq *et al*., 2020) [18].

The green methods of making AgNPs include a number of potential environmental toxins lowered if utilized, while some level of biological function may be imparted into the silver-nanoparticles such as other forms of antioxidant or antimicrobial activity due to the organic coating from the biological source or other. Some of the same challenges exist, however, as in development of reliable purification procedures, including: just as in the case of plant sources of AgNP production, the lack of uniformity in extracts; the inability to standardize the extract composition with respect to concentration, drying process and storage; the lack of understanding of the reaction kinetics; batch variably; and consistency and scale of production; which also may present challenges in a commercial setting (Yousef *et al*., 2022) [31].

Current research is attempting to overcome these challenges using a combination of metabolomic profiling, artificial cultivation of microbial strains and using bioreactors to maintain consistent conditions for biosynthesis (Alamgir *et al*., 2021) [3]. The inclusion of green chemistry in nanotechnology will also allow for the use of more sustainable and safer future applications of nanoparticles.

Table 1: Comparison of AgNP Synthesis Methods

Method	Reducing Agents	Conditions	Shape Control	Toxicity Risk	Reference
Chemical	$NaBH_4$, Hydrazine, Citrate	Harsh (60–100 °C), pH-sensitive	Excellent	High	Rahman *et al*., 2021 [46].
Physical (Laser)	None (energy-based)	High energy input (Laser, UV)	Good	Low	Luo *et al*., 2022 [34]
Green (Plant)	Flavonoids, Polyphenols	Mild (RT–60 °C)	Moderate	Very Low	Gul *et al*., 2023 [21].
Microbial	Enzymes (e.g., reductase)	Mild, aerobic	Good	Low	Muthukumar *et al*., 2019 [37].
Enzyme-assisted	Purified enzymes (laccase, etc.)	Controlled (enzyme-specific)	Moderate	Very Low	Farooq *et al*., 2020 [18].

3. Material Precursors and Influencing Factors

The efficient synthesis and application of silver nanoparticles (AgNPs) are primarily based on precursor material choice and synthesis parameters. These parameters in combination decide the size, shape, surface chemistry, and colloidal stability of the resultant nanoparticles, which in turn influence their functional properties such as antibacterial, antioxidant, or catalytic activity (Iqbal *et al*., 2020) [23].

In total, AgNP synthesis requires three most important types of materials:

1. Silver precursors (usually $AgNO_3$)
2. Reducing agents (e.g., $NaBH_4$, plant extracts)
3. Stabilizing agents (e.g., PVP, proteins, polyphenols)

These all contribute to different stages in the nucleation and growth of nanoparticles. Even factors such as pH, temperature, precursor concentration, and reaction time will dictate particle formation and morphology (Salehi *et al*., 2022) [50].

This chapter discusses the different types of materials that comprise AgNP synthesis and the impacts they have on specific properties of the material. The discussion starts with synthesized proteins from plants, followed by sourced microbial and chemical precursor materials. The chapter closes with a comparison.

3.1 Plant-Based Precursors

Plant-assisted synthesis of silver nanoparticles (AgNPs) is one of the most investigated and potential green processes, mainly due to the simplicity, cost, sustainability, and biocompatibility of the process. Plant extracts have a wide variety of chemical compounds, from different parts of plants, including flavonoids, terpenoids, alkaloids, tannins, and phenolic acids, that can act as a reducing and stabilizing agent (Shahzadi *et al*., 2023) [53].

In the simplest example, a solution of silver nitrate ($AgNO_3$) is mixed with the plant extract, and the reduction of Ag^+ to metallic Ag^0 takes place at ambient temperatures and mild conditions. The reduction often creates a precipitate that can be visually seen as a change in coloration due to surface plasmon resonance, going from pale yellow to dark brown coloration (Iqbal *et al*., 2020) [23]. The plant species, extract concentration, temperature, pH, and reaction time affect the characteristics of the final product of nanoparticles (Yousef *et al*., 2022) [31].

