Chapter

Biological Agents for the Synthesis of Silver Nanoparticles and their Applications

Gudikandula Krishna, Dasari Thrimothi and Reeja Sundaram

Abstract

The field of nanotechnology is experiencing rapid growth owing to its distinctive functionality and diverse range of applications. Nanomedicine is a field of study that investigates the potential applications of nanotechnology in the areas of disease prevention, treatment, diagnosis, and control. The significance of silver nanoparticles lies in their distinct characteristics, capacity to generate varied nanostructures, extensive range of bactericidal and anticancer properties, wound healing and other therapeutic capabilities, and cost-effectiveness in manufacturing. These nanoparticles are particularly noteworthy due to their size, which can range from 1 to 100 nm. This paper provides an overview of diverse physical, chemical, and biological techniques employed for the synthesis of silver nanoparticles. The text delineates various methodologies utilizing silver nanoparticles as agents for combating microbial and biofilm infections, as well as for their potential as antitumorigenic agents. Additionally, the text explores the applications of silver nanoparticles in the field of dentistry and dental implants, their role in promoting bone regeneration, their use in cardiovascular implants, and their potential as promoters of wound healing. The present study investigates the mechanism of action, synthesis techniques, and morphological characterization of silver nanoparticles in order to evaluate their potential applications in medical therapies and disease control.

Keywords: silver nanoparticles, biological synthesis, characterization, antimicrobial agent, antibiofilm, health management activity

1. Introduction

The distinctive characteristics of size, shape, and morphology of nanoparticles facilitate their interaction with bacteria, plants, and animals [1–4]. Silver nanoparticles (Ag NPs) have demonstrated remarkable bactericidal efficacy against a diverse array of microorganisms [5–7]. These entities are formulated from diverse viewpoints, frequently for the purpose of examining their morphology or physical attributes. Certain authors have employed a chemical approach [8] and have erroneously conflated it with green synthesis, albeit unintentionally. The utilization of Ag NPs in various fields such as electronics, catalysis, pharmaceuticals, and biomedicine for regulating microorganism proliferation in biological systems has rendered them environmentally sustainable [6, 9]. The process of synthesizing Ag NPs through biogenic means entails the utilization of microorganisms such as bacteria, fungi, yeast, actinomycetes, as well as plant extracts [9, 10]. In contemporary times, various components of plants, including but not limited to flowers, leaves, and fruits, as well as enzymes, have been employed in the production of gold and silver nanoparticles. The physical characteristics of nanoparticles, including their dimensions, shape, and durability, are contingent upon various factors such as the preparation technique employed, the solvent utilized, the concentration of the solution, the potency of the reducing agent, and the temperature conditions [9, 10].

Among the various nanoparticles that have been developed and characterized, silver nanoparticles hold a prominent position due to their innate ability to function as an antimicrobial agent, even in their solid state. Despite being acknowledged for its importance at an earlier time, its potential was not fully utilized, with the exception of its application in traditional medicine and numismatics. Approximately 320 tons of silver nanoparticles (Ag NPs) are produced annually for utilization in various applications such as nanomedical imaging, biosensing, and food products [11, 12].

The prevalence of multidrug-resistant bacterial and viral strains is persistently rising, attributed to genetic mutations, environmental pollution, and alterations in ecological circumstances. In order to overcome this dilemma, researchers are endeavoring to create pharmaceuticals for the management of said microbial infections. Several metal salts and metal nanoparticles have demonstrated efficacy in impeding the proliferation of various pathogenic bacteria. Silver and silver nanoparticles (Ag NPs) hold a significant position in the category of metals utilized as antimicrobial agents since ancient times [13, 14]. Silver salts are employed as a means of impeding the proliferation of diverse bacterial strains within the human body. Antimicrobial agents are employed in medical applications such as catheterization, wound care, and burn treatment to safeguard against potential infection [15, 16]. According to Das et al. [17], the growth of certain bacteria can be effectively inhibited by small-sized silver nanoparticles (Ag NPs). Silver nanoparticles (Ag NPs) that are produced using silk sericin (SS), a protein that is soluble in water and extracted from silkworms at a pH of 11, are composed of hydrophilic proteins that possess polar groups such as hydroxyl, carboxyl, and amino functional groups. Functional groups present in the aforementioned molecules exhibit reducing properties towards AgNO3, resulting in the formation of metallic silver [18]. It has been proposed that the hydroxyl groups present in SS are capable of forming a complex with silver ions, thereby impeding their aggregation or precipitation [19, 20]. The elemental state of Ag NPs may experience segregation as a result of the presence of large molecules within the solvent. However, it is unlikely that they will form complexes since both entities are neutral. The screening of the antibacterial efficacy of silver nanoparticles (Ag NPs) capped with SS has been conducted against both gram-positive and gram-negative bacterial strains. The study revealed that the minimum inhibitory concentration (MIC) ranges from 0.001 to 0.008 mM for various microorganisms, including *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, and *Acinetobacter baumannii*.

