A Review on Green Synthesis and Physiological Properties of Silver Nanoparticles

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ABSTRACT

The green synthesis of silver nanoparticles (AgNPs) has emerged as a sustainable and eco-friendly alternative to conventional chemical and physical methods, offering significant advantages in terms of safety, cost-effectiveness, and environmental compatibility. This review highlights the various biological entities—such as plant extracts, bacteria, fungi, and algae—used in the green synthesis of AgNPs, elucidating their role as reducing and stabilizing agents. Furthermore, the review discusses the key physicochemical properties of AgNPs, including size, shape, surface charge, and crystallinity, and how these factors influence their stability and biological activity. The interdependence of synthesis parameters and nanoparticle characteristics is also analysed to understand their potential in biomedical, antimicrobial, and catalytic applications. By emphasizing the sustainable approach and tunable properties of AgNPs, this review aims to provide insights into current trends and future prospects in green nanotechnology.

Keywords: Silver nanoparticles, Green synthesis, Physiochemical properties, Biomedical application, Plant extract.

INTRODUCTION

Nanotechnology has emerged as a transformative field of science and engineering, enabling the design, synthesis, and application of materials with dimensions typically below 100 nanometres. At this scale, materials exhibit unique mechanical, chemical, optical, and biological properties that differ significantly from their bulk counterparts. Among various engineered nanomaterials, **silver nanoparticles (AgNPs)** have attracted considerable scientific and industrial interest due to their remarkable antimicrobial activity, catalytic efficiency, electrical conductivity, and optical characteristics. These properties make AgNPs suitable for a wide range of applications, including medical devices, drug delivery systems, wound dressings, food packaging, textiles, water purification, and agricultural products.

In light of these limitations, the development of **eco-friendly, sustainable, and cost-effective synthesis methods** has become a critical area of research. **Green synthesis** of AgNPs, which utilizes natural biological entities such as plant extracts, bacteria, fungi, and enzymes, has emerged as a promising alternative. This approach is grounded in the principles of green chemistry, aiming to reduce or eliminate the use and generation of hazardous substances in the design of chemical products and processes. Biological organisms and extracts are rich in bioactive compounds—such as flavonoids, alkaloids, terpenoids, proteins, and polysaccharides—that serve dual roles as reducing agents (converting Ag^+ ions to metallic Ag^0) and stabilizing or capping agents (preventing agglomeration and ensuring nanoparticle stability).

One of the most attractive aspects of green synthesis is its **versatility and scalability**. For instance, plant-mediated synthesis offers a simple, rapid, and energy-efficient route for producing AgNPs without the need for stringent conditions or expensive equipment. The **composition of phytochemicals** in the extract, reaction parameters (e.g., pH, temperature, reaction time), and silver precursor concentration can be systematically tuned to control the **physicochemical properties** of the resulting nanoparticles—such as particle size, shape, crystallinity, surface charge, and dispersion stability. These properties, in turn, have a profound impact on the nanoparticles' **biological interactions, catalytic performance, and overall functionality**.

Understanding the intricate relationship between synthesis conditions and the resulting **physicochemical characteristics** of AgNPs is crucial for tailoring them to specific applications. For example, smaller AgNPs with high surface reactivity may exhibit enhanced antimicrobial activity, while those with uniform shape and size may be preferred for biomedical imaging or drug delivery. Additionally, surface modifications using natural capping agents can improve biocompatibility and reduce cytotoxicity, which is vital for medical and pharmaceutical uses.