For example, *Azadirachta indica* (neem) extract has been shown to produce spherical nanoparticles, while *Moringa oleifera* leaf extract can result in irregular or polydisperse shapes depending on reaction conditions (Gul *et al*., 2023) [21]. Plant-based synthesis avoids the toxic solvents or surfactants associated with chemical methods, and therefore is advantageous for medicinal and food-related uses. However, a serious limitation is the batch-to-batch variability associated with different phytochemical profiles.

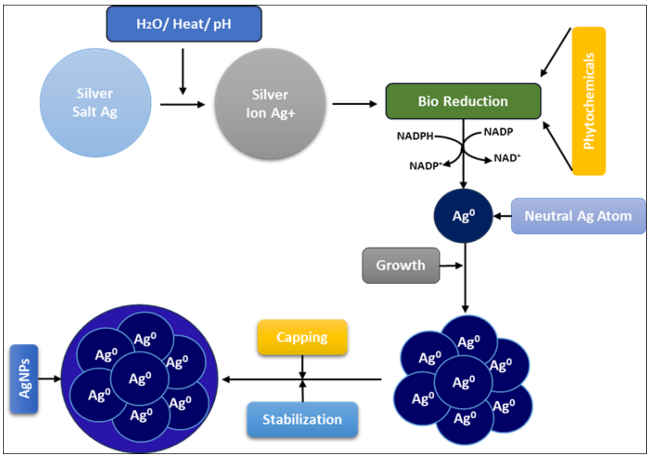

Fig 2: Mechanism of green synthesis of silver nanoparticles (AgNPs).

Plant-derived phytochemicals act as reducing and stabilizing agents, converting silver ions (Ag^+) into metallic silver (Ag^0), followed by nanoparticle capping and growth. Figure created by the author, adapted from the biosynthetic pathway described by Baranwal *et al*. (2022) [10].

Table 2: Effect of Synthesis Method on Silver Nanoparticle Morphology and Size

Synthesis Method	Reducing Agent	Capping Agent	Observed Shape	Size Range (nm)	Reference
Chemical ($NaBH_4$)	Sodium borohydride	Citrate	Spherical	5–20	Kumar *et al*., 2023 [30]
Green (Neem extract)	Phytochemicals	Polyphenols	Irregular/Spherical	10–50	Shahzadi *et al*., 2023 [53].
Microbial	Nitrate reductase	Secreted proteins	Triangular	20–70	Rai *et al*., 2020 [47].
Enzyme-assisted	Laccase	Proteins	Rods, Spheres	15–100	Farooq *et al*., 2020 [18].

3.2 Microbial and Enzyme-Based Precursors

Microbial and enzyme-based production of silver nanoparticles (AgNPs) are another branch of green nanotechnology where biological organisms and/or their isolated biomolecules mediate the reduction of silver to nanoparticles. With an increased emphasis on biocompatibility, eco-safety and reproducibility, biological methods using microorganisms and enzymes has become the preferred approach for pharmaceutical and biomedical purposes (Rai *et al*. 2020) [47].

Bacteria and fungi can be used to synthesize AgNPs using either the intracellular or extracellular method (Duran *et al*., 2015) [24]. In the case of extracellular synthesis, microbial cultures continuously secrete enzymes, e.g. nitrate reductase, hydrogenase etc. This extracellular method synthesizes AgNPs in solution, the advantage being AgNPs are formed outside the cells and can be harvested and purified easier than intracellularly-synthesized AgNPs (Muthukumar *et al*., 2019) [37]. The disadvantage of the extracellular method is that AgNPs are generally transition metals and further characterization is required to purify, size, and stabilize the AgNPs, while biological synthesis with intra-cellular synthesis offers prescriptive factors that may yield more uniform particles based on biological cell confinement and structured growth.

