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(Review Article)

A comprehensive review on the synthesis methods and wide-ranging applications of silver nanoparticles

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Abstract

Silver nanoparticles (AgNPs) have emerged as one of the most extensively researched nanomaterials due to their exceptional physicochemical properties and broad-spectrum applications. This review provides a comprehensive analysis of AgNP synthesis methods, including physical, chemical, and biological approaches. Physical methods produce high-purity nanoparticles but require significant energy input. Chemical methods offer precise control over nanoparticle morphology but often involve hazardous reagents. In contrast, biological or green synthesis providing an eco-friendly and sustainable alternative. The diverse applications of AgNPs span multiple fields, including biomedicine, environmental science, and industrial sectors. Despite their significant potential, challenges such as scalability, environmental impact, and potential toxicity must be addressed to ensure the safe and effective utilization of AgNPs.

Keywords: AgNPs; Applications; Silver Nanoparticles; Synthesis Methods

1. Introduction

Nanotechnology is an interdisciplinary field that focuses on the design, synthesis, and application of materials at the nanoscale, typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts [1]. These nanoscale materials have gained widespread attention due to their enhanced reactivity, increased surface area, and improved mechanical, electrical, and optical characteristics [2]. Among the various nanomaterials, silver nanoparticles (AgNPs) have emerged as one of the most extensively studied due to their remarkable antimicrobial activity, high electrical and thermal conductivity, and optical characteristics. Their small size and high surface-area-to-volume ratio contribute to their enhanced functionality, making them highly valuable for applications in medicine, environmental science, electronics, and industry [3].

The synthesis of AgNPs plays a crucial role in determining their size, shape, stability, and functionality. Various synthesis methods have been developed, including physical, chemical, and biological/green approaches, each with its own advantages and limitations [4]. While chemical synthesis provides high efficiency and precise control over nanoparticle properties, it often involves hazardous reagents. In contrast, green synthesis methods utilize plant extracts, microorganisms, or enzymes, offering a more environmentally friendly alternative [5]. Due to their broad range of applications, AgNPs have been widely explored in biomedicine as antibacterial agents, drug delivery systems, and cancer therapies [6]. However, concerns related to scalability, environmental impact, and potential toxicity remain challenges that must be addressed to ensure their safe and effective use [7].

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2. Synthesis methods of silver nanoparticles

2.1. Physical Methods

Physical methods for AgNPs synthesis involve the use of mechanical or thermal processes to break down bulk silver into nanosized particles without the need for chemical reagents [4]. These methods are particularly advantageous as they produce high-purity AgNPs, free from residual chemicals that may affect their functionality [5]. Common physical techniques include laser ablation, physical vapors deposition (PVD), and high energy ball milling (HEBM), each offering unique benefits in nanoparticle production [8]. Laser ablation utilizes high-energy laser pulses to vaporize a silver target in a liquid or gaseous medium, resulting in the formation of nanoparticles with controlled size and morphology [9]. PVD, on the other hand, involves the vaporization of silver in a vacuum environment, followed by condensation onto a substrate, making it a widely used method for nanoparticle coatings and thin films [10]. Meanwhile, HEBM is a top-down mechanical approach where bulk silver is repeatedly fractured and cold-welded through high-energy collisions in a ball mill, gradually reducing the material to nanoscale dimensions [11]. The advantages of the physical method include its rapid process, the use of radiation as a reducing agent, and the absence of hazardous chemicals. However, its drawbacks involve low production yield, high energy consumption, potential solvent contamination, and inconsistent particle size distribution [5].

2.2. Chemical Methods

Chemical methods are among the most widely used approaches for synthesizing AgNPs due to their simplicity, efficiency, and ability to control particle size and shape. These methods typically involve the reduction of silver salts (e.g., silver nitrate) using chemical reducing agents, such as sodium borohydride, ascorbic acid, or citrate, in the presence of stabilizing agents to prevent nanoparticle aggregation [4]. The choice of reducing and stabilizing agents, reaction conditions, and precursor concentrations significantly influences the morphology, size distribution, and stability of the synthesized AgNPs [7]. Several commonly employed chemical techniques include the sol-gel method, chemical vapor deposition (CVD), and chemical reduction method. The sol-gel method facilitates nanoparticle synthesis through the transformation of a colloidal solution into a gel-like network, allowing for precise control over particle size, shape, and composition [12]. CVD is a technique that involves the deposition of AgNPs onto a substrate through the chemical reaction of vapor-phase precursors [4]. Meanwhile, the chemical reduction method remains the most conventional and widely adopted approach, relying on reducing agents to convert silver ions into nanoparticles under controlled conditions [13]. While these methods ensure high yield and reproducibility, their limitations include the use of potentially toxic chemicals, the need for post-synthesis purification, and environmental concerns [14]. To address these issues, researchers are increasingly exploring green chemistry approaches, utilizing plant extracts and biomolecules as eco-friendly alternatives to traditional chemical reagents [15].

