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Microbial Fabrication of Silver Nanoparticles: From Biosynthesis to Applications

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ABSTRACT

The synthesis of silver nanoparticles (AgNPs) using bacteria has emerged as an attractive, eco-friendly, and cost-effective approach in the field of nanotechnology. This review article comprehensively discusses the diversity of bacteria, including both Gram-positive and Gram-negative strains, capable of producing AgNPs through intracellular and extracellular mechanisms. The characteristics of AgNPs, such as size, shape, and crystallinity, are influenced by the bacterial species and the synthesis conditions. The proposed mechanism of AgNP production involves the reduction of silver ions by bacterial proteins, enzymes, and other biomolecules. The applications of bacterially synthesized AgNPs are vast, encompassing antibacterial, antifungal, antiviral, cytotoxic, antibiofilm, catalytic, and insecticidal activities. The antibacterial activity of AgNPs against various pathogenic bacteria, including antibiotic-resistant strains, is particularly promising. Furthermore, AgNPs exhibit potential in cancer therapy, environmental remediation, and the development of biosensors. Despite the numerous advantages of bacterially synthesized AgNPs, further research is needed to elucidate their long-term effects on human health and the environment. This review highlights the immense potential of bacteria as a sustainable source for AgNP production and their diverse applications, paving the way for future advancements in nanomedicine and biotechnology.

Keywords: bacteria, diversity, extracellular, intracellular, silver nanoparticles (AgNP's)
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INTRODUCTION

Due to their numerous uses in fields such as medicine, electronics, energy, catalysis, biosensors, and good activity against microorganisms, silver nanoparticles (AgNPs) have recently gained significant research attention and growing demand (Kang et al., 2016). According to reports, AgNPs can be produced chemically (using techniques such as microwave-assisted synthesis, microemulsion, pyrolysis, Tollen's method, and electrochemistry), photochemically (using the photo reduction, which is initiated by UV and photoreduction), physically (using techniques such as milling, ablation using lasers, irradiation, and evaporation-condensation), and biologically (using microbes and plants) (Singh et al., 2015). The physiochemical processes necessary for synthesizing AgNPs are costly, time- and energy-intensive, demand extreme temperatures and vacuum environments, and produce harmful by-products that could injure humans and represent a number of dangers to the environment (Borase et al., 2014).

Therefore, given their economic efficacy, safeness, and safety, and contribution to environment sustainability, biological approaches such as the synthesis of AgNPs using greener methods are chosen over the existing approaches (Jayaseelan et al., 2012). The employment of bacteria to synthesize AgNPs is growing among biological methods due to their sustainable behavior, bio-compatible behavior, cost efficacy, benign, and ease of production in large quantities (Law et al., 2008). The first time that *Pseudomonas stutzeri* AG 259, bacteria useful in mining silver that converts ions of silver atoms, that is, AgNP, was reported in literature (Klaus et al., 1999). The aforementioned report encouraged the producing AgNPs by various other bacterial species. The characteristics of several bacteria, including both Gram-positive negative, sequestered from various environments and capable in synthesizing AgNPs have been

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presented in Table 1. Current research sheds light on various bacterial genres and strains that are identified to produce AgNPs in terms of characteristics of particles and their uses.

CHARACTERISTICS OF SILVER NANOPARTICLES

AgNPs have several uses and key properties, which creates a strong demand for their manufacturing. The primary distinguishing characteristics of AgNPs are minute sizes (ranging between 1 and 100 nm, that fall between levels of atomic and bulk sizes of materials). The size of the nanoparticles produced during the biogenic production of AgNPs entirely relies on the agents used to cause reduction and the bacterial genre employed. The original bacterium employed for manufacturing AgNPs (sizes of 200 nm) through cultivation in elevated amounts of AgNO3 was reported as P. stutzeri AG259, which was silver-resistant. Similarly, AgNPs obtained from *Bacillus* sp. culture ranged between 5 and 15 nm (Pugazhenthiran et al., 2009). Table 1 shows the diameters of AgNPs formed by several bacterial species. Given that AgNPs have several desirable characteristics, including a large ratio of surface-to-volume, lower melting points, higher superconductivity, higher changeover temperature, low stability of the structure, particular optic properties, and a higher reaction rate, their smaller size is very helpful (Al-Katib et al., 2015).