Microbial extracts typically act as both reducing and capping agents, adding a natural coating of protein to nanoparticles, which retains their colloidal stability and biocompatibility. Different geometrics and response from Pseudomonas, Bacillus, and Aspergillus species exhibited triangular, spherical, and rod-shaped nanoparticles which had a range of AgNPs from 10–100nm in size, respectively, with strains and conditions responses (Alamgir *et al*., 2021) [3].

In a method of synthesis by enzymes, pure enzymes such as laccase, catalase or lipase can be used to cause the reduction of silver ions. It is typically more expensive and time consuming compared to other methods; however, it has benefits like better control of size and shape, less variability, as well as enabling *in vitro* biomedical applications (Farooq *et al*., 2020) [18]. These enzyme-mediated nanoparticles typically have greater antimicrobial or anticancer activity because the enzymes can also have bioactive potential once attached to the nanoparticle surface.

Despite various advantages to microbial and enzyme mediated synthesis, they will still have limitations such as longer kinetics, issues with scalability, and needing to maintain sterile conditions. Steps towards next generation, biologically safe nanomaterials through microbial and enzyme mediated processes are important explorations.

This foundational knowledge of material precursors provides the basis for evaluating how AgNPs function across diverse sectors, which is explored in the following chapter.

4. Functional Applications of Silver Nanoparticles

Silver nanoparticles (AgNPs) have a diverse collection of functional uses, which has resulted in their rapid incorporation into multiple industries, including healthcare, food packaging, agriculture, catalysis, and environmental remediation. Their remarkable biological activity, high surface-to-volume ratio, and tunable surface chemistry allow them to be very effective in applications ranging from inhibiting microbial growth to modulating reactive oxygen species. (Arora *et al*., 2022) [8].

AgNPs have been investigated for antifungal, antiviral, plant growth-promoting, and even optoelectronic applications, with the current review restricting its discussion on four topics most represented in recent literature and which are pertinent to health and environmental sustainability:

- Antibacterial
- Antioxidant
- Biomedical
- Environmental applications

Each functional class is then influenced via the synthesis strategy, size, shape, surface chemistry of the nanoparticles. We discuss the mechanisms of action, important outcomes, and new directions in each of these areas, while also refencing recent studies on new green and hybrid synthesis approaches.

4.1 Antibacterial Applications

Of all functional roles, silver nanoparticles (AgNPs) are likely the most famous regarding broad-spectrum antibacterial activity. It has been shown that AgNPs can inhibit both Gram-positive and Gram-negative bacteria, including multidrug-resistant bacteria such as Staphylococcus aureus, Escherichia coli, and Pseudomonas aeruginosa. The antibacterial effectiveness of AgNPs decreases when aspects of their size, surface area, shape, and zeta potential are modified, which occurs in the synthesis methods of AgNPs. The antibacterial activity of AgNPs is mediated through several methods, including physical interactions and biochemical interactions. First, AgNPs can attach to or interact with bacterial cell walls, causing structural modification of the cell wall and modifications in membrane permeability. Membrane permeability changes lead to leaking of cellular contents, cell lysis, and eventually death (Srikar *et al*., 2020) [55]. Second, AgNPs can penetrate the cell membrane and interact with proteins and DNA, inhibiting metabolic processes such as replication and enzyme action (El-Saadony *et al*., 2021) [16].

A principal mechanism of bactericidal action is reactive oxygen species (ROS), which produces superoxide and hydroxyl radicals. ROS produce oxidative stress in microbial cells to damage; lipids, nucleic acids, and proteins. Eventually leading to apoptosis-like bacterial death (Abbaszadegan *et al*., 2019) [1]. Silver ions (Ag^+) from silver nanoparticles act in conjunction by denaturing the thiol group in bacterial enzymes which adds redundancy to the bacterial defense systems (Tran *et al*., 2022) [56].