2.3. Biological Methods

Biological or green synthesis methods is an environmentally friendly approach that utilizes natural sources such as plants, bacteria, and fungi to produce nanoparticles. One widely studied green synthesis strategy is the use of plant extracts as reducing agents, which not only facilitate the reduction of silver ions but also act as stabilizing agents, ensuring the formation of AgNPs with controlled size and shape [16]. The biochemical composition of plant extracts varies significantly depending on the plant species and the specific plant part used for extraction. These extracts contain a diverse range of biomolecules, including alkaloids, terpenoids, sugars, *NADH-dependent reductase*, phenols, flavonoids, proteins, and tannins [17]. These biomolecules typically possess functional groups such as amine, carbonyl, methoxide, or hydroxyl, which play a crucial role in reducing metal ions and stabilizing nanoparticles during synthesis [18]. Several studies have highlighted that carbonyl and hydroxyl groups present in flavonoids, terpenoids, carbohydrates, and phenolic compounds serve as key reducing agents, playing a vital role in the transformation of Ag^+ ions into Ag^0 nanoparticles [19]. Additionally, proteins, peptides, and the carbonyl groups of amino acids have been shown to exhibit strong binding affinity to Ag^0, forming a protective layer around AgNPs, which enhances their colloidal stability in solution [20]. This method offers several advantages, including a simple and cost-effective process, high nanoparticle stability, short synthesis time, non-toxic byproducts, and easy scalability for large-scale production [21]. To prevent the formation of unwanted or hazardous byproducts, reliable and sustainable green synthesis technologies must be further developed [22].

3. Applications of silver nanoparticles

3.1. Biomedical Fields

Silver nanoparticles (AgNPs) have gained significant attention in the biomedical field due to their antimicrobial, anti-inflammatory, anticancer, and wound-healing properties [23]. Their strong antibacterial activity, attributed to silver ion release and reactive oxygen species (ROS) generation, makes them effective against a broad range of pathogenic bacteria, including antibiotic-resistant strains [24]. AgNPs are also widely explored in drug delivery systems, where their nanoscale size enhances targeted therapy and controlled drug release. Additionally, they exhibit cytotoxic effects on cancer cells, making them a promising candidate for cancer treatment and photothermal therapy [25]. In wound healing, AgNPs are incorporated into dressings and coatings for medical devices to prevent infections and promote tissue regeneration, reducing the risk of microbial contamination in healthcare settings [23].

3.2. Environmental Applications

In the environmental sector, AgNPs play a crucial role in water purification, pollution control, and antimicrobial coatings. Their exceptional ability to disinfect and eliminate harmful microorganisms makes them ideal for use in filtration systems and water treatment technologies [26]. AgNP-based nanomaterials have been employed for the degradation of organic pollutants and the removal of heavy metals from wastewater, providing an eco-friendly approach to water remediation [27]. Furthermore, AgNP coatings on surfaces such as public transport, hospitals, and household items help reduce microbial contamination, lowering the transmission of infectious diseases [28]. Their incorporation into air purification systems also aids in neutralizing airborne pathogens and pollutants, enhancing overall environmental safety [29].

3.3. Industrial Sectors

Silver nanoparticles are extensively utilized in various industrial sectors, including electronics, textiles, and food packaging [30]. In the electronics industry, AgNPs are integrated into conductive inks, sensors, and flexible electronic components due to their high electrical conductivity and stability [31]. The textile industry benefits from AgNP's antimicrobial properties, as they are embedded in fabrics and clothing to create antibacterial and odor-resistant textiles [32]. Additionally, the food and packaging industry employs AgNP-based nanocomposites to enhance food preservation and shelf life by preventing microbial growth and contamination. Their role in coatings, adhesives, and paints further extends their industrial significance, providing self-cleaning and antimicrobial properties for a wide range of consumer and commercial applications [33].

4. Conclusion

Silver nanoparticles (AgNPs) have proven to be valuable nanomaterials due to their unique physicochemical properties and vast application potential. The choice of synthesis method is crucial, as it influences nanoparticle characteristics such as size, shape, stability, and functionality. Physical and chemical methods provide high efficiency and precise control but often require high energy consumption or involve toxic reagents, highlighting the importance of exploring more sustainable alternatives. Biological or green synthesis methods offer an eco-friendly approach by utilizing natural reducing agents, reducing the environmental footprint of AgNP production. The widespread applications of AgNPs in biomedicine, environmental science, and industry underscore their significance in modern technological advancements. However, concerns regarding potential toxicity and environmental implications necessitate further research. Future efforts should focus on optimizing synthesis techniques, enhancing biocompatibility, and establishing regulatory frameworks to ensure safe and responsible AgNP implementation. The continuous development of AgNP technology presents promising opportunities for addressing global challenges in healthcare, environmental sustainability, and industrial innovation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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