Table 1: Names of the bacteria that have been found to produce silver nanoparticles ($AgNO_3$)

Bacteria	Shape	Size (nm)	Location*	Reference
Gram-positive				
Streptomyces sp. 09 PBT 005	spherical	198–595	in-vitro	Saravana Kumar et al. (2015)
Streptomyces sp. SS2	spherical	67.95 ± 18.52	in-vitro	Mohanta and Behera (2014)
Streptomyces kasugaensis M338-M1^T	spherical	13.2	in-vitro	Wypij et al. (2017)
Streptomyces celluloflavus NRRL B-2493^T				
Streptomyces glaucus	spherical	4–25	in-vitro	Tsibakhashvili et al. (2011)
Streptomyces albidoflavus	NA	10–14	in-vitro	Priyadarshini et al. (2013)
Streptomyces hygroscopicus	spherical	20–30	in-vitro	Sadhasivam et al. (2010)
Pilimelia columellifera subsp. *pallida*	spherical	12.7–15.9	in-vitro	Golińska et al. (2016)
Sinomonas mesophila MPKL 26	spherical	4–50	in-vitro	Manikprabhu et al. (2016)
Deinococcus radiodurans	spherical	4–50	in-vitro	Kulkarni et al. (2015)
Sporosarcina koreensis DC4	spherical		in-vitro	Singh et al. (2016)
Streptacidiphilus durhamensis HGG16n	spherical	8–48	in-vitro	Buszewski et al. (2018)
Streptacidiphilus sp. CGG11n	spherical	4–45	in-vitro	Railean-Plugaru et al. (2016)
Brevibacterium frigoritolerans strain DC2	spherical	97	in-vitro	Singh et al. (2015)
Bhargavaea indica strain DC1	spherical, triangular, hexagonal,	30–100	in-vitro	Singh et al. (2015)
Weissella oryzae DC6	pentagonal, icosahedral, Spherical	10–30	in-vitro and intracellular	Singh et al. (2016)

Bacteria	Shape	Size (nm)	Location*	Reference
Nocardiopsis valliformis strain OT1	circle	5–50	NA	Rathod et al. (2016)
Staphylococcus aureus	spherical	160–180	in-vitro	Nanda and Saravanan (2009)
Microbacterium resistens	spherical	10–20	in-vitro	Wang et al. (2016)
Rhodococcus sp.	spherical	10–15	intracellular	Otari et al. (2015)
Pedicoccus pentosaceus	NA	NA	intracellular	Sintubin et al. (2009)
Lactobacillus sp.	NA	50	in-vitro and intracellular	Brayner et al. (2007)
L. mindensis	spherical	2–20	in-vitro	Dhoondia and Chakraborty (2012)
Lactococcus lactis	spherical	35	in-vitro	Viorica et al. (2017)
Leuconostoc lactis	spherical	35	in-vitro	Saravanan et al. (2017)
Geobacillus stearothermophilus	spherical	5–50	in-vitro	Mohammed Fayaz et al. (2011)
Exiguobacterium sp.	spherical	10–50	in-vitro	Tamboli and Lee (2013)
Corynebacterium sp. SH09	NA	10–15	in-vitro	Zhang et al. (2005)
Brevibacterium casei	spherical	10–50	in-vitro	Kalishwaralal et al. (2010)
Bacillus sp.	NA	5–15	in-vitro and intracellular	Pugazhenthiran et al. (2009)
Bacillus thuringiensis	NA	43.52–142.97	in-vitro	Banu et al. (2014)
Bacillis subtilis	triangular, hexagonal	20–60	in-vitro	Kannan et al. (2011)
B. subtilis	spherical	60	in-vitro	Kannan et al. (2011)
B. subtilis	spherical	5–60	in-vitro	Sathiyanarayanan et al. (2013)
B. subtilis ANR 88	spherical	4–18	in-vitro	Saifuddin et al. (2009)
B. magaterium	hexagonal and cubical	15–50	in-vitro	Rane et al. (2017)
Bacillus cereus	spherical	15	in-vitro	Zaki et al. (2011)
	hexagonal	10–20	in-vitro	Prakash, et al. (2011)
B. methylotrophicus	spherical	10–30	in-vitro	Pourali and Yahyaei (2016)
Bacillus pumilus	spherical	77–92	in-vitro	Wang et al. (2016)
Bacillus licheniformis	spherical	18.69–63.42	in-vitro	Elbeshehy et al. (2015)
Bacillus stearothermophilus	spherical	14 ± 4	in-vitro	Shanthi et al. (2016)
B. thuringiensis	NA	20–40	in-vitro	El-Batal et al. (2013)
S. aureus				
Staphylococcus epidermidis	spherical, oval, rod,	<60	intracellular	Verma et al. (2018)
	and triangular Spherical		in-vitro	

