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A Review of the Biogenic Synthesis, Description, and Antibacterial Action of Silver Nanoparticles

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Abstract

The increasing recognition of the need for a sustainable environment has led to a heightened emphasis on the synthesis and use of green nanoparticles. Silver nanoparticles (AgNPs) have garnered considerable interest among a range of metal nanoparticles. Silver nanoparticles (AgNPs) are traditionally produced using physical and chemical means, utilizing compounds with reducing capabilities. However, these chemicals pose a risk to the environment owing to their toxicity, leading to a pressing need to establish and advance environmentally benign procedures.Biological alternatives, such as green syntheses, are being developed to address deficiencies. These alternatives use biological molecules derived from plants in the form of extracts,which have shown superiority over chemical and physical methods.The process of synthesizing metal nanoparticles involves the precise assembly of plant-derived biological components in a tightly controlled way.This paper highlights the extensive range of plant species that may be used to develop a fast and efficient process using environmentally friendly methods, as opposed to conventional approaches. Additionally, it discusses the antifungal properties of these plants.

Keywords: Silver, nanoparticles, Characterization, Biologicalsynthesis, Techniques, Applications

1. INTRODUCTION

"Nanotechnology" is the newest and one of the most promising and active areas of modern research. The technology deals with the design, synthesis, and manipulation of particles size ranging from 1–100 nm [1]. Within this size range, the chemical, physical, and biological properties change in the fundamental way of both individual atoms and their corresponding bulk material[2].This very small size increases the surface area-to-volume ratios of particles. The nanoparticles synthesized using plant extract have gained huge consideration in recent years due to their remarkable properties and wide range of applications in catalysis [3], plasmonic [4], optoelectronics [5], biological sensor[6], water treatment, pharmaceutical applications [7], and agriculture and crop protection[8].Stunning growth in this emerging technology has opened novel fundamental and applied frontiers, including the synthesis of nanomaterial and utilization of their physicochemical and optoelectronic properties [9].The application of nanotechnology has increased in large number of areas such as optics, mechanics, chemical industries, space industries, electronics, energy science, single electron transistors, light emitters, nonlinear optical devices, photo-electrochemical, catalysis, biomedical, cosmetics, drug/gene delivery, and food and feed [10,11,12,13].Among various nanoparticles used for all the above-mentioned purposes, the metallic AgNPs are contemplated as the most promising, as they possess remarkable antimicrobial properties due to their greater surface area to volume ratio, which is of curiosity for researchers due to the growing microbial resistance against metal ions and antibiotics and the development of resistant strains [15]. Nanoparticles are seen as a solution to many technologies and environmental challenges [14,16,17,18]. The biological synthesis methods of NPs reduce hazards to the global efforts. The development and implementation of these sustainable processes should adopt the fundamental principles of green chemistry. These principles draw attention on maximizing the efficiency of chemical processes without compromising the safety concern of the products.

2. SILVER NANOPARTICLES

Among the various metallic nanoparticles, AgNPs are one of the most promising products in the nanotechnology industry. The development of consistent processes for the synthesis of AgNPs is an important field of current nanotechnology research. AgNPs have a wide range of use because of their unique characteristics such as optical, electrical and magnetic properties, which can be incorporated into antibacterial, antiviral, and antifungal applications,composite fibers,biosensor materials, cosmetic products, food industry uses, and electronic components [19,20]. The AgNPs are also reported as medical and pharmaceutical agents that have directly encountered by a human system in such products as shampoos, detergents, soaps, toothpaste, and cosmetics [21]. The biomedical use of AgNPs includes their application as antibacterial [22], antifungal [23], anti-inflammatory [24,25], antiviral [26], and anti-diabetic agents [27]. In recent studies, AgNPs were also reported in the diagnosis and treatment of cancer and as drug carriers by either active or passive mechanisms [28]. The antibacterial effects of silver have been noticed since antiquity and, in a variety of applications, silver is currently used to control bacterial growth including in dental work, catheters, and burning wounds. It is widely known that Ag ions and Ag-based compounds are highly toxic to microorganisms, showing strong biocidal effects [29]. Due to the optical properties of AgNPs, these are mainly used in photonic devices and in molecular diagnostics. An increasing application is the use of AgNPs for antimicrobial coatings. Many textiles and biomedical devices contain AgNPs that continuously release a low level of silver ions to provide protection against bacteria [30]. AgNPs were used as catalysts for the reduction of many aqueous aromatic nitro compounds in which $NaBH_4$ alone could not reduce aromatic nitro compounds. $NaBH_4$ was reported to enhance the catalytic activity of AgNPs by reducing the oxide layer to regenerate the fresh surface of the silver particles [2].

