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Silver nanoparticles: A review of their therapeutic potential and biocompatibility

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Abstract

Silver nanoparticles (AgNPs) have gained significant attention due to their unique physicochemical properties and wide range of applications in various fields, including medicine, industry, and environmental science. These nanoparticles, typically ranging from 1 to 100 nm, exhibit enhanced antimicrobial activity, making them particularly useful in the treatment and prevention of infections caused by both antibiotic-resistant and non-resistant microorganisms. This review highlights the beneficial effects of AgNPs, focusing on their antibacterial, antifungal, antiviral, and anti-inflammatory properties, as well as their role in wound healing. AgNPs demonstrate remarkable effectiveness against a broad spectrum of pathogens, including Gram-positive and Gram-negative bacteria, fungi, and viruses. Their small size enables better cellular penetration, enhancing their therapeutic potential. Additionally, AgNPs have shown promise in reducing inflammation and promoting tissue regeneration in wound healing applications. Despite these benefits, the increasing use of AgNPs raises concerns regarding their safety and potential toxicity, necessitating further research to understand their long-term effects on human health and the environment. This review also discusses the challenges and future directions for the safe application of AgNPs in various industries and biomedical fields.

Keywords: Silver nanoparticles (AgNPs), antibacterial, antifungal, antiviral, anti-inflammatory, wound healing, nanotechnology

Introduction

Silver nanoparticles (AgNPs) are a class of nanomaterials that have attracted considerable attention in recent years due to their unique size-dependent properties and broad spectrum of biological activities. These nanoparticles, typically ranging from 1 to 100 nanometers in size, exhibit distinct physical, chemical, and biological characteristics compared to bulk silver, including enhanced surface area, increased reactivity, and improved antimicrobial properties. As a result, AgNPs have found applications in a variety of fields, such as medicine, environmental science, and industry, making them one of the most widely studied and applied nanomaterials to date (Burrell *et al.*, 1999; Sondhi & Sondhi, 2004; Buzea *et al.*, 2007) ^[2, 11, 3].

In medicine, AgNPs are particularly valuable for their potent antibacterial, antifungal, and antiviral properties, which make them effective in the treatment and prevention of infections, especially those caused by antibiotic-resistant microorganisms. Their small size enables them to easily penetrate cell membranes, facilitating their ability to interact with and disrupt bacterial cells or viruses (Yin *et al.*, 1999; Elechiguerra *et al.*, 2005; Doshi *et al.*, 2023) ^[15, 5, 18]. Moreover, AgNPs can be used in wound healing, as they promote tissue regeneration, reduce inflammation, and prevent infection (Tian *et al.*, 2007) ^[13]. These properties have made them a promising candidate for use in medical devices, wound dressings, and therapeutic formulations (Prabhu & Poulouse, 2012) ^[9].

In addition to their biomedical applications, AgNPs have been widely utilized in industrial and environmental contexts. In the textile industry, they are incorporated into fabrics to provide antimicrobial properties, thus preventing the growth of bacteria and fungi on garments (Lee & Jeong, 2005) ^[8]. They are also used in coatings, paints, and water filtration systems due to their ability to inhibit microbial growth and degrade pollutants (Vasilev *et al.*, 2009) ^[14]. Furthermore, AgNPs are used in the development of sensors, drug delivery systems, and diagnostic tools, showcasing their versatility and wide-ranging utility (Gros *et al.*, 1981; Davis, 2002) ^[6, 4].

Despite the significant benefits associated with the use of AgNPs, their safety and potential toxicity remain areas of active research. The unique properties of AgNPs, such as their small size and high surface reactivity, may pose potential risks to human health and the environment if not properly managed (Wiesner *et al.*, 2006) [17]. It is crucial to evaluate both the therapeutic advantages and the possible adverse effects of AgNPs to ensure their safe application in various sectors. This review aims to provide an overview of the beneficial effects of silver nanoparticles, with a focus on their antibacterial, antifungal, antiviral, anti-inflammatory, and wound-healing properties, while also addressing the potential risks associated with their use.

Antibacterial Effects

AgNPs possess significant antibacterial properties against a wide spectrum of both Gram-positive and Gram-negative bacteria (Burrell *et al.*, 1999; Yin *et al.*, 1999; Sondhi and Sondhi, 2004) [2, 15, 11]. This includes antibiotic-resistant strains, making them a promising alternative in the fight against resistant infections (Burrell *et al.*, 1999) [2]. AgNPs with diameters ranging from 5 to 32 nm have been found to enhance the antibacterial activity of various antibiotics, such as penicillin G, amoxicillin, erythromycin, clindamycin, and vancomycin, against pathogens like *Escherichia coli* and *Staphylococcus aureus* (Shahverdi *et al.*, 2007) [10]. Their usage as antibacterial agents is especially evident in applications such as textiles, where cotton fibers containing AgNPs exhibit bactericidal effects (Lee and Jeong, 2005) [8]. Furthermore, AgNPs can prevent the growth of algae on external surfaces, such as walls, when used in paints (Vasilev *et al.*, 2009) [14].

Antifungal Effects

AgNPs have been shown to be effective fungicides, demonstrating activity against a broad spectrum of fungi, including *Aspergillus*, *Candida*, and *Saccharomyces* species (Burrell *et al.*, 1999) [2]. These nanoparticles also display fungicidal properties against yeast isolated from bovine mastitis, making them useful in veterinary applications (Kim *et al.*, 2007) [7].

Antiviral Effects

Research has demonstrated that AgNPs, particularly those with diameters between 5 and 20 nm, can inhibit HIV-1 virus replication (Sun *et al.*, 2005) [12]. Additionally, the antiviral activity of AgNPs against HIV-1 has been shown to be size-dependent, with nanoparticles ranging from 1 to 10 nm exhibiting significant effects (Elechiguerra *et al.*, 2005) [5].

Anti-inflammatory Effects

AgNPs also have anti-inflammatory properties, influencing the expression of matrix metalloproteinases (Kirsner *et al.*, 2001). They suppress the expression of pro-inflammatory cytokines such as tumor necrosis factor (TNF)- α , interleukin (IL)-12, and IL-1 β , and induce apoptosis of inflammatory cells (Bhol and Schechter, 2005, 2007) [1]. Studies conducted on BALB/c mice demonstrated that nanocrystalline silver effectively suppressed the expression of TNF- α and IL-12 and induced apoptosis of inflammatory cells, offering comparable effects to steroid creams used for treating dermatitis (Bhol and Schechter, 2005) [1]. Furthermore, AgNPs have been shown to modulate

cytokines involved in wound healing, with significant effects observed in burn wound healing processes (Tian *et al.*, 2007) [13].

Conclusion

Silver nanoparticles exhibit a wide range of beneficial effects due to their unique physicochemical properties. They have proven efficacy in antibacterial, antifungal, antiviral, and anti-inflammatory applications, positioning them as invaluable agents in various biomedical and industrial sectors. Despite their promising potential, it is essential to consider the safety aspects of AgNPs to avoid potential toxicity risks. Further research is required to fully understand the long-term effects of silver nanoparticles, particularly in human health and environmental contexts.

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