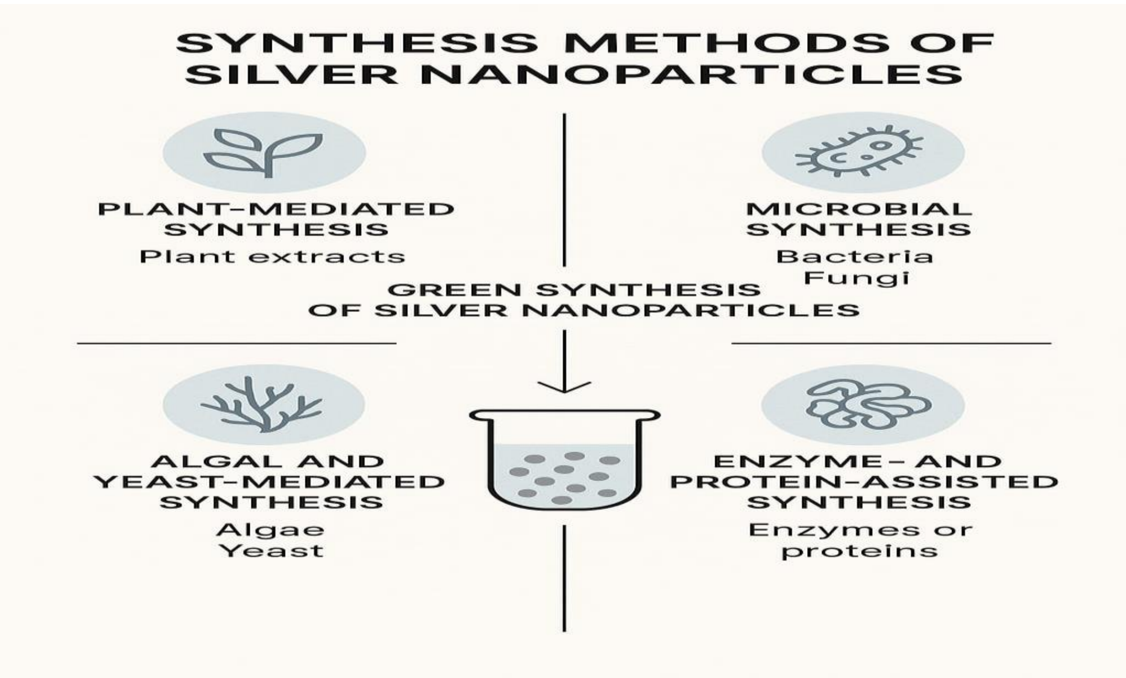
This review aims to provide a comprehensive overview of the **green synthesis of silver nanoparticles**, with an emphasis on the biological mechanisms involved, the influence of synthesis parameters on nanoparticle properties, and the potential applications across various sectors. Key topics include:

- The role of different biological sources in nanoparticle formation,
- Detailed analysis of the physicochemical properties of green-synthesized AgNPs,
- Current and emerging applications in medicine, agriculture, and environmental technologies,
- Challenges and future directions in scaling and standardizing green synthesis for industrial use.

By critically analysing the current state of research, this review seeks to highlight the **advantages, limitations, and future prospects** of green-synthesized AgNPs, ultimately contributing to the development of safer, more sustainable nanomaterials for real-world applications.

Synthesis Methods of Silver Nanoparticles

Green synthesis of silver nanoparticles (AgNPs) involves eco-friendly, biocompatible methods that utilize biological organisms or natural extracts to reduce silver ions (Ag^{+}) into metallic silver (Ag^{0}). This approach is gaining popularity due to its simplicity, environmental safety, and potential scalability. The key biological sources used in green synthesis include plant extracts, bacteria, fungi, and algae. These natural materials act as both reducing and stabilizing agents, eliminating the need for harsh chemicals.



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1. Plant-Mediated Synthesis

Plant extracts are widely used due to their rich content of phytochemicals such as flavonoids, alkaloids, terpenoids, phenolics, and proteins. These compounds facilitate the reduction of Ag^+ to Ag^0 and stabilize the nanoparticles. The synthesis process typically involves mixing silver nitrate solution with the plant extract under controlled temperature and pH conditions. Examples include the use of neem, green tea, aloe vera, and tulsi for AgNP synthesis.

2. Microbial Synthesis

Bacteria and fungi can produce AgNPs either extracellularly or intracellularly. In bacterial synthesis, species such as *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa* have shown the ability to reduce silver ions. Fungi like *Aspergillus niger* and *Fusarium oxysporum* are also effective due to their high tolerance to metal ions and secretion of reductive enzymes. Microbial synthesis is often more stable but may require longer reaction times and specific growth conditions.

3. Algal and Yeast-Mediated Synthesis

Marine and freshwater algae, including *Sargassum* and *Chlorella*, have also been used for AgNP synthesis. These organisms produce various metabolites that facilitate reduction and capping of nanoparticles. Yeasts such as *Saccharomyces cerevisiae* have shown potential for intracellular synthesis of AgNPs under controlled conditions.