3. PAST AND IDEA OF NANOTECHNOLOGY

The history of nanoparticles is quite long and, during the last two decades, major developments within nanoscience have taken place. In 1970, Norio Taniguchi coined the term “nanotechnology.” But the concept of nanotechnology was initially defined by Nobel Prize winner Richard Feynman in his renowned address at the California Institute of Technology on 29 December 1959. The topic of nanoparticles was mentioned in one of his articles published in 1960 titled “There is Plenty of Room at the Bottom.” He pointed out that if a single bit of information required only 100 atoms, then all the books ever written could be kept in a cube with sides measuring 0.02-inch in length [31].

The nanoparticles are being used in many sectors including in the biomedical field, water treatment, the electrical industry, biological textiles, chemistry, and human health. Depending upon shape and size, colloidal metal particles play a critical role in different applications, including in the preparation of magnetic, electronic devices, wound healing, antimicrobial gene expression, and the preparation of biocomposites, the noble metal colloids having the specific optical, catalytical, and electromagnetic properties [32]. Nanotechnology is a recent invention in scientific research, but its basic concepts have been developed over a long period of time [33], since people have been coating glass windows with tiny coloured metal particles for a long time, particularly silver, to create a glassy yellow color.

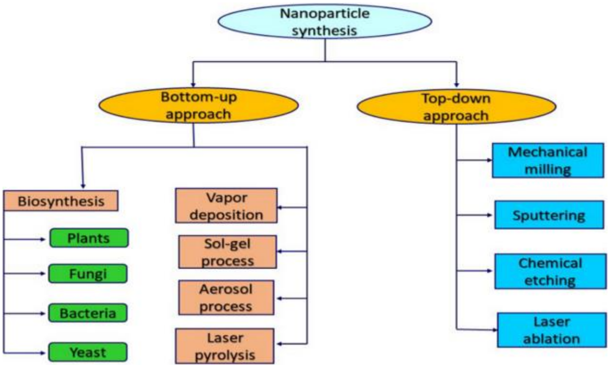
4. TAXONOMY OF NANOPARTICLES

Nanoparticles are classified mainly into two categories: inorganic and organic nanoparticles. Carbon nanoparticles (fullerenes) are one of the organic nanoparticles. On the other hand, inorganic nanoparticles contain gold and magnetic nanoparticles and silver and semiconductor nanoparticles such as titanium dioxide and zinc oxide. There is an increasing interest in inorganic nanoparticles, as they offer superior material properties with functional usefulness. Due to their small structure and benefits over chemical imaging agents and medications, they have been investigated as a possible instrument for medical applications as well as for treating diseases. Gold nanoparticles have been widely employed in imaging, medication delivery, and biological target thermotherapy [34]. Inorganic nanoparticles such as metallic and semiconductor nanoparticles show core optical properties which may augment the transparency of polymer-particle composites. For those reasons, inorganic nanoparticles have gained much interest in studies devoted to optical properties in composites [35].

5. METHODS OF AgNP SYNTHESIS

In AgNPs synthesizing and stabilization, several physical and chemical methods have been used. In recent years, Nanoparticle synthesis is one of the most fascinating areas of scientific research, and there is an increasing focus on manufacturing nanoparticles in environmentally acceptable ways (green chemistry). Mixed-valence polyoxometalates, polysaccharides, Tollens, irradiation, and biological processes are examples of green synthesis approaches that have advantages over traditional methods which use chemical agents that are detrimental to the environment. This chapter addresses the synthesis of AgNPs using physical, chemical, and green methods. The various types of methods used for the synthesis of nanoparticles are represented in **Figure 1**.

Figure 1. Different types of method used for the synthesis of nanoparticles.



5.1. Physical Methods

In physical processes, there are various methods including plasma arcing [36], ball milling [37], thermal evaporation [38], spray pyrolysis [39], ultra-thin films [40], electron irradiation [41], pulsed laser desorption [42], lithographic techniques [43], sputter deposition [44], layer by layer growth [45], and the diffusion flame [46] synthesis of nanoparticles. In these methods, the nanoparticles synthesized by evaporation condensation, which could be conducted in a tube furnace at atmospheric pressure and is used to make metal nanoparticles.

