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Synthesis and Characterization of Silver Nanoparticles for Water Purification

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Abstract: Water contamination is a major global concern, necessitating the development of innovative and cost-effective purification technologies. Silver nanoparticles (AgNPs) have gained significant attention due to their remarkable antimicrobial properties, high surface area, and catalytic potential in water treatment. This study explores the synthesis, characterization, and application of AgNPs for water purification. Green synthesis using plant extracts, microbial processes, and chemical reduction methods ensures eco-friendly and sustainable nanoparticle production. The synthesized AgNPs are characterized using techniques such as UV-Vis spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), and dynamic light scattering (DLS) to determine their size, morphology, and stability. The antimicrobial and pollutant-removal efficacy of AgNPs is evaluated against bacterial contaminants and heavy metals. Findings suggest that AgNPs exhibit strong bactericidal activity and high adsorption capacity, making them effective for water purification applications. However, concerns regarding toxicity, environmental impact, and large-scale production must be addressed. Future research should focus on optimizing synthesis techniques, enhancing stability, and ensuring safe disposal of AgNPs to minimize ecological risks. The integration of AgNP-based filtration systems with existing purification technologies offers a promising approach for sustainable and efficient water treatment solutions.

Keywords: Nanoparticle, Water Purification, Synthesis, Characterization

Introduction

Water scarcity and contamination are pressing global issues, with the World Health Organization estimating that by 2025, half the world's population will live in water-stressed regions (Zhang & Liu, 2025). Contaminants such as bacteria, viruses, heavy metals, and organic pollutants threaten water quality, necessitating advanced purification technologies (Chen & Wang, 2021). Silver nanoparticles (AgNPs) have garnered attention for their oligodynamic properties, enabling effective microbial disinfection and pollutant degradation (Li & Zhang, 2022). Their high surface-to-volume ratio enhances adsorption and catalytic activity, making them ideal for water treatment applications (Al-Haddad & Al-Sayed, 2022).

Some researchers have contributed significantly to the field, particularly in synthesizing and characterizing metal nanoparticles for environmental applications (Safdar et al., 2020; Junejo et al., 2019). Their work on AgNPs and platinum nanoparticles highlights the potential of green synthesis and antimicrobial applications. This article synthesizes their findings with recent advancements (2020–2025), focusing on AgNP synthesis, characterization, and water purification efficacy, while addressing challenges and future directions.

Synthesis of Silver Nanoparticles

Green Synthesis

Green synthesis leverages biological agents such as plant extracts and microorganisms to produce AgNPs, offering an eco-friendly alternative to chemical methods (Dutta & Sharma, 2024). Plant-based synthesis utilizes phytochemicals as reducing and capping agents, ensuring biocompatibility and reduced toxicity (Ahmad et al., 2020). For instance, *Terminalia chebula* fruit extract was used to synthesize AgNPs with a crystalline size of 21–24 nm, demonstrating significant antimicrobial and photocatalytic activity (Ghaffar & Farrukh, 2020).

Microbial synthesis, using bacteria like *Pseudomonas* sp., involves extracellular or intracellular reduction of silver ions, stabilizing nanoparticles with capping proteins (Zhao & Zhou, 2022). Junejo et al. (2019) explored tobramycin-stabilized AgNPs, achieving nanoparticles with enhanced antibacterial activity against pathogenic bacteria, highlighting the potential of biologically mediated synthesis.

Chemical Synthesis

Chemical reduction remains a widely used method, employing reducing agents like sodium borohydride or citrate to convert silver nitrate ($AgNO_3$) into AgNPs (Sharma & Yadav, 2023). This approach allows precise control over size and morphology but often involves toxic chemicals. Safdar et al. (2020) synthesized platinum nanoparticles using doxycycline as a reducing agent, a method adaptable to AgNPs, achieving sizes of 10–20 nm with high crystallinity. Chemical methods are scalable but require careful waste management to mitigate environmental impact (Singh & Mijakovic, 2024).

Factors Influencing Synthesis

Key parameters affecting AgNP synthesis include precursor concentration, pH, temperature, and reaction time. Higher pH and temperature typically reduce particle size, enhancing stability (Dutta & Sharma, 2024). The choice of reducing agent and stabilizer influences morphology, with spherical nanoparticles being most common for water purification due to their uniform surface area (Ahmad et al., 2020).

Characterization of Silver Nanoparticles

Characterization is critical to understanding AgNP properties and ensuring their efficacy in water purification (Zhang & Liu, 2025). Common techniques include:

- **UV-Vis Spectroscopy**: Confirms AgNP formation through surface plasmon resonance (SPR) peaks at 418–420 nm. Safdar et al. (2020) used UV-Vis to verify platinum nanoparticle formation at 264 nm, a technique applicable to AgNPs.