4. Enzyme- and Protein-Assisted Synthesis

Isolated enzymes or proteins from natural sources can also be used to synthesize AgNPs. Enzymes such as nitrate reductase play a central role in reducing silver ions. This method offers high control over particle size and morphology, although it may involve more complex purification-steps.

Overall, the green synthesis route is influenced by several factors including temperature, pH, concentration of silver precursor, and duration of the reaction. Fine-tuning these parameters allows control over nanoparticle characteristics, making this method both flexible and efficient for various applications.

Comparison of Green Synthesis Methods for Silver Nanoparticles

Synthesis Method	Biological Source	Common Organisms/Extracts	Typical Particle Size Range (nm)	Applications
Plant-mediated	Plant extracts	Neem (*Azadirachta indica*), Green tea, Aloe vera Tulsi	10–100	Antimicrobial agents, wound heling food packaging
Bacterial synthesis	Bacteria	*Bacillus subtilis, Escherichia coli Pseudomonas aeruginosa*	5–50	Biosensors, drug delivery, antimicro/al coatings
Fungal synthesis	Fungi	*Fusarium oxysporum, Aspergillus niger, Peniciltium sp,*	10–60	Antifungal agents, cancer therapy bioremediation
Algal synthesis	Algae	*Sargassum wightiti, Chlorella vulgaris Spirulina platensis*	15–70	Water purification, antibacterial textiles environmental cleanup
Enzyme/ protein-assisted	Yeasts	Nitrate reductase, laccase, protein isolates	10–80	Controlled drug rele-ase, targeted therapy catalytic processes

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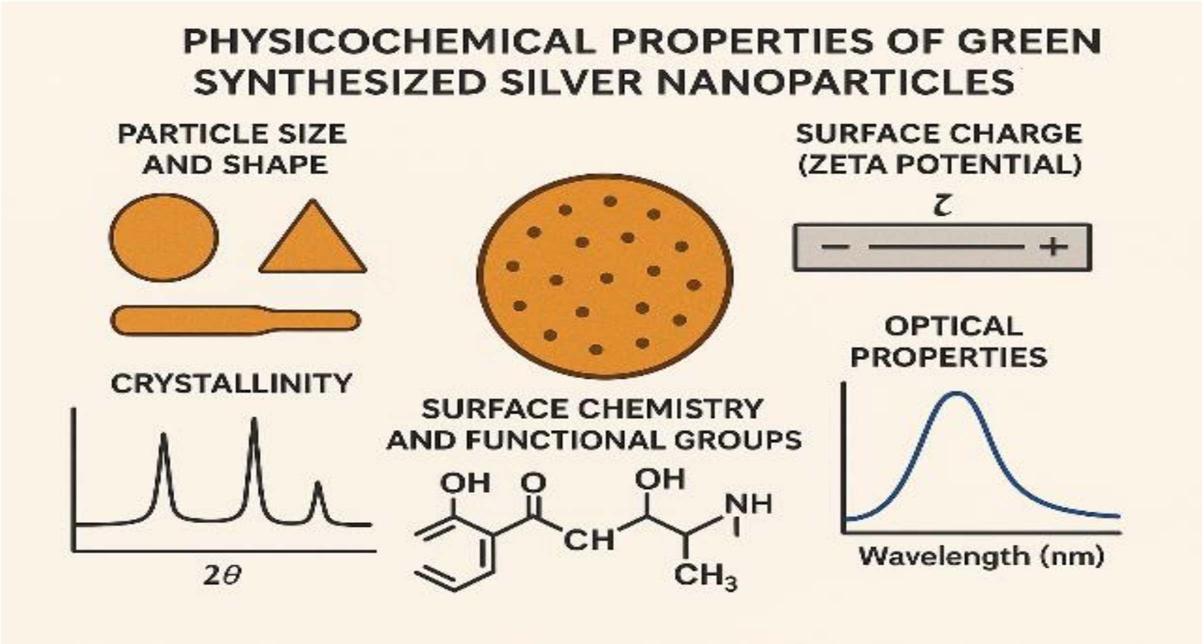
Physicochemical Properties of Green Synthesized Silver Nanoparticles

The functional behavior and potential applications of silver nanoparticles (AgNPs) are largely determined by their physicochemical properties. Green synthesis methods significantly influence these properties through the nature of the biological reducing agents and reaction conditions. Key physicochemical attributes include size, shape, surface charge, crystallinity, and surface chemistry.