The starting material within a boat centered at the furnace is vaporized into a carrier gas. The evaporation/condensation technique has previously been used to synthesize various nanoparticles, including Au, PbS, Ag, and fullerene. However, utilizing a tube furnace to make AgNPs has a number of disadvantages, including the fact that a tube furnace occupies a large space and need a high energy input while increasing the environmental temperature around the source material, and it takes a lot of time to gain thermal stability. In addition, a typical tube furnace requires power using up to more than several kilowatts and a pre-heating time of several tens of minutes to attain a stable operating temperature. Furthermore, AgNPs have been synthesized with the laser ablation of metallic bulk materials in solution [47,48,49,50]. One of the biggest advantages of laser ablation compared to another physical methods for synthesizing metal nanoparticles is the absence of chemical reagents in solutions. Therefore, pure colloids can be produced by this method which will be useful for more applications [51,52].

5.2. Chemical Methods

In chemical processes, nanoparticles are synthesized using several methods such as electro-deposition, sol-gel process [53] chemical solution deposition [53], chemical vapor deposition [54,55], the Langmuir Blodgett method, the soft chemical method, catalytic route, hydrolysis [56], co-precipitation, and the wet chemical method. Chemical reduction is the most common method for synthesis of AgNPs. Various organic and inorganic chemicals have been used as reducing agents; sodium borohydride ($NaBH_4$), elemental hydrogen, sodium citrate, ascorbate, Tollens reagent, *N*,*N*-dimethylformamide (DMF), polyol process, and poly (ethylene glycol)–block copolymers are used for the reduction of silver ions (Ag^+) in non-aqueous or aqueous solutions. The above-mentioned chemicals reduce silver nitrate into AgNPs. Silver ions (Ag^+) are reduced into metallic silver (Ag^0) by reducing agents, which is followed by agglomeration into oligomeric clusters. Capping agents are also used for size stabilization of the nanoparticles. These clusters eventually lead to the formation of metallic colloidal silver particles [57,58]. A lot of nanoparticles can be synthesized in a short span of time, which is one of the biggest advantages of this method. It is needed to use protective reducing agents to stabilize nanoparticles to avoid their agglomeration during the course of AgNPs preparation and protect the nanoparticles that can be absorbed on or bind onto nanoparticle surfaces Surfactants having functionalities for interactions with particle surfaces (e.g., thiols, amines, acids, and alcohols) can stabilize particle development and protect particles from precipitation, agglomeration, or losing their surface features. Polymeric substances such as poly (vinyl alcohol), poly (vinyl pyrrolidone), poly (methacrylic acid), poly (ethylene glycol), and polymethyl methacrylate have been shown to be efficient nanoparticle stabilizers [59].

These conventional methods use high radiation and concentrated reducing and stabilizing agents that are hazardous to human health and non-ecofriendly by-products. As a result, biological nanoparticle synthesis is a one-step bio-reduction process that consumes less energy to synthesize eco-friendly NPs [60]. Biological approaches rely on environmentally favorable resources such as plant extracts, bacteria, fungus, and microalgae such as cyanobacteria, diatoms, and seaweed [61,62].

5.3. Biological Methods

Nanoparticle synthesis by biological methods is a growing area of nanotechnology [63]. Plant extracts [64], bacteria [65], and fungus [66] are some eco-friendly resources for the biological synthesis of nanoparticles. As this synthesis of AgNPs does not employ the use of hazardous chemicals, it provides a variety of advantages in terms of environmental benefits and compatibility for pharmaceutical and other biological applications. Green synthesis has been proven to be better to conventional approaches in term of being cost-effective, nontoxic to the environment, and easily scaled up for large production [67].

5.3.1. Synthesis of AgNPs Using Bacteria

In 1999, Klaus and colleagues reported the first evidence of bacterial-mediated AgNP production and detected AgNP aggregation inside the cells of *Pseudomonas stutzeri* AG259, a bacterium isolated from a silver mine [68].