Bacteria	Shape	Size (nm)	Location*	Reference
Streptococcus thermophiles		28–122		Rezvani Amin et al. (2016)
Thermoactinomyces sp.	spherical	20–40	in-vitro	El-Shanshoury et al. (2011)
Ureibacillus thermosphericus	spherical	10–100	in-vitro	Deepa et al. (2013)
Nocardiopsis sp. MBRC-1	spherical	45 ± 0.15	in-vitro	Juibari et al. (2011)
Arthrobacter sp. B4	face-centered cubic	9–72	in-vitro	Manivasagan et al. (2013)
Gram-negative				
Pseudomonas deceptionensis DC5	spherical	127	in-vitro	Yumei et al. (2017)
Pseudomonas aeruginosa	spherical, disc shaped	6.3 ± 4.9	in-vitro and intracellular	Jo et al. (2016)
	spherical	8–24		
	quasispherical	5–25		
P. aeruginosa BS-161R	spherical	13	in-vitro	Srivastava and Constanti (2012)
P. aeruginosa ATCC 27853	spherical	33–300	in-vitro	Kumar and Mamidyala (2011)
P. aeruginosa	spherical	25–45	in-vitro	Peiris et al. (2017)
	pseudospherical			
P. aeruginosa SN5	NA	35–60	in-vitro	Quinteros et al. (2016)
P. aeruginosa DM1	spherical	45–100	in-vitro	Naik et al. (2017)
Pseudomonas sp.	face-centered cubic variable	50	in-vitro	Kumari et al. (2017)
Endosymbiont *Pseudomonas fluorescens* CA 417	face-centered cubic	5–50	in-vitro	Ali et al. (2016) and Punjabi et al. (2017)
Escherichia coli	spherical	20–50	in-vitro	Syed et al. (2016)
E. coli	spherical	42.2–89.6	in-vitro	Kushwaha et al. (2015)
		15.0 ± 7.6		
Novosphingobium sp. THG-C3	spherical	8–25	NA	Chumpol and Siri (2017)
Ochrobactrum anthropi strain PH5	spherical	35–85	intracellular	Du et al. (2016) and Gahlawat et al. (2016)
O. rhizosphaerae		10		
Bradyrhizobium japonicum 36	rod and oval	5–50	NA	Thomas et al. (2014)
Proteus mirabilis	spherical	10–20	in-vitro and intracellular	Rasulov et al. (2016)
Moganella sp.	quasi-spherical	10–40	in-vitro	Samadi et al. (2009)

Bacteria	Shape	Size (nm)	Location*	Reference
Klebsiella pneumonia	spherical	15–37 5–32	in-vitro	Parikh et al. (2011)
Klebsiella oxytoca DSM 29614	spherical	NA	in-vitro	Kalpana and Lee (2013)
Idiomarina sp.	NA	25	intracellular	Baldi et al. (2016)
Gluconobacter roseus	NA	10	in-vitro	Seshadri et al. (2012)
Geobacter sulfurrreducens	NA	NA	in-vitro	Singh et al. (2016)
Enterobacter aerogenes	spherical	25–35	in-vitro	Krishnaraj and Berchmans (2013)
Aeromonas sp.	face-centered cubic spherical	6.4 8–16	in-vitro and intracellular	Karthik and Radha (2012)
Xanthomonas oryzae	spherical, triangular, and rod shape	14.86	in-vitro	Singh et al. (2017)

**in-vitro or intracellular*

The melting temperature drops because of the higher surface-to-volume ratios, as the liquid/vapor interface energy is lower due to the small crystal size compared to the average solid/vapor interface energy.