1. Particle Size and Shape

Size is a critical factor that affects the reactivity, bioavailability, and toxicity of AgNPs. Green synthesis typically produces nanoparticles ranging from 1 to 100 nm. The phytochemicals or biomolecules used in the synthesis act as stabilizers and influence the nucleation and growth phases of nanoparticles. Depending on the synthesis conditions and biological source, AgNPs can adopt various shapes such as spherical, triangular, rod-like, and hexagonal. Smaller-sized nanoparticles exhibit greater surface area, enhancing their catalytic and antimicrobial properties.

2. Surface Charge (Zeta Potential)

Surface charge, typically measured as zeta potential, indicates the stability of nanoparticles in suspension. A high absolute value of zeta potential (positive or negative) suggests better colloidal stability due to electrostatic repulsion between particles. Green synthesized AgNPs often show good stability, attributed to the capping action of biomolecules that prevent aggregation.

3. Crystallinity

Crystallinity defines the structural order of atoms within the nanoparticles. X-ray diffraction (XRD) studies have shown that green synthesized AgNPs typically possess a face-centered cubic (fcc) crystalline structure. Crystalline AgNPs exhibit enhanced optical, thermal, and mechanical properties, which are important for various industrial and biomedical applications.

4. Surface Chemistry and Functional Groups

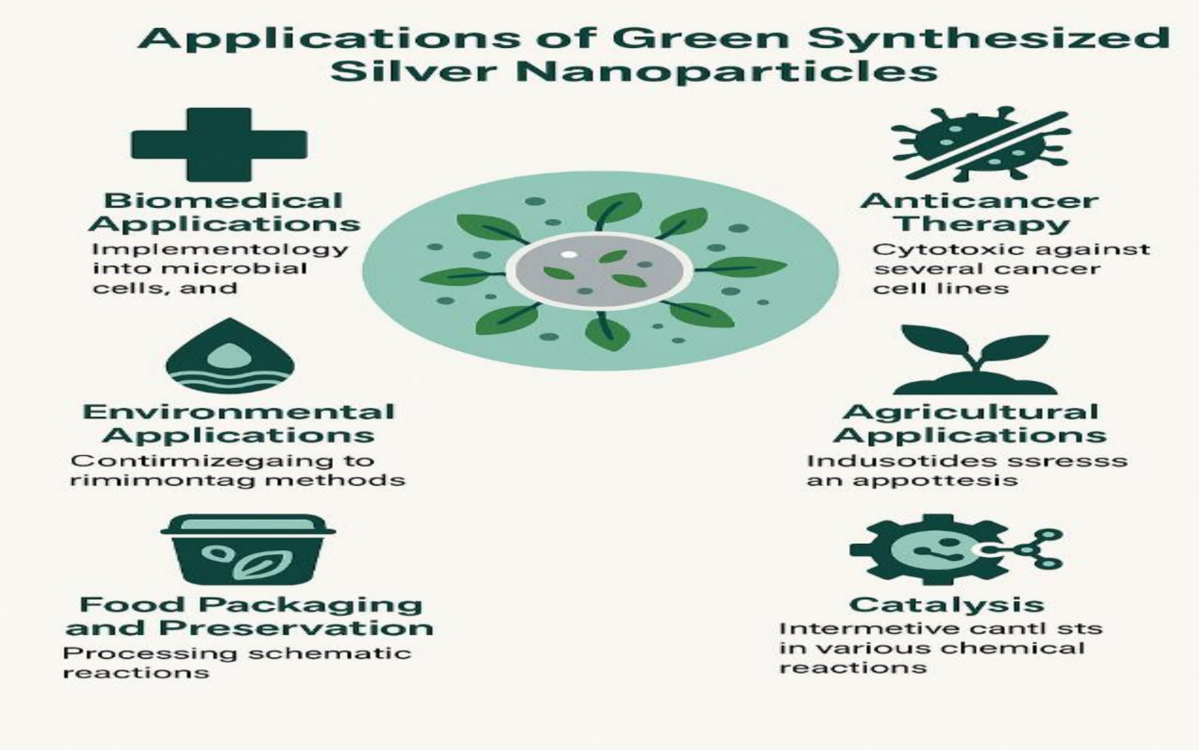
The surface of green synthesized AgNPs is typically coated with biomolecules from the reducing agents, such as proteins, polyphenols, and flavonoids. These functional groups are detectable using Fourier-transform infrared spectroscopy (FTIR) and play a significant role in stabilizing the nanoparticles, influencing their interaction with biological systems, and enhancing-biocompatibility.