Rapid synthesis of AgNPs using keratinase was obtained from a novel keratin-degrading bacterial strain, *Bacillus safensis* LAU 13. UV spectrophotometry showed the maximum absorbance at 409 nm. The FTIR results indicated that proteins were the capping and stabilization molecules in the synthesis of AgNPs. The XRD data showed that the particles are crystalline in nature with an average size of ~8.3 nm and have a face-centred cubic phase. These particles were used against clinical isolates of *E. coli* and showed effective antibacterial activity [69]. AgNPs of spherical shape were synthesized using *Bacillus methylotrophic* DC3, isolated from the soil of Korean ginseng, a traditionally known oriental medicinal plant in Korea. The synthesized AgNPs were characterized using FE-TEM and the particles showed sizes in the range of 10–30 nm. The UV-vis absorption spectrum showed the maximum absorbance peak at 416 nm. In recent contributions, the synthesis of nanoparticles using bacteria including *Pseudomonasdeceptionensis*, *Weissellaoryzae* [70], *Bacillusamyloliquefaciens, Bacillus licheniformis*, and *Rhodobacter sphaeroides* [71,72,73] was reported. The extracellular synthesis of AgNPs was reported with the use of bacteria such as *Acinetobactercalcoaceticus* [74], *Gluconobacterroseus* [75], *Klebsiellapneumonia* [76], *Salmonellatyphimurium* [77], *Pseudomonasaruginosa* [78], *Xanthomonasoryzae* [79],and *Rhodococcus* sp. [80].

5.3.2. Synthesis of AgNPs Using Fungi

Extracellular synthesis of AgNPs using *Fusarium oxysporum* can be carried out in several kinds of materials, such as cloths [81]. The filamentous fungus *Aspergillus fumigates* is known for the rapid synthesis of AgNPs ranging from 5 to 25 nm [82]. The fungus, *Aspergillus flavus*, accumulated AgNPs on the surface of its cell wall in 72 h when challenged with a silver nitrate solution. After being dispersed by ultrasonication, these nanoparticles had an absorption peak in the UV-visible spectrum at 420 nm, which corresponded to the plasmon resonance of AgNPs. According to transmission electron micrographs of nanoparticles in aqueous solution, the fungus produced relatively monodisperse AgNPs with an average particle size of 8.92 ± 1.61 nm.

The formation of metallic silver has been confirmed by X-ray diffraction analysis of the nanoparticles. The Fourier transform infrared spectroscopy confirmed the presence of protein as the stabilizing agent surrounding the AgNPs [83]. The intracellular synthesis of AgNPs using fungus *Fusarium oxysporum* has been investigated. It was observed that, when exposed to the fungus, the aqueous silver ions are reduced in the solution, thereby leading to the formation of an extremely stable silver hydrosol. The size of AgNPs is in the range of 5–15 nm, and the proteins secreted by the fungus stabilize them in solution [84]. Mukherjee describes a unique biological approach for the manufacture of AgNPs using the fungus Verticillium. When the fungal biomass was exposed to aqueous Ag+ ions, the metal ions were reduced intracellularly, resulting in the production of AgNPs with diameters of 25 ± 12 nm. According to electron microscope investigation of thin sections of fungal cells, the silver particles were generated below the cell wall surface, perhaps due to metal ion reduction by enzymes present in the cell wall membrane [85].

It is also proclaimed by the extracellular biosynthesis of AgNPs using a common fungus, Alternaria alternata. These nanoparticles were assessed for their part in increasing the antifungal activity of fluconazole against Candida albicans, Phoma glomerata, Trichoderma sp., Phoma herbarum, and Fusarium semitectum. In the study, it was concluded that the antifungal activity of fluconazole was increased against the test fungi in the presence of AgNPs [86].

6. PROCEDURES USED FOR CHARACTERIZATION OF NANOPARTICLES

Nanoparticles are characterized according on their size, shape, surface area, and disparity [87]. In many applications, the uniformity of these parameters is essential. The following are the most prevalent techniques for identifying nanoparticles: dynamic light scattering, scanning electron microscopy, transmission electron microscopy, UV-visible spectrophotometry, atomic force microscopy, Fourier transform infrared spectroscopy, powder X-ray diffraction, and energy-dispersive spectroscopy [88].