AgNPs are reported to be single-phased, crystalline, and have FCC symmetry, as reported by an X-ray diffraction structural investigation (Mulvaney, 1996). They come in various colors and shapes, such as spheres, rods, ovals, hexagons, cubes, and pseudospherical (Table 1) (Kulkarni et al., 2015; Wypij et al., 2017).

COMPARISON OF INTRACELLULAR AND EXTRACELLULAR SYNTHESIS OF $AGNO_3$

According to reports, depending on where the reduction of silver ions takes place, bacteria can be produced by nanoparticles on the in-cell (intracellular), *in vitro* (extracellular), or even by both ways (Table 1).

Extracellular Synthesis

In the extracellular synthesis of $AgNO_3$, Ag^+ ions are broken down by bacteria into their rudimentary form (Ag°) that builds on the outside of the cell and produces AgNPs. Concerning the media used for culturing bacteria, AgNPs are produced extracellularly, and the resulting nanoparticles can have different shapes, such as triangles, spheres, hexagons, circles, ovals, cubes, or disks (Nanda & Saravanan, 2009; Otari et al., 2015). In cases of biogenous reduction, the agent used for reducing Ag^+ to Agdegrees is either a tiny soluble secreted enzyme or a protein found on the bacterial cell wall. Functional characterization of the different bacterial genre that produces AgNPs extracellularly in the environment (Table 1). *Aeromonas sp*. SH10's dry mass of the cell converts Ag^+ to Agdegrees and releases it in the medium. *Bacillus licheniformis*, *B. pumilus*, and *Bacillus persicus* can produce AgNPs with sizes of 72–92 nm on the cell's exterior (Elbeshehy et al., 2015). AgNPs produced extracellularly can be quickly recovered using centrifugation at a high speed of about 10–12 thousand revolutions per minute, where they are collected and preserved in the form of a pellet that can be redissolved in other solvents of choice. As a result, they are at the top of their game for several purposes and are used in fields such as optronics, electronics, automation, imaging, and sensors (Benn & Westerhoff, 2008).

Intracellular Synthesis

Transport of silver ions in the interior of bacteria is a component of the intracellular creation of AgNPs and is aided by membrane proteins. Some silver-resistant bacteria limit silver salts' harmful effects by converting Ag^+ to Agdegrees, which builds up either in the periplasm or on the cell's wall. According to reports, the amount of Agdegrees accumulated on bacterial cell walls can account for up to 25% of their mass. $AgNO_3$ solution is reduced by *P. stutzeri* AG259, yielding 200 nm AgNPs and a minor amount of crystalline with monoclinic form Ag sulfide acanthite (Ag2S) (Klaus et al., 1999). Similar to this, *Corynebacterium sp*. SH09 can produce AgNPs, which form a diamine Ag combination on cell walls and range in size from 10 to 15 nm (Verma et al., 2018). Additional procedures are needed to recover the AgNPs created inside the cell, such as bacterial cell lysis using a physical approach (ultrasonication), a thermal method (autoclaving), or a chemical way (application of salts and detergents) (Fesharaki et al., 2010). Notably, some bacteria, such as *P. mirabilis* and *Vibrio alginolyticus*, produce AgNPs made by intracellular and extracellular mechanisms depending on the media used for growth (Samadi et al., 2009). In the media and the periplasm, AgNPs (5–15 nm) were reported to have been produced by *Bacillus* species by Pugazhenthiran et al. (2009)

MECHANISM OF AGNP PRODUCTION

Bacteria have a genetic and biochemical process, for tolerating extreme circumstances of the environment and surviving in the environment when exposed to various environmental parameters (temperature, pH, and salt concentration).