While there have been numerous publications on the biosynthesis and characterization of silver nanoparticles, there is a dearth of information regarding their green synthesis, biological properties, and mechanism of action [18]. This review aims to provide a comprehensive overview of the biosynthesis process of silver nanoparticles (Ag NPs) using various sources such as plant extracts, bacteria, fungi, viruses, and actinomycetes. The potential of these agents as biological agents and their mechanisms of action have been the subject of discussion [21].

2. AgNP synthesis methods

Various techniques are utilized in the production of silver nanoparticles, encompassing physical, chemical, and biological methods. It is noteworthy that every approach possesses its own set of merits and demerits. In the process of biogenic synthesis of silver nanoparticles, the biological entity functions as a capping, reducing, or stabilizing agent, thereby facilitating the reduction of Ag^+ to Ag^0 [22]. In recent years, there has been a surge in the popularity of biological methods that rely on natural products derived from microorganisms and plants. This can be attributed to their low cost, high yields, and minimal toxicity to both the environment and human health [23]. The subsequent sections outline various techniques employed in the synthesis of silver nanoparticles.

2.1 Biological techniques

The manufacture of silver nanoparticles through physical and chemical means is a costly, protracted, and environmentally unfriendly process. Therefore, it is of utmost significance to devise a technique that is both ecologically and financially sustainable; the production method in question is devoid of hazardous chemicals [24] and circumvents the complications that arise from chemical and physical manufacturing techniques. Biological techniques serve to address these lacunae and possess diverse utilities in healthcare administration by means of controlling diverse biological processes. Biological production techniques encompass the utilization of microorganisms such as fungi, bacteria, and yeasts, as well as botanical sources. The popularity of utilizing nanoparticles in medical applications is largely attributed to the sources cited.

According to reports, the utilization of microorganisms and plants for nanoparticle production is a safe and cost-effective method that poses relatively lower environmental risks compared to chemical synthesis [25, 26]. Furthermore, it has been observed that microorganisms and plants possess the capability to assimilate and amass inorganic metallic ions from their ambient milieu [27]. The production of silver nanoparticles through biological means primarily entails the utilization of microorganisms and plant-based sources (**Figure 1**) [28].

2.2 Production in bacteria

A recent investigation was conducted to synthesize silver nanoparticles by means of reducing aqueous Ag + ions with the aid of culture supernatants derived from diverse bacterial strains. The expeditiousness of this methodology was exhibited, as the amalgamation of silver ions with the cellular filtrate resulted in the production of silver nanoparticles in a mere 5-minute timeframe. Additionally, the present study documented that piperine exhibited partial inhibition of the process of reducing Ag^+ to metallic silver nanoparticles [29]. It is noteworthy that the nitro reduction activity exhibited by *Enterobacteriaceae* is impeded by the naturally occurring compound piperine. It is postulated that the process of bioreduction, which involves the conversion of silver ions to silver nanoparticles, may experience partial hindrance due to the presence of various strains of Enterobacteriaceae, including *Klebsiella pneumonia*.