5. Optical Properties

AgNPs exhibit a distinct optical characteristic known as surface plasmon resonance (SPR), typically observed between 400–450 nm in UV–Vis spectroscopy. This property arises from the collective oscillation of electrons on the nanoparticle surface when excited by light and is used to monitor nanoparticle formation and stability.

Applications of Green Synthesized Silver Nanoparticles

Green synthesized silver nanoparticles (AgNPs) have attracted considerable interest across various fields due to their enhanced biocompatibility, reduced toxicity, and effective functional properties. Their broad-spectrum antimicrobial activity, catalytic efficiency, and optical behavior make them versatile in applications ranging from healthcare to environmental management.



1. Biomedical Applications

AgNPs are widely studied for their antimicrobial, anti-inflammatory, and anticancer properties. Their small size enables easy penetration into microbial cells, where they disrupt cellular membranes and interfere with vital biological processes. Green synthesized AgNPs have demonstrated effectiveness against a variety of pathogens, including antibiotic-resistant strains. Additionally, they are being explored for use in wound dressings, drug delivery systems, and biosensors due to their biocompatibility and surface functionalization capacity.

2. Anticancer Therapy

Recent studies have shown that AgNPs synthesized via green methods exhibit cytotoxic effects against several cancer cell lines, including breast, lung, and colon cancers. The biomolecules used in the synthesis may enhance selective toxicity towards cancer cells while minimizing damage to healthy tissues. AgNPs induce oxidative stress, DNA damage, and apoptosis in cancer cells, making them a promising adjunct in cancer therapy.

3. Environmental Applications

Green synthesized AgNPs are employed in water purification systems due to their ability to degrade organic pollutants and eliminate microbial contaminants. Their catalytic activity is also used in the reduction of harmful dyes and heavy metals from industrial effluents, contributing to environmental remediation efforts.

4. Agricultural Applications

In agriculture, AgNPs are used as nano-pesticides and nano-fertilizers to enhance crop protection and yield. Their antimicrobial properties help control plant pathogens, while their nano-size facilitates better absorption and utilization by plants. Green synthesis ensures these applications are safer for the environment and non-target organisms.

5. Food Packaging and Preservation

AgNPs are increasingly being incorporated into food packaging materials to prevent microbial contamination and extend shelf life. The use of green synthesized nanoparticles ensures that these materials are safe and free from harmful chemical residues, aligning with the demand for sustainable food technologies.

6. Catalysis

Due to their high surface area and active sites, AgNPs act as efficient catalysts in various chemical reactions, including oxidation and reduction processes. Their use in catalysis contributes to greener industrial practices by reducing energy consumption and minimizing the use of hazardous substances.

Comprehensive List of Green Synthesis Methods

Plant-Mediated Synthesis: Shahzadi et al. (2025) explore the use of plant extracts such as *Ocimum sanctum*, *Curcuma longa*, and *Azadirachta indica* for the synthesis of silver nanoparticles (AgNPs), highlighting their reducing and stabilizing properties.

Microbial Synthesis: Patel et al. (2023) provide a comprehensive analysis of bacterial and fungal roles in AgNP biosynthesis, focusing on both extracellular and intracellular production mechanisms.

Algal and Yeast-Mediated Synthesis: Nkosi et al. (2024) investigate the potential of algae and yeast for AgNP synthesis, particularly through bioflocculant-assisted processes.

Enzyme-Assisted Synthesis: Vidyasagar et al. (2023) examine the enzyme-mediated synthesis of AgNPs, detailing the role of enzymes such as nitrate reductase in the reduction of silver ions.

Physicochemical Properties

Size and Shape: Rajak et al. (2023) report the synthesis of spherical AgNPs approximately 5 nm in size using *Curcuma longa* flower extract, characterized by UV-Visible spectroscopy, X-ray diffraction (XRD), and High-Resolution Transmission Electron Microscopy (HR-TEM).