The level to which Ag salts can cause toxicity can be assessed from diverse methods contingent on the type of bacteria (Buszewski et al., 2018). Specific strains of *E. coli* can resist Ag ions by giving out ions out of the cell; by contrast, some reduce the harmful effects of Ag ions by breaking them to their rudimentary form and creating AgNPs. Agdegrees build up inside the cell by *P. stutzeri's* reduction of Ag ions from Ag^+ to Agdegrees. Even though the decisive process of AgNP generation by the bacteria is still not understood, numerous ideas have been proposed to explain the function of bacterial proteins or enzymes and genes (Railean-Plugaru et al., 2016). AgNPs are synthesized by bacteria using bottom-up processes that start with small entities like atoms and molecules and end with reduced oxidation reactions (Figure 1) in the biogenous reduction of silver ions at or near ambient pressure, temperature, and pH. The mechanism entails crystal stability, capping, reduction, and entrapment of silver ions. There must be a source for internal or extracellular syntheses that requires trapping the silver ions. According to some theories (Law et al., 2008; Singh et al., 2015), Given intracellular synthesis, silver ions can be brought into the cell for reduction into rudimentary silver. According to several investigations, the cell wall's proteins and carbohydrates play a significant part in the entrapment of silver ions, where the bio-reduction process can occur (Kalishwaralal et al., 2010). Owing to the existence of carboxylate groups, most bacterial cell surfaces have a negative charge, It is understood that electrostatic relations among the positively charged Ag ions and the negatively charged carboxylate ions on the surface cause the Ag ions to be entrapped on the cell surface. The active symport of Na+ and Ag ions from the region of the extracellular environment reduces the transmembrane proton pitch produced by some bacteria. The take up of silver ions within the cell and the beginning of AgNP synthesis are caused by some proteins forming the silver-binding membrane, which draws silver ions and consumes the energy released during the ATP hydrolysis to do so. When extracellular synthesis occurs, the cell secretes extracellular polymeric compounds made of proteins and polysaccharides that can cling to and trap ions. Reducers such as proteins, enzymes, carbohydrates, and amino acids—also produced from the cells—break down the trapped ions outside the cells (Oves et al., 2013). Several studies indicate that NADH-dependent reductase is a must-situation for creating silver nanoparticles (AgNPs), where NADH-H+ contributes its electrons to silver ions, which are then reduced to their elemental form and build up as AgNPs. It has been noted that some bacteria, including *Acinetobacter* sp., use nitrate reductase as a reducing agent in the manufacture of AgNPs (Singh et al., 2015). AgNO3 has been reported to be reduced to AgNPs by nitroreductase A (Nfsa), an oxygen-insensitive nitroreductase enzyme found in

Enterobacteriaceae. Peptides with disulfide connections may also be employed to decrease Ag^{+} to Ag^{0}, Some amino acids, including arginine, aspartic acid, cysteine, glutamic acid, lysine, and methionine, play a role in the reduction of silver ions or silver nanocrystals that function as catalysts by generating hydroxyl ions that interact with reducing agents like aldehyde. The synthesis of AgNPs by bacteria depends on a number of variables, including a high pH and a partial pressure of H_2 gas. The activation of the reductase subunit of the oxidoreductase enzyme is significantly influenced by high pH. Silver ions are also converted to AgNPs by the semiquinone structure created from tyrosine in an alkaline environment through the ionization of phenol groups. Open-chain aldehydes oxidize with Ag+ ions to produce a corresponding carboxylic acid and accumulate AgNPs to avoid agglomeration in an alkaline situation. Tryptophan is transformed into the transitory tryptophyl radical at high pH levels, contributing electrons to the silver ions and reducing them to elemental silver. In particular, protein cell walls stabilize silver nanoparticles and prevent silver ions from penetrating any surfaces.