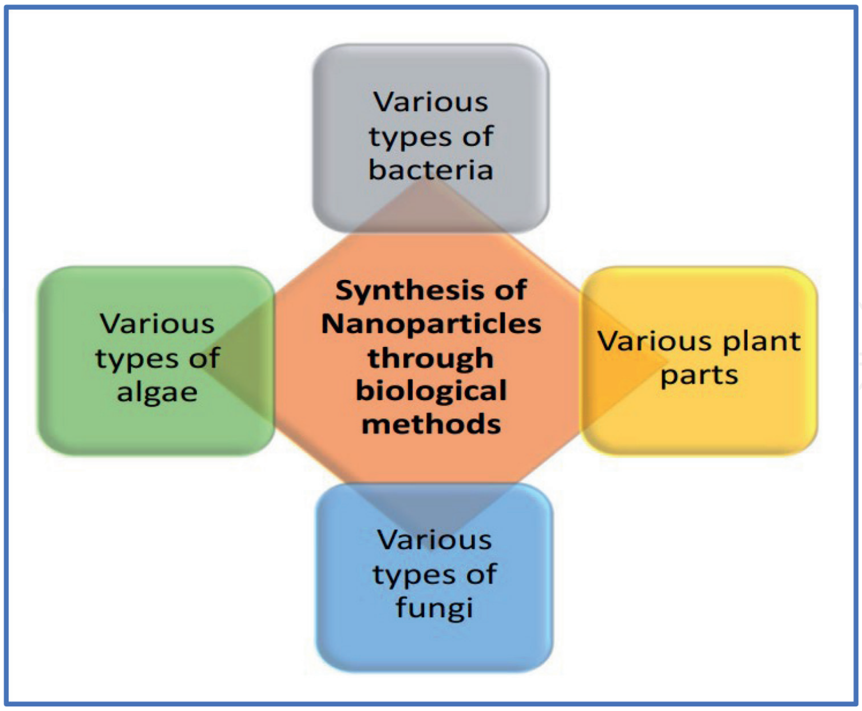

Figure 1.
Various biological approaches for the production of silver nanoparticles.

The optimization of silver nanoparticle production by *Lactobacillus casei* subspecies casei was investigated by Korbekandi et al. The study confirmed the bio-reductive synthesis of silver nanoparticles [30]. The study conducted by Liu and colleagues demonstrated the production of nanoparticles through the desiccation of *Bacillus megaterium* cells [31]. According to Das et al. a particular bacterial strain is used in the extracellular manufacture of silver nanoparticles. According to the study, the application of AgNO3 to Bacillus strain CS 11 led to the extracellular production of silver nanoparticles [32]. It was also reported that piperine exhibited partial inhibition of the reduction process of Ag + to form metallic silver nanoparticles [29]. It is interesting that the nitro reduction activity exhibited by Enterobacteriaceae is impeded by the naturally occurring compound piperitone. It is postulated that the process of bio-reduction, which involves the conversion of silver ions to silver nanoparticles, may experience partial inhibition due to the presence of various strains of Enterobacteriaceae, including *Klebsiella pneumoniae*. The optimization of silver nanoparticle production by *Lactobacillus casei* subspecies casei was investigated by Korbekandi et al. who confirmed the bio-reductive synthesis of silver nanoparticles [30]. The study conducted by Liu and colleagues demonstrated the generation of nanoparticles through the desiccation of *Bacillus megaterium* cells [31]. The extracellular production of silver nanoparticles by a bacterial strain has been described by Das et al. The research findings indicate that the application of $AgNO_3$ to Bacillus strain CS 11 led to the extracellular synthesis of silver nanoparticles [32].

2.3 Synthesis/production based on fungi

Diverse fungal species have been documented to participate in the synthesis of silver nanoparticles [33]. The rapidity of silver nanoparticle synthesis by fungi has been observed to be significant. The biosynthesis of silver nanoparticles by fungi has been a subject of study for numerous researchers [34]. A study has demonstrated the extracellular synthesis of spherical silver nanoparticles through the interaction between Fusarium solani and silver nitrate [35]. The biosynthesis of silver nanoparticles by the Humicola sp. has been reported by Syed et al. The study demonstrated that the reduction of a precursor solution occurred through the interaction between Humicola sp. and Ag + ions, resulting in the production of extracellular nanoparticles [36]. The production of silver nanoparticles through bio-reduction of silver nitrate, induced by the extract of *Pleurotus cornucopia*, has been reported by Owaid et al. [37]. The biosynthesis of silver nanoparticles with antifungal properties was investigated by Xue et al. through the utilization of Arthroderma fulvum in an experimental setting [38]. According to Vigneshwaran et al.'s findings, the fungus *Aspergillus flavus* exhibited the accumulation of silver nanoparticles on its cell wall surface as a result of its interaction with a silver nitrate solution [39]. Additionally, Bhainsa and D'Souza conducted a study on the extracellular synthesis of silver nanoparticles utilizing *Aspergillus fumigatus*. The findings suggest that the amalgamation of silver ions and the cell filtrate resulted in the production of silver nanoparticles within a brief duration [40]. The utilization of *Fusarium oxysporum* leads to the extracellular synthesis of silver nanoparticles, which exhibit a size range of 5–50 nm [41]. Furthermore, the introduction of a silver nitrate solution to *Phanerochaete chrysosporium* mycelium resulted in the production of silver nanoparticles [42]. The bio-reductive synthesis of silver nanoparticles was demonstrated by Korbekandi et al. through the utilization of *Fusarium oxysporum* [43].