Surface Charge and Stability: Patel et al. (2023) discuss the influence of surface charge and the role of capping agents in maintaining the colloidal stability of AgNPs, which helps prevent aggregation.

Crystallinity and Surface Chemistry: Vidyasagar et al. (2023) highlight the crystalline nature of AgNPs and emphasize the importance of surface functionalization for improving biocompatibility and enhancing reactivity.

Applications

Biomedical Applications: Shahzadi et al. (2025) review the antimicrobial, anticancer, and antioxidant properties of plant-mediated AgNPs, exploring their therapeutic potential in various-medical-applications.

Environmental Applications: Nkosi et al. (2024) investigate the use of AgNPs in water purification, focusing on their ability to remove pollutants and pathogens.

Agricultural Applications: Farooq et al. (2023) discuss the application of AgNPs as nano-pesticides and nano-fertilizers, noting their effectiveness in enhancing crop protection and improving-yields.

Food Packaging and Preservation: Patel et al. (2023) explore the incorporation of AgNPs into food packaging materials, highlighting their role in preventing microbial contamination and extending-shelf-life.

Catalysis: Shahzadi et al. (2025) review the catalytic properties of AgNPs, focusing on their involvement in various chemical reactions and their potential in environmental remediation.

Safety and Regulatory Aspects

Cytotoxicity: Patel et al. (2023) examine the cytotoxic effects of AgNPs on different cell lines, stressing the importance of dose-dependent studies to evaluate their safety profile.

Regulatory Guidelines: Vidyasagar et al. (2023) address the regulatory standards for nanomaterials, discussing the frameworks set by agencies such as the FDA and EPA.

Critical Analysis and Comparative Insights

Despite widespread research supporting the green synthesis of silver nanoparticles (AgNPs) using various biological entities, significant discrepancies persist due to differences in synthesis approaches, choice of biological materials, and characterization methodologies.

For example, **plant-based synthesis** often results in AgNPs with a wide size range, posing challenges for reproducibility and suitability in biomedical applications. Studies employing *Azadirachta indica* and *Camellia sinensis* have shown particle sizes from 5 to 100 nm, but often without precise control over particle shape or distribution. This heterogeneity can influence both therapeutic performance and potential toxicity.

Conversely, **bacterial and fungal methods** tend to produce more uniform and stable nanoparticles, attributed to the involvement of biomolecules such as enzymes and proteins. However, these methods typically require controlled growth environments and longer synthesis times, which hinder their scalability. For instance, while *Fusarium oxysporum* is frequently used, its intracellular synthesis process complicates purification and poses a barrier to industrial-scale production.

Enzyme-mediated synthesis allows for tighter regulation of nanoparticle characteristics, but the high costs and technical difficulties of enzyme extraction and stabilization (e.g., nitrate reductase) have limited its broader adoption. Moreover, direct comparative studies evaluating the toxicity of enzyme-derived versus plant-derived AgNPs are currently lacking.

Existing Gaps and Limitations

- **Absence of Standardized Protocols:**

  There is no universal procedure for green synthesis. Research often tailors protocols to specific plant or microbial systems, which hampers reproducibility and inter-study comparison. Parameters such as pH and temperature are inconsistently reported, making it difficult to generalize findings.

- **Limited Mechanistic Insight:**

  While some studies identify functional phytochemicals involved in nanoparticle formation, the actual chemical pathways remain poorly understood. Real-time monitoring using advanced techniques like LC-MS or NMR is seldom employed.

- **Variability in Toxicity and Biocompatibility:**

  The biological effects of AgNPs can differ based on the synthesis route, yet few investigations directly compare toxicity or pharmacokinetics across AgNPs synthesized from diverse sources under controlled conditions. This limits progress toward their clinical translation.

- **Unclear Environmental Fate:**

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Most studies focus on immediate effectiveness (e.g., antimicrobial activity) rather than long-term ecological impact. Interactions with soil microbiota or aquatic life, for instance, remain underexplored, leaving major questions around their environmental persistence.