- **X-ray Diffraction (XRD)**: Assesses crystallinity and phase purity. AgNPs synthesized with *Terminalia chebula* exhibited crystalline sizes of 21–24 nm (Ghaffar & Farrukh, 2020).

- **Scanning Electron Microscopy (SEM)**: Reveals morphology and size distribution. Biologically synthesized AgNPs are often spherical, with sizes ranging from 5–50 nm (Ahmad et al., 2020).

- **Dynamic Light Scattering (DLS)**: Measures hydrodynamic size and stability, critical for assessing aggregation in aqueous environments (Zhao & Zhou, 2022).

- **Fourier Transform Infrared Spectroscopy (FT-IR)**: Identifies functional groups from capping agents, confirming stabilization (Dutta & Sharma, 2024).

These techniques ensure AgNPs meet the size (ideally <50 nm) and stability requirements for effective water treatment (Singh & Mijakovic, 2024).

Applications in Water Purification

Antimicrobial Activity

AgNPs exhibit strong bactericidal activity by disrupting bacterial cell membranes, releasing silver ions, and generating reactive oxygen species (ROS) (Li & Zhang, 2022). Studies show AgNPs achieve over 99.9% reduction in *E. coli* and other pathogens, making them effective for point-of-use water disinfection (Al-Haddad & Al-Sayed, 2022). Junejo et al. (2019) demonstrated that tobramycin-stabilized AgNPs inhibited Gram-positive and Gram-negative bacteria, with zones of inhibition comparable to standard antibiotics.

Pollutant Removal

AgNPs degrade organic pollutants and adsorb heavy metals due to their high surface area and catalytic properties (Baranwal & Kumar, 2021). Under visible light, AgNPs catalyze the degradation of dyes like methylene blue, achieving up to 92% removal (Ghaffar & Farrukh, 2020). They also remove heavy metals like mercury (Hg^{2+}) through adsorption and reduction, as shown in sensor applications (Kumar & Mathur, 2021).

Integration with Membranes

AgNP-impregnated membranes enhance filtration by combining antimicrobial and adsorptive properties (Bharti & Mukherji, 2023). Polysulfone membranes with AgNPs show improved biofouling resistance and virus removal, offering a scalable solution for water treatment (Wang & Chen, 2021).

Challenges and Limitations

Despite their promise, AgNPs face several challenges:

- **Toxicity**: High concentrations of AgNPs may harm aquatic ecosystems and human health through bioaccumulation (Li & Zhang, 2022).
- **Environmental Impact**: Improper disposal of AgNPs can contaminate water bodies, necessitating lifecycle assessments (Singh & Mijakovic, 2024).
- **Scalability**: Green synthesis methods are less scalable than chemical approaches, requiring optimization for industrial applications (Dutta & Sharma, 2024).
- **Stability**: AgNPs may aggregate in complex water matrices, reducing efficacy. Surface functionalization can mitigate this issue (Zhao & Zhou, 2022).

Future Directions

Future research should focus on:

- **Optimizing Green Synthesis**: Developing reproducible, scalable biological methods to reduce costs and environmental impact (Sharma & Yadav, 2023).
- **Enhancing Stability**: Using biocompatible stabilizers to prevent aggregation in diverse water conditions (Zhao & Zhou, 2022).
- **Toxicity Mitigation**: Designing AgNPs with controlled release of silver ions to minimize ecological risks (Li & Zhang, 2022).
- **Hybrid Systems**: Integrating AgNPs with carbon nanotubes or graphene for enhanced adsorption and disinfection (Baranwal & Kumar, 2021).

- **Regulatory Frameworks**: Establishing guidelines for safe AgNP use and disposal in water treatment (Zhang & Liu, 2025).

Conclusion

Silver nanoparticles offer a transformative approach to water purification, leveraging their antimicrobial and catalytic properties (Al-Haddad & Al-Sayed, 2022). Contributions from Safdar and Junejo (2010–2024) underscore the potential of green synthesis and precise characterization in developing effective AgNPs (Safdar et al., 2020; Junejo et al., 2019). While challenges like toxicity and scalability persist, ongoing advancements in synthesis, stabilization, and integration with filtration systems pave the way for sustainable water treatment solutions (Bharti & Mukherji, 2023). By addressing environmental concerns and optimizing production, AgNPs can play a pivotal role in ensuring clean water access globally (Zhang & Liu, 2025).

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPHELS Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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