2.4 Synthesis/production in algae

The aforementioned methodology presents a viable alternative to conventional physical and chemical techniques for synthesizing nanoparticles, owing to its cost-effectiveness and environmentally sustainable nature [44]. In addition, it has been observed that algae exhibit a significant ability to absorb metals. Observations have indicated that biological entities, such as marine algae, possess the ability to facilitate particular chemical reactions. The ability to perform this function is crucial for contemporary and pragmatic biosynthetic strategies [45]. According to a recent study utilizing algae extract, the alteration of hue from yellow to brown may serve as an indicator of the reduction of silver ions to silver nanoparticles. Furthermore, Rajesh Kumar et al. observed a significant deepening of the brown hue of silver nanoparticles after 32 hours of incubation. This finding suggests a positive correlation between the duration of incubation and the intensity of the observed coloration [46]. The present study reports the synthesis of silver nanoparticles via reduction of aqueous solutions of silver nitrate, utilizing powder and solvent extracts of *Padina pavonia*. Moreover, the nanoparticles obtained exhibited notable stability, rapid formation kinetics, and diminutive dimensions [47]. The production of silver nanoparticles was reported by Salari et al. via bio-reduction of silver ions, which was induced by Spirogyra variants [48].

2.5 Synthesis/production in virus

The utilization of viruses for the production of artificial nanocrystals, including but not limited to cadmium sulfide, silicon dioxide, ferrous oxide, and zinc sulfide, represents a distinctive methodology. The investigation of methods for generating semiconductor nanoparticles, including zinc sulfide and cadmium sulfide, is currently a topic of great interest in the electronics industry and the field of green chemistry. The employment of intact viruses in the synthesis of nanomaterials has been a topic of investigation for numerous years [49]. The extrinsic capsid protein of the virus serves a beneficial function in the creation of nanoparticles through the production of a metal ion-binding interface with notable reactivity [50]. At the exterior of the tobacco-mosaic virus [TMV], the total number of capsid proteins is 2130. Peptides possess the potential to serve as interlocking components for the construction or production of three-dimensional conduits intended for diverse medical applications [51]. The reduction in size of the synthesized nanoparticles was observed upon the addition of Au and Ag salts in moderate quantities to TMV, prior to the introduction of plant extracts from *Nicotiana benthamiana* or Hordeum vulgare. The augmented quantities of free nanoparticles observed at higher concentrations of tobacco mosaic virus (TMV) in comparison to the control group indicate a relatively modest production of the nanoparticles. The utilization of TMV as a biological template for the metallization of nanowires was also observed [52]. In contrast to a scenario without the virus, the existence of a pathogen not only resulted in a decrease in the length of biosynthesized nanoparticles but also significantly augmented their synthesis.

2.6 Synthesis/production in Actinomycetes

Actinomycetes exhibit the ability to produce both intracellular and extracellular nanoparticles through their metabolic processes. The process of intracellular synthesis takes place at the mycelia surface as a result of electrostatic attraction between Ag + ions and the negatively charged carboxylate groups found in the enzyme located on the mycelia cell wall. Subsequently, the enzymes present in the cellular wall facilitate the reduction of Ag + ions, leading to the formation of silver nuclei. The aggregation of silver nuclei results in the generation of silver nanoparticles at the nanoscale level [53]. The process of synthesizing gold nanoparticles was carried out using Rhodococcus sp., which is a type of alkalotolerant Actinomycetes. The presence of nanoparticles on the Actinomycetes' cell walls was confirmed by transmission electron microscopy (TEM) images, indicating that the nanoparticles were synthesized intracellularly [54]. It has been revealed that Rhodococcus NCIM 2891 can be used for the intracellular manufacture of silver nanoparticles [55]. After 72 hours of contact with HAuCl4, the previously yellow biomass of *Streptomyces hygroscopicus* changed pink, indicating the production of extracellular gold nanoparticles [56]. The production of silver, manganese, and zinc nanoparticles by Streptomyces sp. HBUM171191 was observed upon exposure of the wet biomass to the respective metal solutions. The alteration in hue of the biomass, transitioning from a light-yellow shade to brown, dark yellow, and dark yellow, respectively, is indicative of the synthesis of silver, manganese, and zinc nanoparticles [57]. The enzymatic processes associated with the nitrogen cycle have been identified as a potential mechanism for the extracellular biosynthesis of nanoparticles. It is possible that they could assume responsibility for the enzymatic reduction of metals through electron shuttle [58]. Thea-NADH-dependent nitrate reductase is a significant contributor to the process of reducing Ag + ions to silver nuclei. Actinomycetes were responsible for mediating the extracellular creation of nanoparticles by the use of Streptomyces glaucus71MD [59]. Within 12 hours, a pure culture of Streptomyces sp. ERI-3 was able to convert a colorless solution of silver nitrate to a color that was more reddish-brown [60], indicating the creation of silver nanoparticles.