Future Research Directions

To overcome these challenges, future research should aim to:

- Perform systematic comparisons of synthesis conditions (e.g., pH, temperature, precursor concentration) across biological systems to determine their influence on nanoparticle traits.
- Apply omics technologies and molecular tools to map out biosynthetic pathways and pinpoint active metabolites responsible for nanoparticle formation.
- Carry out comprehensive toxicological assessments—including in vivo and chronic exposure models—to establish safety profiles for various AgNP formulations.
- Design and optimize scalable microbial bioreactors for consistent and economical production.
- Investigate the degradation, bioaccumulation, and ecological effects of AgNPs to support environmental risk assessments and regulatory compliance.

Safety, Cytotoxicity, and Regulatory Considerations

Although silver nanoparticles (AgNPs) synthesized through green methods are typically viewed as more environmentally friendly and biocompatible than those produced via conventional chemical processes, questions about their safety and potential toxicity—especially in biomedical and ecological contexts—persist.

Cytotoxic Effects of AgNPs

AgNPs are well-known for their antimicrobial and anticancer activities, largely due to their ability to:

- Induce the generation of reactive oxygen species (ROS),
- Compromise cellular membranes, and
- Disrupt critical biological processes such as DNA replication and protein synthesis.

However, these mechanisms, while effective against pathogens and cancer cells, can also harm healthy mammalian cells. Research indicates:

- **Smaller nanoparticles** (less than 20 nm) are generally more toxic due to their increased surface area and enhanced reactivity.
- **Surface functionalization** using biomolecules from plant extracts or proteins may reduce cytotoxicity by improving nanoparticle compatibility with biological systems.
- **Toxicity depends on multiple factors**, including particle concentration, exposure duration, and cell type.

In vitro experiments have revealed oxidative damage, mitochondrial impairment, and apoptotic cell death in cell lines such as HEK-293, A549, and L929 at elevated AgNP concentrations. Animal studies involving mice and zebrafish have shown nanoparticle accumulation in vital organs like the brain, liver, and kidneys, raising concerns about long-term exposure.

Regulatory Frameworks and Risk Assessment

Although AgNPs are increasingly incorporated into commercial products, regulatory standards specific to nanomaterials are still under development:

- The **U.S. Food and Drug Administration (FDA)** reviews nanoparticle-based products within existing regulations, handling them on a case-by-case basis rather than through dedicated nano-specific guidelines.
- The **Environmental Protection Agency (EPA)** treats nanosilver as a pesticidal substance, requiring product registration for those with antimicrobial claims.
- In Europe, the **European Chemicals Agency (ECHA)** mandates thorough safety evaluations of nanomaterials under the REACH regulation, including data on toxicity and environmental behavior.
- The **Organisation for Economic Co-operation and Development (OECD)** has established standardized protocols for assessing nanomaterial safety, encompassing cytotoxicity, genotoxicity, and ecotoxicity.

Challenges and Strategic Recommendations

- **Testing Inconsistencies:** There remains a critical lack of unified testing procedures for evaluating nanoparticle toxicity across different contexts.
- **Perceived vs. Proven Safety:** While green-synthesized AgNPs are believed to be safer alternatives, they still demand extensive toxicological validation before approval for medical, food-related, or environmental use.
- **Need for Regulatory Differentiation:** Future regulations should recognize and address the distinctions between green-synthesized and chemically-synthesized nanoparticles, especially considering their divergent surface properties and biological interactions.

CONCLUSION

Green synthesis of silver nanoparticles (AgNPs) offers a sustainable, cost-effective, and environmentally friendly approach to nanoparticle production, making it a promising alternative to traditional methods that rely on toxic chemicals and high energy consumption. The use of biological materials such as plant extracts, microorganisms, and enzymes not only eliminates harmful reagents but also provides an efficient means to control the size, shape, and stability of AgNPs.

The physicochemical properties of green synthesized AgNPs, including particle size, shape, surface charge, crystallinity, and surface chemistry, play a significant role in determining their functionality and suitability for various applications. These properties are closely linked to the biological agents used in synthesis, making it possible to tailor nanoparticles for specific uses.

The diverse applications of AgNPs across biomedical, environmental, agricultural, and industrial fields demonstrate their vast potential. Their antimicrobial, anticancer, and catalytic properties, along with their ability to safely interact with biological systems, make them suitable for numerous innovative applications. However, further research is needed to fully understand their long-term effects, toxicity, and environmental impact.

In conclusion, green synthesis of AgNPs represents a significant advancement in nanotechnology, contributing to more sustainable practices and offering exciting opportunities for future developments across a wide range of industries.

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