AgNPs have been used for textiles, wound dressings, food packaging, surgical masks, and as an antibacterial coating on medical devices. Green produced AgNPs are often appended with phytochemicals, suggesting higher biocompatibility and long-lasting antibacterial properties which indicate the best potential for healthcare or food related uses (Benakashani *et al*., 2021) [11]. In addition to AgNPs, hybrid strategies incorporating AgNPs with antibiotics showed synergistic effects in combating drug resistant pathogens.

However, expanding AgNP applications contributes to bacteria may evolve resistance and possible cytotoxicity of human cells. Ongoing studies are evidence of bacterial cell inhibition and exploring ways to optimize antimicrobial properties and limit unwanted side effects by examining release systems, developing surface functionalization, and monitoring doses (Chopra *et al*., 2023) [14].

4.2 Antioxidant Applications

Not only do silver nanoparticles (AgNPs) possess antibacterial activity, they also have shown potential as an antioxidant primarily in their ability to quench free radicals and inhibit pathways of oxidative stress. Oxidative stress is associated with the formation of reactive oxygen species (ROS) and ROS development is a primary contributing factor in the pathogenesis of chronic diseases (González-Ballesteros *et al*., 2020) [20], including cancers, neurodegenerative disorders, and cardiovascular diseases. The antioxidant activity of AgNPs is dependent on the size, surface area, surface modification, and the method of synthesis, especially when green synthesis methods leave phytochemical residues with antioxidant properties.

Some studies reported green-synthesized AgNPs using plant extracts, including Moringa oleifera, Camellia sinensis, and Punica granatum, had better DPPH and ABTS radical scavenging activity than silver nanoparticles synthesized chemically (Saif *et al*., 2022) [49]. The AgNPs produced from plant-based sources were often made in the presence of phytochemical residues such as polyphenols, flavonoids, and terpenoids on their surface able to donate electrons, and neutralize free radicals.

Mechanistically, AgNPs are able to terminate chain reactions with free radicals, reduce peroxides, and chelate metal ions that are involved in the oxidative cascade. Antioxidant activity from AgNPs have been measured with several *in vitro* assays, including DPPH, FRAP, and superoxide dismutase (SOD) mimicry with effectiveness usually dependent on time and dosage (Rafiq *et al*., 2023) [45].

There is a recently increased interest in the use of antioxidant-functionalized AgNPs in cosmetics, wound healing formulations, and nutraceutical coatings where it is valuable to have agents that reduce oxidative stress. However, due to their dual redox activity (both pro-oxidant and antioxidant depending on the conditions), proper optimization is need due to its dual activity prior to clinical use, or food-grade applications (Akter *et al*., 2021) [2].

4.3 Biomedical Applications

The biomedical sector has seen one of the most rapid needs for silver nanoparticle (AgNP) innovation because of their broad-spectrum bioactivity, their biocompatibility and ease of surface modification. Their applications vary from wound healing, to drug delivery, new cancer therapies and diagnostics, which makes them attractive candidates for novel medical technologies (Mousavi *et al*., 2022) [36].

AgNP's anti-inflammatory and antimicrobial properties are helpful when thinking of their inclusion into wound dressings, surgical masks and catheter coatings. These small particles may penetrate tissue and microbial membranes, limiting the potential of infection and allowing the body to regenerate tissues (Shaikh *et al*., 2021) [52]. In terms of wound healing, AgNP embedded hydrogels and bandages have shown faster healing rates, reduced scarring and fighting infections, notably, with antibiotic resistant pathogens.

As treatments of Cancer, AgNP's as both targeted drug carriers or anticancer agents themselves, are being explored with many studies pointing towards functionalizing AgNP's with antibodies, peptides or chemotherapeutics to prevent damage to healthy tissues, while targeting to the cancerous tissues. AgNP's cause cytotoxicity in tumor cells through oxidative stress, damaging the mitochondria of the tumor cells and activating their apoptosis pathway (Jang *et al* 2023) [25].