3. Biological applications of AgNPs

Because of their one-of-a-kind qualities, silver nanoparticles (AgNPs) have found widespread use in a variety of fields, including the healthcare sector, the food storage business, as well as environmental and medicinal applications. There have been a number of reviews and book chapters written on the subject of the application of AgNPs in a variety of different fields. Antibacterial, antifungal, antiviral, antiinflammatory, anticancer, and antiangiogenic treatments are only a few of the biological and medicinal applications that we would like to highlight here using silver nanoparticles (AgNPs). In this article, we focused specifically on previously published seminal works, and we concluded with more current revisions. **Figure 2** provides a diagrammatic representation of a number of different applications utilizing AgNPs.

3.1 Anti-bacterial activity of AgNPs

Silver nanoparticles (AgNPs) have emerged as a potential substitute for antibiotics in combating bacterial infections, owing to their capacity to surmount the bacterial resistance that has developed against conventional antibiotics (**Figure 3**). Consequently, the development of silver nanoparticles (AgNPs) as antibacterial agents is deemed imperative. AgNPs exhibit potential as antibacterial agents owing to their crystallographic surface structure and large surface-to-volume ratios, among other promising nanomaterials. Sondi and Salopek-Sondi's seminal study, as documented in [61], showcased the efficacy of AgNPs in combating *Escherichia coli*. The study revealed that the treatment of *E. coli* cells with AgNPs resulted in the accumulation of AgNPs in the cell wall and the formation of "pits" in the bacterial cell walls, ultimately leading to cell death. Additionally, the study demonstrated the antimicrobial properties of AgNPs. The antibacterial activity of smaller particles with a greater surface-to-volume ratio was found to be more efficient than that of larger particles in the identical *E. coli* strain [62]. Moreover, it should be noted that the antibacterial efficacy of silver nanoparticles (AgNPs) is contingent not only on their size but also on their shape [63]. Silver nanoparticles (AgNPs) were produced using four distinct saccharides, resulting in an average size of 25 nm. The AgNPs exhibited notable antimicrobial and bactericidal properties against both Gram-positive and Gram-negative bacteria, including methicillin-resistant *Staphylococcus aureus* and other highly resistant strains. As

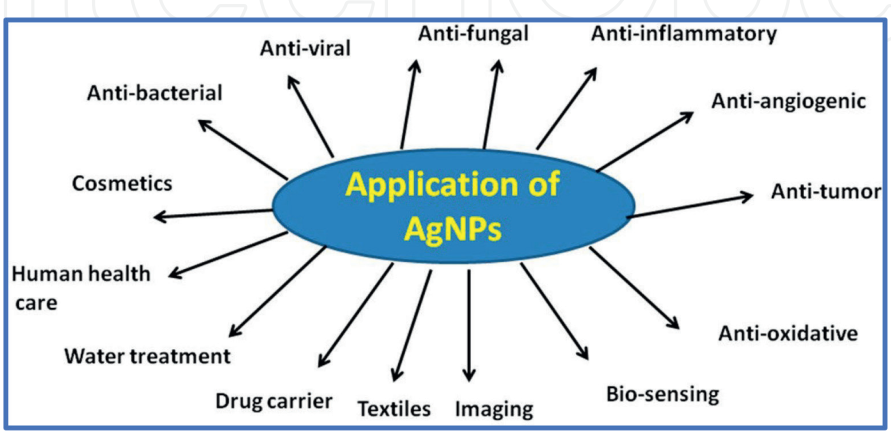

Figure 2.
AgNPs have a wide range of potential applications.