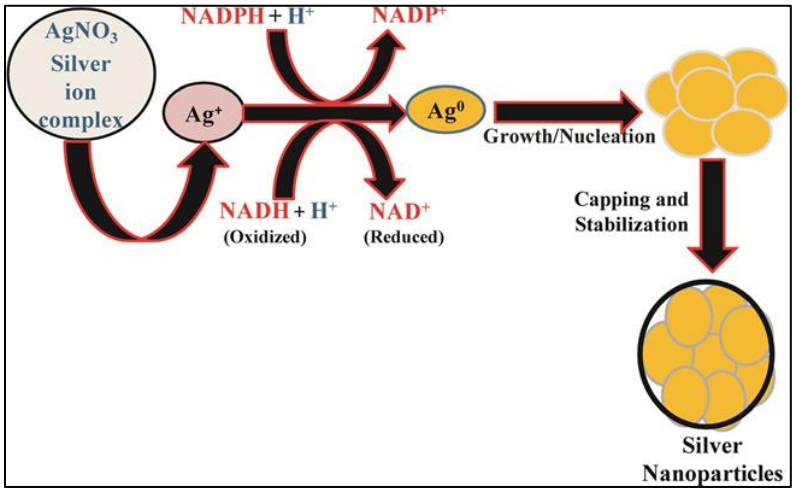

Figure 1. *Production of silver nanoparticles ($AgNO_3$) by bacteria assisted NADH- dependent nitrate reductase enzyme*

APPLICATION OF SILVER NANOPARTICLES IN DIFFERENT FIELDS

Due to its environmentally benign production process and distinctive physical and chemical features, the manufacture of biological AgNP has received enormous research attention and importance. AgNPs have a variety of uses, including cytotoxicity, antibacterial and antifungal properties, biosensors, and catalysis (Borase et al., 2014). The following categories—which have all been thoroughly examined and discussed—cover the different uses of AgNPs (Figure 2).

Antibacterial Activities

The antibacterial action of AgNPs synthesized through bacteria has been seen in the literature (Nanda & Saravanan, 2009; Saravana Kumar et al., 2015; Singh et al., 2015; Singh et al., 2015). AgNPs have been seen to have good antibacterial action against a variety of bacteria which are both Gram-positive and negative, like *Bacillus subtilis*, *B. cereus*, *Enterococcus hirae*, *S. aureus*, *S. epidermidis*, and *Streptococcus pyogenes* and *E. coli*, *Klebsiella planticola*, *Klebsiella pneumoniae*, *Proteus vulgaris*, *P. aeruginosa*, *Salmonella* sp., *Shigella flexneri*, and *Vibrio cholerae* (Nanda & Saravanan, 2009; Saravana Kumar et al., 2015). The nontoxic properties and improved antibacterial activity of AgNPs against pathogenic bacteria is attributed to their minute sizes and higher surface zone (Nanda & Saravanan, 2009). The best bactericidal activity was demonstrated by AgNPs of size 5 nm against *S. aureus* NCIM 5,201, *B. subtilis* MTCC 441, and *E. coli* MTCC 443. The benefit of AgNPs' tiny size is that they may quickly enter bacterial cells (Gahlawat et al., 2016). AgNPs have a strong affinity for sulfur, phosphorus, proteins, and DNA, which

makes it likely that these nanoparticles will attack these molecules. Upon entering the center of the cell, AgNPs create high-molecular-weight regions; however, due to the electron transport chain, bacterial cells congest by shielding their DNA from AgNPs. During the division of the cell, Ag ions released from AgNP's affects the bacteria, causing the death of the cell.