For the characterization of silver and gold nanoparticles, wavelength ranges of 400–450 nm [89] and 500–550 nm [90] are used, respectively. The characterization of the surface charge and the size distribution of the particles suspended in a liquid solution were demonstrated by DLS [91]. Electron microscopy such as SEM and TEM are commonly used for morphological characterization at the nanometer-to-micrometer scale [92]. TEM has a 1000-time higher resolution compared with the SEM. FTIR spectroscopy is a useful technique for characterizing the surface chemistry [93]. Table 2 shows various nanoparticle characterization techniques. FTIR is used to identify organic functional groups of plants biomolecules (e.g., hydroxyls, carbonyls) adhering to the surface of nanoparticles, as well as other surface chemical residues. The XRD technique is used to determine the crystal structure, characterization, and phase identification of nanoparticles [94]. In this technique, X-rays penetrate the nanomaterial, and the generated diffraction pattern is compared to standards to obtain structural information. Using energy-dispersive spectroscopy, the elemental composition of metal nanoparticles is established [95].

7. APPLICATION OF AGNPS AS ANTIBACTERIAL ACTION

7.1Antibacterial Action Mechanisms

Presently, the literature mostly supports three pathways that have been found either in combination or independently, via which AgNPs demonstrate their antibacterial effect [96,97,98]. The first hypothesis suggests that AgNPs exert their effects on the cell membrane. They are capable of entering the outer membrane and accumulating in the inner membrane. This accumulation leads to the adhesion of the nanoparticles to the cell, causing destabilization and damage. As a result, the membrane becomes more permeable, leading to leakage of cellular content and ultimately cell death [99,100]. Furthermore, there is data indicating that AgNPs have the ability to bind with proteins containing sulfur in the bacterial cell wall. This contact has the potential to inflict structural harm, ultimately resulting in the rupture of the cell wall.

The second hypothesis suggests that nanoparticles have the ability to disrupt and penetrate the cell membrane, causing changes in its structure and permeability. Furthermore, these nanoparticles can enter the cell and interact with sulfur or phosphorus groups found in intracellular components like DNA and proteins, thereby affecting their structure and functions. Similarly, they may modify the respiratory chain in the inner membrane by interacting with thiol groups in the enzymes, causing the production of reactive oxygen species and free radicals. This leads to harm to the internal cellular machinery and triggers the apoptotic process. Another process that is suggested to occur simultaneously with the other two is the liberation of silver ions from the nanoparticles. These ions, because of their size and charge, have the ability to interact with cellular components, causing changes in metabolic pathways, membranes, and [101,102]even genetic material

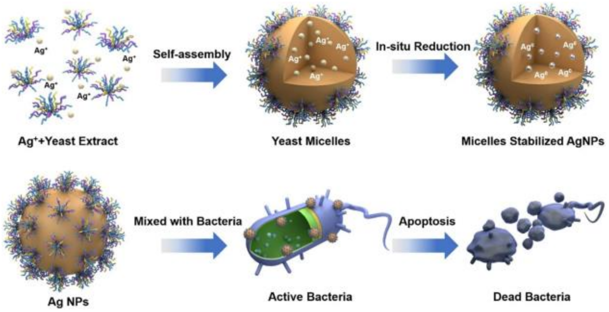
7.2Determinants of Antibacterial Action of AgNPs

In addition to explaining the mechanisms behind the antibacterial activity of AgNPs, it has also been determined how the qualities of these nanoparticles, such as their chemical composition, size, charge, and surface characteristics, affect their ability to kill bacteriaو In regards to size, Lu et al. [103] examined its impact on the antibacterial efficacy of AgNPs against the bacteria that cause caries and periodontal disorders. AgNPs with diameters of 5, 15, and 55 nm were produced by chemical reduction using polyvinylpyrrolidone (PVP). The antimicrobial effectiveness of these AgNPs against E. coli, Fusobacterium nucleatum, Streptococcus mutans, Streptococcus sanguis, Streptococcus mitis, and Aggregatibacter actinomycetemcomitans was assessed. The 5 nm nanoparticles exhibited superior antibacterial properties, as shown by their minimum inhibitory concentrations (MIC) ranging from 25 to 50 μg/mL for the examined microbes, except for the E. coli strain, which had a MIC value of 6 μg/mL.

The significant disparity in MICs compared to the other microorganisms examined may be explained to the aerobic nature of E. coli, in contrast to the anaerobic nature of the other pathogenic bacteria. The study hypothesizes that this impact may be attributed to the oxidation of AgNPs in aqueous media when exposed to air, which subsequently lowers their antibacterial ability [104].