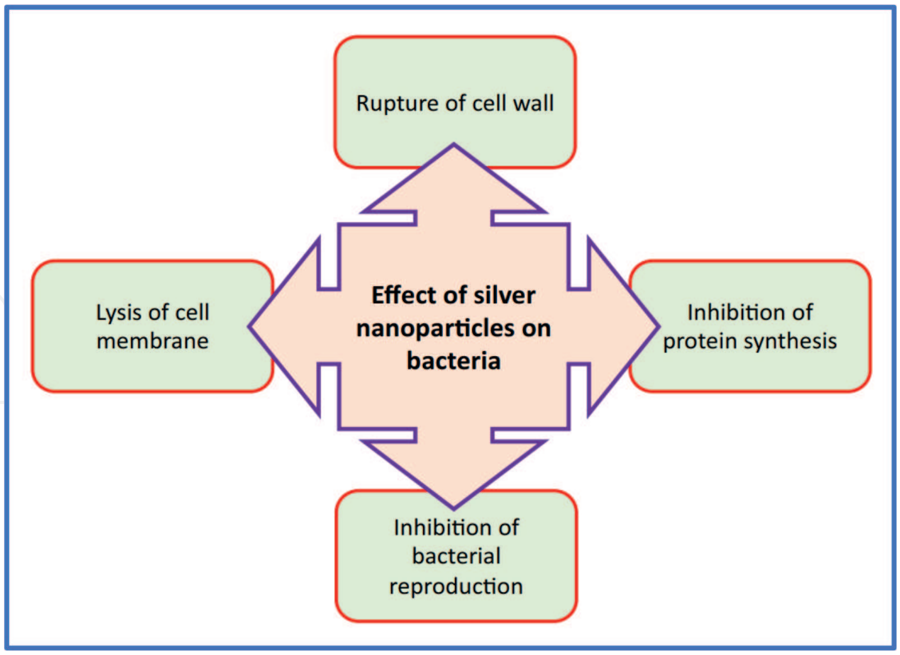

Figure 3.
A schematic representation of the mechanisms underlying the antibacterial activity of silver nanoparticles.

previously noted, the efficiency of AgNPs is determined not only by their size but also by their shape, as they exhibit a shape-dependent interaction with the Gram-negative organism *E. coli* [64]. Additionally, a comprehensive investigation was conducted to assess the efficacy of silver nanoparticles (AgNPs) in combating yeast, *E. coli*, and *Staphylococcus aureus* antimicrobial activity. The findings indicate that yeast and *E. coli* exhibited complete growth inhibition at low concentrations of AgNPs, whereas a minor impact was observed in *S. aureus* [65]. The present study assessed AgNPs that were biologically synthesized from the culture supernatants of *Klebsiella pneumoniae*. The impact of Ag-NPs on the efficacy of different antibiotics, including penicillin G, amoxicillin, erythromycin, clindamycin, and vancomycin, was evaluated against *Staphylococcus aureus* and *E. coli*. The results indicated that the presence of Ag-NPs led to an increase in the effectiveness of the aforementioned antibiotics [66]. In comparison to silver nanoparticles, hydrogel-silver nanocomposites exhibited remarkable antibacterial efficacy against *Escherichia coli*. The composite of chitosan-Ag-nanoparticle, synthesized in a single reaction vessel, exhibited superior antimicrobial properties compared to its constituent parts at equivalent concentrations. This can be attributed to the preferential formation of small AgNPs bound to the polymer during the one-pot synthesis process, which allows for dispersion in media with a pH of 6.3 or lower [67]. The utilization of culture supernatants of *Staphylococcus aureus* for the biological synthesis of AgNPs resulted in noteworthy antimicrobial activity against methicillin-resistant *S. aureus*, methicillin-resistant *Staphylococcus epidermidis*, and *Streptococcus pyogenes*. However, the antimicrobial activity against *Salmonella typhi* and *Klebsiella pneumoniae* was only moderate [68]. The present study investigated the cellular mechanisms underlying the induction of cell death by AgNPs in *E. coli*. Specifically, the study examined the leakage of reducing sugars and proteins as indicators of cell death. Moreover, it has been observed that AgNPs possess the ability to disrupt the permeability of bacterial membranes by creating numerous pits and gaps. This suggests that AgNPs have the potential to impair the structural integrity of bacterial cell membranes [69]. The AgCHX complex consisting of silver nanocrystalline and chlorhexidine, exhibited potent antibacterial efficacy against a range of Gram-positive/negative bacterial strains and methicillin-resistant *Staphylococcus aureus* (MRSA) strains. The results indicate that the nanocrystalline Ag (III)CHX exhibited significantly lower minimal inhibitory concentrations (MICs) compared to the ligand (CHX), AgNO3, and the established benchmark. Silver sulfadiazine is a topical antimicrobial agent commonly used in the treatment of burns and other skin injuries [70].