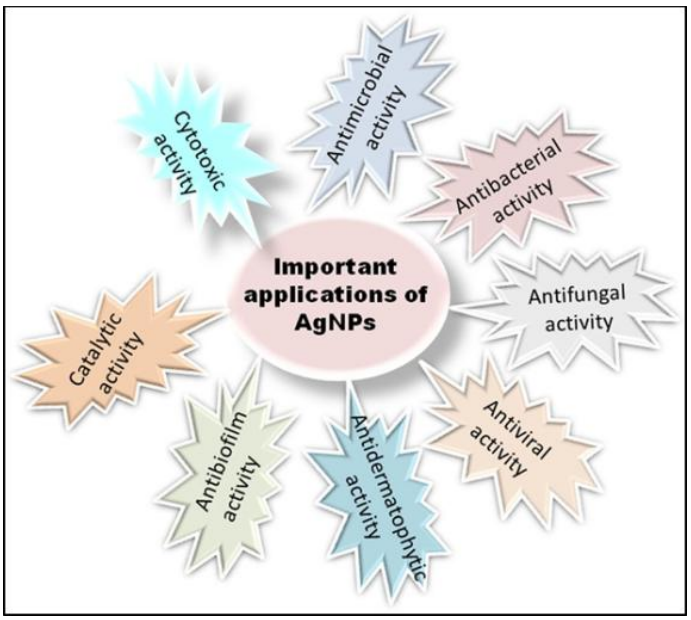

Figure 2. *Utilization of silver nanoparticles in various applications*

Shrinking of the cytoplasmic membrane, denaturation of proteins, inhibition in uptake or absorption of phosphate, release of potassium ions in cells of bacteria, glucose inhibition, oxidation of succinate, glycerol, and fumarate, and enzyme inactivity by formation of complex with functional group of electron donor upon the residues of amino acids and DNA are the other ways in which AgNP's show their antibacterial activity.

Antifungal Activity

AgNPs generated in-vitro or intracellularly possess antifungal properties, according to a number of investigations (Gajbhiye et al., 2009). The antifungal characteristic of AgNPs could be linked to the oligo dynamicity that manifests changes in permeable characteristics of the cell membrane, protein denaturation, and suppression of replicating ability of DNA. AgNPs' wide surface area aids in more significant contact with the fungus. The activity of AgNPs against numerous species of fungus was evaluated, and it was seen to have good activity in comparison to existing conventional antibiotics like *Phoma glomerata*, *Phoma herbarum*, *Fusarium semitectum*, *Trichoderma* sp., and *Candida albicans* (Gajbhiye et al., 2009). AgNPs produced utilizing reducing agents and stabilizers have been discovered to increase the activities of various antifungal medicines, including fluconazole, which demonstrates inhibitory activity against *C. albicans*, *P. glomerata*, and *Trichoderma sp.* (Gajbhiye et al., 2009). Extracellularly produced AgNP particles with sizes of 27 nm exhibited antifungal efficacy against *Fusarium oxysporum*. Consequently, the discovery and design of medicines will benefit from this valuable complete information on the wide range of silver nanoparticles made by bacteriologically synthesizing silver in the forthcoming years.

Cytotoxicity

Biogenic AgNPs were discovered to be harmful to various cell lines in applications of nanoparticles in the biomedicines field by various mechanisms, including rupture of mitochondrial membrane, alterations or inductions in apoptosis, and induced damage of DNA (Singh et al., 2015). The antiproliferative action of AgNPs is used in the chemotherapy of malignant cells with various responses, which may be caused by

AgNPs interfering with functions of proteins like protein aggregation and unfolding and cellular chemistry induction. AgNPs were hazardous to the MDA-MB-231 human breast cancer line of cells and NIH-3T3 mouse embryonic fibroblast, leading to cellular effects such as cytotoxicity, genotoxicity induction, morphology modification, and oxidation stress. The concentration of AgNPs employed determines the cytotoxicity of AgNPs on cells. AgNPs were evaluated for their cytotoxicity at various concentrations, and it could be seen that at 50 g/ml, AgNPs had no discernible effect on cell viability. However, at 1,000 g/ml, cell viability was considerably reduced.

Antibiofilm Activity

About 80% of microbial illnesses in people are brought on by biofilm, a stratum of proteins, polysaccharides, and DNA formed via microorganisms on their own. The utilization of nanoparticles in treating biofilm-related illnesses is well documented in various papers. AgNps could cause a significant reduction in the formation of *P. aeruginosa* and *S. epidermidis* biofilms. According to the reports by Kalishwaralal et al. (2010), AgNps were effective and significantly reduced *S. epidermidis* and *P. aeruginosa* biofilms. AgNPs could penetrate the biofilms of bacteria and prevent the formation of glycocalyx matrix and adhesion of bacteria. AgNPs can infiltrate into bacterial biofilms and release silver ions without getting disrupted or detached, and they present a more excellent surface-to-mass ratio. AgNPs and antibiotics may be a beneficial combination for eliminating the biofilms. Mu et al. (2016) put forward a synergetic method, which reported using gentamicin-enriched AgNPs to prevent the growth of new biofilms and dislodge existing ones.