AgNPs have also been used in biosensing and imaging, given their plasmonic properties, which allow for high-sensitivity identification of biomarkers, DNA, or pathogens. Silver-based quantum dots and surface-enhanced Raman scattering (SERS) platforms have yielded ultra-sensitive diagnostics in clinical settings (Lee and Han, 2022) [32].

However, issues surrounding AgNPs' potential cytotoxicity to human cells persist, especially at high doses or with repeated exposures. Strategies being employed to improve biocompatibility, and release profiles include surface engineering techniques (e.g., protein corona interactions, PEGylation, polymer encapsulation) (Martínez-Castañón *et al*., 2020) [35].

Importantly, AgNPs continue to be attractive candidates for personalized medicine, minimally invasive therapies, and point-of-care diagnostics. Unfortunately, the incomplete understanding of the *in vivo* fate of AgNPs, their long-term effects, and regulatory hurdles needs to be addressed before their safe and effective transfer into clinical practice within mainstream healthcare can be attained.

4.4 Environmental Applications

The global environmental challenges of today have created demand for more sustainable approaches. Silver nanoparticles (AgNPs) have emerged in high demand for water purification, environmental sensors, pollution remediation, and antifouling technologies. Their strong anti-microbial properties and catalytic activity have made AgNPs advantageous as a technology when determining the reduction or degradation of microbial pathogens or contaminants (Verma *et al*., 2021) [57].

The most significant use of AgNPs is as disinfectants in water through active agents in filters, membranes, and coated surfaces, but also removed bacteria, viruses, and algae from drinking and wastewater systems. Studies have shown AgNPs have shown reductions over 99% of the pathogens Escherichia coli and Vibrio cholera in controlled systems. While this technology clearly meets the needs of resource-constrained regions (Thakur *et al*., 2021) [58], AgNPs have been demonstrated to be added to a hybrid material, which enhances their photocatalytic degradation of organic pollutants including dyes, pesticides, and pharmaceuticals (Park *et al*., 2023) [42].

In environmental monitoring, silver-based nano sensors address the needs of detection of heavy metals (e.g., Hg^{2+}, Pb^{2+}) and nitrate or phosphate levels by taking full advantage of the unique optical and electronic behavior of AgNPs in continually varying environmental situations (Alghamdi *et al*., 2021) [5]. Silver nanoparticles allow qualitative (colorimetric) or quantitative (electrochemical) real-time, low-cost detection in field conditions.

AgNPs are also being utilized in antifouling coatings, not just for ships' hulls, but also on marine structures because of their ability to deter the attachment of biofilms, barnacles, and algae. These coatings reduce fuel use, maintenance, drag, and prevent the introduction of toxic antifouling agents that contaminate marine ecosystems (Kwak *et al*., 2022) [59].

Nevertheless, with the increasing release of AgNPs into the environment from wastewater, from industries, and consumer products, there are concerns with regards to their ecotoxicity, as laboratory studies have shown, for example, that AgNPs can accumulate in aquatic organisms, have across the shallow benthic community, structure and function of microbial ecosystems, and biases nutrient cycling in bacterial/microbe populations (Nasser and Ali, 2019) [39]. Current studies focus on how to achieve eco-safe formulations via biopolymer coatings or controlled-relief systems to minimize external unintended environmental damage.

AgNPs still offer promising potential as a tool for environmental sustainability, yet ongoing to providing positive experiences, balancing usability with safety is still proving to be a challenge for regulators, manufacturers, and researchers.