3.2 Antiviral activity of AgNPs

Nanoparticles present a viable substitute to pharmaceuticals in the management and regulation of viral pathogen proliferation. The process of biosynthesizing silver nanoparticles has the potential to yield highly effective antiviral agents that can effectively impede the functions of viruses. The bio-silver nanoparticles were investigated by Suriyakalaa et al. for their anti-HIV properties during the initial phase of the reverse transcription process, yielding compelling results [71]. Metallic nanoparticles synthesized through biosynthesis possess numerous binding sites for gp120 present in the viral membrane, thereby regulating the virus's functionality. According to another study, bio-based nanoparticles have been found to be efficient virucidal agents against both free HIV and cell-associated virus [72]. Studies have shown that silver nanoparticles exhibit antiviral properties against HIV-1 at concentrations that do not cause harm to cells. The present study aimed to assess the mechanism of antiviral activity of silver nanoparticles against HIV-1 through a range of in vitro assays [73]. According to a different study, the monkeypox virus was resistant to the antiviral effects of silver nanoparticles with or without a polysaccharide covering. The present investigation has revealed that silver nanoparticles exhibit significant inhibitory effects against monkeypox virus infection *in vitro* [74].

Pre-exposure of Tacaribe virus to silver nanoparticles was found to enhance the virus's cellular uptake in host cells. The observation was made that the introduction of silver treatment resulted in a noteworthy decrease in the production of viral RNA. This discovery serves as evidence that silver nanoparticles possess the ability to impede the infection of arenavirus *in vitro* [75]. According to a recent study, it was found that out of the three types of silver nanoparticle-MHCs that were tested, Ag30-MHCs exhibited the most effective viral inactivation [76].

3.3 Antifungal activity of AgNPs

The antifungal properties of silver nanoparticles have been demonstrated against various fungal species [77, 78]; however, the underlying mechanism remains incompletely comprehended. The presence of silver nanoparticles has been observed to disrupt the integrity of the cellular membrane structure. The suggested mechanism for the antifungal activity of silver nanoparticles against *Candida albicans* species involves the inhibition of the budding process and damage to the membrane integrity [79]. The present investigation employed nano-Ag sepiolite fibers that contained monodispersed silver nanoparticles as the silver source to examine their antibacterial and antifungal properties. Soda with a low melting point. The incorporation of nanoparticles into lime glass powder resulted in favorable antibacterial and antifungal properties [80]. According to a study, the combination of fluconazole and silver nanoparticles exhibited the most significant inhibition against *Candida albicans*. The present investigation employed *Alternaria alternata* fungus for the purpose of extracellular biosynthesis of silver nanoparticles [81]. The study determined that the growth of fungi was significantly reduced by the presence of silver nanoparticles at concentrations ranging from 30 to 200 mg/L [82]. Additionally, the supernatant of the GP-23 strain was utilized in the production of silver nanoparticles, which exhibited potent antifungal properties [83]. The utilization of *Trichoderma harzianum* cell filtrate was employed in the synthesis of silver nanoparticles, yielding their production in a mere 3 hours. Subsequent analysis via TEM revealed the presence of both ellipsoid and spherical nanoparticles, with a size range spanning from 19 to 63 nm and an average size of 34.77 nm [84]. According to Jalal et al.'s findings through transmission electron microscopy analysis, the application of silver nanoparticles on Candida cells led to a significant distortion of the cellular structure. Moreover, the augmentation of cell contraction was observed as a result of the interaction between nanoparticles and the fungal cell wall and membrane. The observed outcome was the disruption of the cellular membrane structure, which impeded the typical budding process as a result of compromised membrane integrity and damage [85]. In their study, Jalal et al. demonstrated the antimicrobial properties of silver nanoparticles derived from Syzygium cumini against Candida species. The authors concluded that these nanoparticles possess the ability to inhibit the proliferation, germ tube, and biofilm formation, as well as the secretion of hydrolytic enzymes by Candida species [86].