Another research may be emphasized on the size impact, whereby 5 distinct AgNPs were synthesized using chemical reduction, and their inhibitory efficacy against *E. coli* and *Pseudomonas aeruginosa* was assessed.The analysis showed that nanoparticles with a diameter of 15 to 50 nm inhibited the growth of *P. aeruginosa* by 8 mm and E. coli by 1.5 mm. On the other hand, nanoparticles with a diameter of 30 to 200 nm formed agglomerates and had the least activity, with inhibition halos of 0.8 mm for *P.aeruginosa* and 0.7 mm for *E.coli.*A recent study examined the antibacterial effects of laser-generated silver nanoparticles (AgNPs) of different sizes on *E. coli* bacteria. An inverse association was seen between the antibacterial activity and the size of the AgNPs. The nanoparticles with an average size of 19 nm exhibited the highest level of effectiveness in inhibiting bacterial growth. In this study, the researchers demonstrated that smaller AgNPs had a greater ability to generate reactive oxygen species, making them more potent in combating *E. coli* [105]. Regarding the impact of the charge, research has shown that positively charged nanoparticles exhibited stronger antibacterial effects [106,107].The study conducted by Abbaszadegan et al. [108] indicates that the antibacterial properties of AgNPs rely on the electrostatic attraction between positively charged AgNPs and negatively charged bacterial cells. This attraction is regulated by the charge of both the AgNPs and the microorganisms و the release rate of silver ions from the nanoparticles is influenced by both the size and surface properties, which is worth mentioning. The dimensions of the nanoparticle have an impact on the extent of contact and interaction between the nanoparticle and the surrounding medium, whilst the electrical charge and surface composition have a role in determining the stability of the nanoparticles [109]. Studies have shown that smaller nanoparticles dissolve more quickly in various substances, releasing silver ions in the process. This might have a significant impact on the antibacterial properties of nanoparticles[110].The stability of the products generated is a crucial element that affects the ultimate antibacterial activity, alongside the size and charge of the nanoparticles [111]. In the event that the generated AgNPs exhibit poor stability, they will have a tendency to aggregate and coalesce into larger particles. It has been shown that nanoparticles with larger dimensions possess less antibacterial efficacy. The primary factors influencing the stability of AgNPs are their charge and coating. Primarily, the zeta potential of nanoparticles determines their stability. It has been determined that AgNPs can be considered stable if their surface charge is greater than +30 mV or less than -30 mV [112]. This is because such charges prevent the nanoparticles from clumping together due to repulsive interactions.The determination of this value is influenced by both the synthesis process and the choice of coating agent[113] The coating refers to the outermost layer of the nanoparticle, which acts as the first point of contact between the nanoparticles and the components of the medium. Additionally, it also influences the antibacterial activity [114].The nanoparticle coating may be altered by including various chemicals either during the manufacturing process or after [115]. Therefore, nanoparticles may be chemically produced using antibacterial chemicals to enhance their inherent antibacterial properties, therefore increasing the desired antibacterial impact in the final nanoparticle. Subsequent examination has shown that the process of coating nanoparticles with polymers or organic substances produces nanoparticles that have little or no harmful effects on human cells, while nevertheless retaining their toxicity against tested bacteria.The numbers 56 and 57. For instance, the use of chitosan as a coating for AgNPs has shown significant inhibitory effects against *S. aureus, P. aeruginosa, and Salmonella typhimurium*. This resulted in a reduction in colony count by up to 95% after a 4-hour period of contact, as reported in reference [116].

Figure 3. Application of biologically synthesized nanoparticles in various fields



8. CONCLUSION AND FUTURE PERSPECTIVE

Due to the diverse properties, functionalities and wide applications of silver nitrate nanoparticles, biogenic AgNPs stand out as one of the most versatile materials. The AgNPs synthesized from metallic silver by using various methods are generally used in food, consumer products, and medical products because of their antibacterial, antifungal, and antioxidant activity. Silver has been most considerably studied and used since ancient times to prevent spoilage and fight infections. Biogenic synthesis of AgNPs offers several advantages over chemical and physical methods, such as single pot, cost effectiveness, ecofriendliness, easily scaling up for large scale production, and no need to use high pressure, energy, temperature, and hazardous chemicals. The delivery of nanoparticles based on nanotechnology has given propitious results for enhanced plant growth, nutrition, and plant disease resistance, and this has been accomplished through the site-specific delivery of essential nutrients and fertilizers with the help of controlled-release formulations of nanoparticles. Nanoencapsulation allows for the slow and sustained release of the active substances and provides better penetration, thus improving the herbicide application.

Conflicts of Interest

The authors declare that the work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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