Table 3: Functional Applications of Silver Nanoparticles: Mechanisms and Outcomes

Application Area	Mechanism of Action	Observed Outcomes	Reference
Antibacterial	Cell wall disruption, ROS generation, enzyme inactivation	Inhibits both Gram-positive and Gram-negative bacteria	El-Saadony *et al*., 2021 [16].
Antioxidant	Free radical scavenging, electron donation, chelation	Reduces DPPH/ABTS radicals, protects against oxidative stress	Saif *et al*., 2022 [49].
Biomedical	Drug delivery, DNA/protein interaction, anti-inflammatory action	Enhanced wound healing, targeted cancer cell apoptosis	Mousavi *et al*., 2022 [36].
Environmental	Microbial deactivation, catalytic degradation of pollutants	Water purification, removal of dyes/pesticides, antifouling use	Park *et al*., 2023 [42].

4.5 Integrated Perspectives on AgNP Applications

Due to their extraordinary physical, chemical, and surface properties, silver nanoparticles (AgNPs) have an extraordinary applicability in a variety of different fields. Their potential applications range from effective antibacterial agents to sophisticated biomedical applications with scalable applications to address critical global health and environmental issues (Prabhu *et al*., 2022; Rajan *et al*., 2023) [44, 48]. Their role in the antioxidant and environment-based sectors basically highlights their ability to alleviate oxidative stress and provide solutions for sustainability and remediation strategies (Ezeh *et al*., 2020) [17].

AgNPs function based on their size, shape, surface charge, and source of synthesis. Green synthesis methods added biocompatibility and environmental value to AgNPs, while hybrid systems have improved specificity and controllability (Ovais *et al*., 2023) [41]. However, with nanomaterial use rising in medical and consumer products causes concern for user cytotoxicity, resistance to pathogens, and environmental accumulation.

Developing innovative and sustainable methods for synthesis and surface engineering is important to establish potential functional benefits of AgNPs while reducing any unwanted functionality and risk. The next chapter addresses the issues of user cytotoxicity, environmental toxicology, and frameworks to support safe and sustainable nanotechnology.

5. Toxicological and Environmental Risks of Silver Nanoparticles

The allergenicity of silver represents an emerging and concerning issue with regards to silver nanoparticles (AgNP) applications. Silver NP have been proven effective in the realm of antimicrobial formulations as well as biomedical application but may represent a risk of "adverse effects on our health, non-target organisms or environmental risk" when we consider chronic or uncontrolled exposure (Santos *et al*., 2022) [51].

Silver NP may gain access to biological systems via inhalation, ingestion, or dermal absorption, as well as organize themselves into metabolically active organs, like the brain, liver, and kidneys. Much of the toxic effects seen in exposure to silver NPs arise from oxidative stress, which is a consequence of a toxic accumulation of reactive oxygen species (ROS), and solely from the release of Ag^+, which impairs the function of enzymes and DNA (Wang *et al*., 2021) [61]. Research has found evidence of exposure related to mitochondrial dysfunction, inflammation, genotoxicity and organ dysfunction in animal models (Heidari *et al*., 2021) [22]. Toxicity of AgNPs is often size- and dose-dependent; smaller particles exhibit stronger toxicity and higher doses exhibit greater toxicity.

Environmentally, releases of AgNPs can occur via disposal of nano-enabled products, wastewater, or industrial processes. Once in soil or water, AgNPs can attach to and interact with natural organic matter, or aggregate to become larger particles, but under certain conditions, releases toxic Ag^+, a bioavailable ion, harmful to aquatic microorganisms such as bacteria, larger eukaryotic microorganisms, algae, and invertebrates (Tan *et al*., 2023) [62], which can disrupt microbial community structure and microbiomes, reduce biodiversity, and alter biogeochemical processes.

To minimize risk, researchers are examining safe-by-design practices such as surface modification with biocompatible coatings or slow-release nano formulations that limit ion leaching (Alves *et al*., 2020) [63]. Along with these efforts, regulatory agencies are beginning to develop risk assessment frameworks for nanomaterials, while regulations and standardized procedures for assessing AgNP toxicity in wet and dry ecosystems, and complex interactions using reference materials, are still developing.

Based on the potential of AgNPs, as well as the liabilities and knowledge gaps, long-term safety will require continued research, informed regulation, and responsible innovation.