3.4 Antiparasitic action of AgNPs

The larvicidal properties of silver nanoparticles against Aedes aegypti [87] and Culex quinquefasciatus, which are dengue vectors, have been identified. A study was conducted by Allahverdiyev et al. to assess the impact of silver nanoparticles on the biological parameters of Leishmania tropica. The findings of this investigation have substantiated the antileishmanial properties of silver nanoparticles, which can be attributed to their ability to impede the proliferation activity of promastigotes. Additionally, it was observed that silver nanoparticles exhibited the ability to impede the viability of amastigotes within host cells, and this phenomenon was augmented by the existence of ultraviolet radiation [88]. The antiparasitic activity of silver and copper nanoparticles synthesized by Saad et al. was investigated. The results indicated that the viability of *Cryptosporidium parvum* oocysts was significantly reduced by silver nanoparticles. The results indicate that silver nanoparticles exhibited notable efficacy and safety in combatting parasitic infections caused by *Entamoeba histolytica* and *Cryptosporidium parvum* [89].

3.5 Antifouling action of AgNPs

Biofouling represents a significant obstacle encountered by the water industry and public health. The efficacy of silver nanoparticles derived from the *Rhizopus oryzae* fungal species has been evaluated for the remediation of water contaminated with pollutants. The utilization of *Lactobacillus fermentum* cells in the production of silver nanoparticles has been observed to effectively regulate biofilm formation. Additionally, the antifouling characteristics of these nanoparticles have been verified. In addition, silver nanoparticles have been utilized in various environmental applications, including but not limited to air, water, and surface disinfection [90]. A recent investigation has indicated that the direct application of silver nanoparticle coatings onto ecologically sound surfaces can lead to a proficient control of biofouling [91].

3.6 Antibiofilm activity

In contemporary times, silver nanoparticles have emerged as a potential agent for impeding biofilm formation. However, the precise mechanism underlying the inhibitory effect of silver nanoparticles remains elusive. The classification of antibiofilm strategies was conducted by Chen et al. who identified two distinct categories: (i) interventions that specifically impede the formation of biofilms and (ii) the utilization of modified biomaterials in biomedical devices to prevent and resist biofilm formation [92]. Prior studies have corroborated novel methodologies for surface modification of biomedical apparatuses with the aim of impeding microbial attachment, adhesion, and proliferation [93]. The present investigation examined the antibiofilm efficacy of silver nanoparticles against multidrug-resistant Gram-negative bacterial isolates, and it was found that they successfully inhibited biofilm formation [94]. Martinez-Gutierrez et al. drew the conclusion that silver nanoparticles effectively hindered the formation of biofilms and exhibited bactericidal properties against established biofilms based on their research findings [95].

A study was conducted by Palanisamy et al. to investigate the impact of silver nanoparticles on biofilm formation. The study exhibited that the silver nanoparticles effectively hindered the development of biofilms in antibiotic-resistant strains [96]. A recent study was conducted to assess the interaction between silver nanoparticles and Pseudomonas putida biofilms. The study demonstrated that the utilization of silver nanoparticles effectively inhibited the formation of biofilms [97]. The antibiofilm activity of silver nanoparticles against biofilms created by Pseudomonas aeruginosa and Staphylococcus epidermidis was examined by Kalishwaralal et al. The application of silver nanoparticles on these organisms resulted in the suppression of biofilm formation [98]. Mohanty et al. conducted a study to assess the antibacterial efficacy of silver nanoparticles against a range of human pathogens.

4. Conclusion

The broad spectrum of applications of silver nanoparticles, including their use as antimicrobial and antitumor agents, as well as in food packaging, agriculture, and healthcare, positions them as a crucial component in health management. Moreover, it is widely recognized that the majority of practical applications of antibiotics demonstrate resistance, resulting in a lack of efficacy. Therefore, the presence of bacteria that form biofilms poses a significant issue. The issue of antibiotic resistance has garnered heightened global attention, leading to a focus on alternative treatment approaches. The potential employment of silver nanoparticles and the surface coating or impregnation of nanomaterials are among the alternative strategies that can be utilized as antibiofilm agents. Furthermore, silver nanoparticles have been extensively researched and employed in the treatment of diverse ailments, encompassing cancer, wound healing, dental implants, and other therapeutic interventions that involve the modulation of biological activities. Through increased comprehension and advanced technological capabilities, the utilization of these innovative particles within the medical field will establish a standardized framework for preventing and treating multidrug resistance and biofilm pathogens.

Conflict of interest

The authors state no conflict of interest.

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