Catalytic Activity

Organic pollutants in the Environment that are produced in the form of effluents in the plastic, textile, and other sectors pose a serious threat to land-dwelling and marine ecosystems and are resilient to remediation's that are physicochemical remediation. For their catalytic activity in reducing organic molecules like colors and pollutants to less hazardous chemicals, AgNPs have been investigated (Fesharaki et al., 2010). The effectiveness of AgNPs in decreasing the amount of bond dissociation energy between methylene blue, an organic dye, and sodium borohydride within a few hours of exposure shows that they have catalytic activity. In the presence of sodium borohydride, it has been discovered that AgNPs catalyze the reduction of 4-nitrophenol. AgNps are beneficial in processes such as recycling due to the structure of pores, geometries (shapes and sizes), reasonable specificity and selectivity, and good surface areas. Silver nanoparticles were used to demonstrate the photocatalytic degradation of contaminants into benign compounds. This might be explained by surface plasmon resonance, which enhances water-repelling characteristics and dissociation while preventing graphene sheet aggregation. When compared to traditional catalysts, the use of biogenous silver nanoparticles for applications that need catalytic activity is more efficient, cost-effective, and environmentally benign, providing a viable option for the biological degradation and biological remediation of contaminants in the environment.

Antiviral Property

AgNPs have exhibited antiviral action with the hepatitis B virus, herpes simplex virus, monkeypox virus, influenza virus, and HIV. AgNPs can stimulate chemokines and cytokines synthesis that inter-react with exposed glycoprotein knob that contains sulfur for prevention of viral attachment and infiltration, reduce TNF- expression, and transcription inhibition, all of which are crucial for the pathogenesis of HIV-1. At the beginning of viral reproduction, AgNPs act as virucidal or inhibitors of viruses that are resistant to mutation and independent of cell tropism determinants. AgNPs attach to protein structures surrounding the viral membrane, preventing the interaction of HIV-1 envelop glycoprotein (gp120-CD4) necessary for viral entry and causing denaturation of proteins (Borkow & Lapidot, 2005).

Other Applications

Pesticides are a vital part of pest management and control, although using chemically synthesized insecticides is unsuccessful since insects have developed resistance to them. Nanotechnology is considered one of the most favorable methods for controlling insects and other pests because of its nontoxic characteristics, increased infiltering power, huge surface capacity, and remarkable forte. AgNPs can kill mosquito larvae by clustering together, piercing the larval membrane, and attaching to proteins or DNA that contain sulfur. This results in the denaturation of enzymes and cell organelles (Fesharaki et al., 2010). AgNPs have been reported to be efficacious against maggots of *Aedes aegypti* and *Anopheles stephensi* (Borkow & Lapidot, 2005). AgNPs are also significant in applications, including cosmetics, antimicrobial mediators, food-packing, coatings, textiles, bio-medicals, and wound-healing processes (Borkow & Lapidot, 2005).

CONCLUSIONS AND FUTURE DIRECTIONS

The growing emphasis on green chemistry has driven the development of environmentally friendly methods for silver nanoparticle (AgNP) production. This review has highlighted the various biological sources for AgNP synthesis and their most promising applications in environmental processes and medical devices. The utilization of microorganisms for green synthesis of AgNPs represents an innovative frontier in nanotechnology with significant potential to shape future developments in nanoscience.

Analysis of the scientific literature reveals that studies on AgNP applications have predominantly been conducted in vitro, with limited reports of their application in living systems. In vivo studies provide considerably less information regarding potential mechanisms of AgNP toxicity compared to in vitro research. While the applications of AgNPs are expected to expand, additional data concerning their environmental accumulation and potential long-term effects on humans and animals remains essential.

Despite the promising advantages of bacterially synthesized AgNPs, comprehensive research is still needed to elucidate their long-term impacts on human health and environmental systems. Bacteria represent a sustainable resource for AgNP production, with diverse applications that show significant potential for advancement in nanomedicine and biotechnology. We anticipate that biosynthesized AgNPs will soon establish new pathways for various biomedical applications such as nanodrugs.

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