Table 4: Summary of AgNP Toxicity Findings in Recent Studies

Study Model	Exposure Type	Observed Effects	Reference
Rats (oral exposure)	90 days, 5–50 mg/kg/day	Liver inflammation, kidney damage, mitochondrial dysfunction	Wang *et al*., 2021 [61].
Zebrafish embryos	Waterborne, 0.1–1.0 mg/L	Developmental abnormalities, oxidative stress, delayed hatching	Tan *et al*., 2023 [62].
Human lung epithelial cells	*In vitro*, 10–100 µg/mL	ROS generation, DNA damage, reduced cell viability	Al-Ghazaly *et al*., 2021 [4].
Soil microbial community	Soil amendment, 10 mg/kg	Decreased microbial diversity, altered nitrogen cycling	Santos *et al*., 2022 [51].
Freshwater algae (*Chlorella*)	48 h, 0.01–0.1 mg/L	Growth inhibition, photosynthetic disruption, Ag^+ ion release	Chen *et al*., 2019 [12].

6. Future Perspectives

Silver nanoparticles (AgNPs) are still one of the most interesting nanomaterials and their variety of applications, from biomedicine to food preservation to environmental clean-up, is quite remarkable. As we imagine the future of AgNPs, we must simultaneously address not only the methods to develop further functionality, but also the biosafety, the environmental footprint, and the regulations surrounding these materials (Narayanan *et al*., 2021) [38].

An even more troublesome issue is incorporating existing green or hybrid synthesis pathways that maximize nanoparticle stability, specificity, biocompatibility, along with functionality. Microfluidic technology, bioreactor-based synthesis, and AI-assisted modelling are showing some very good promise for nanoparticle scalability and consistency of synthesis (Raza *et al*., 2023; Singh & Jain, 2022) [64, 24]. These developments could play a very important role in targeted drug delivery, controlled release, and biosensing technologies such as cancer therapeutics and in situ biosensing daisies (Baranwal *et al*., 2022) [10].

The equally troubling toxicity conundrum. Coatings such as PEGylation, a biopolymer surface coating, and protein corona engineering are potential strategies that could mitigate cytotoxicity and improve biocompatibility for majority majority of the applications (Santos *et al*., 2022) [51]. In the future, we must better incorporate safe-by design approaches, predictive eco-toxicology modelling, and pan-disciplinary regulations across stakeholders to achieve safety and potentially support public trust (Zhou *et al*., 2022) [40].

7. Conclusion

This review has taken a look at the rapidly growing area of silver nanoparticles (AgNPs) through their synthesis strategies, material assessments, applications and toxicological concerns. The area has advanced well past the historic physical and chemical modestly utilized green or sustainable synthesis pathways that incorporate some form of biological system whether that be plant, microorganism, or enzyme. These more environmentally friendly methods are also contributing to internationally recognized sustainability goals and can improve the biocompatibility of AgNPs for potentially-sensitive applications. Material precursors are key to nanoparticle characterization, size, morphology, and stability. The incorporation of biological materials, especially plants and microorganisms, is pertinent to research into functionality relevant to medical, environmental, pharmaceutical and antimicrobial activity, i.e. green synthesis enables anti-oxidation or significant degradation of pollutants.

A single AgNP preparation may exhibit antibacterial activity that is based on multiple mechanisms of action that include cell wall degradation, the formation of reactive oxygen species (ROS), and catalytic degradation of pollutants. Although AgNPs have massively positive utility in many areas, their reactivity raises the potential for toxicity to biological systems and/or the environment. The potential benefits and negative consequences of AgNP changes greatly based on the dose of exposure, exposure pathways and surface modifications. Therefore, future research must apply safe-by-design principles to ensure continuous safe and sustainable advancement of this field. As always, recognizing the importance of long-term (>30 days) toxicological assessments, and using standardized tests, protocols, and properly designed studies will be critical.

8. References

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