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RESEARCH ARTICLE

Silver Nanoparticles: Synthesis, Characterization, and Emerging Applications in Agriculture and Biomedicine for Enhancing Crop Production and Human Health

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Abstract

Nanotechnology is an emerging field with vast potential in agriculture and biomedicine due to its unique physicochemical properties. Silver nanoparticles (SNPs), typically ranging from 1–100 nm, have garnered significant interest for their antimicrobial, antioxidant, and therapeutic effects. This review focuses on the synthesis, characterization, and multifunctional applications of SNPs in both the agricultural and biomedical sectors. Various synthesis methods, including biological approaches, are explored, along with the mechanisms through which SNPs exert their effects. In agriculture, SNPs have shown promise in enhancing soil quality, improving plant growth, and controlling crop diseases through nano-fertilizers and nano-pesticides. In the biomedical field, SNPs are used in antibacterial and antibiofilm treatments, wound healing, dentistry, bone and cardiac implants, and cancer therapy. Given the increasing global population and the urgent need for sustainable solutions in food and healthcare systems, SNPs offer a promising avenue for improving crop productivity and human health.

Keywords: Silver Nanoparticles; Biological Synthesis; Antimicrobial agent; Antibiofilm; Health Management Activity

Introduction

Nanotechnology refers to those areas of science and engineering that involve phenomena occurring at the nanometer scale, typically between 1–100 nm. It is employed in the design, synthesis, characterization, and application of materials, structures, devices, and systems. Although nanoscale structures naturally occur in biological systems-such as molecules within the human body or components of food-it has only been in the last few decades that scientists have intentionally and effectively manipulated matters at this scale. This ability to control matter at the nanoscale is what sets nanotechnology apart from other technological fields. While scientific discovery has evolved significantly since the dawn of humanity, the emergence of nanotechnology is relatively recent. Over the past 30 years, nanotechnology has seen remarkable advancements, beginning in the 1980s and gaining prominence in the early 2000s, with wide-ranging commercial applications. Nanoparticles (NPs), defined as particles with dimensions ranging from 1 - 100 nanometers, exhibit unique physical and chemical properties-such as altered color, strength, reactivity, magnetism, and thermodynamics-compared to their bulk counterparts. These characteristics make them valuable for applications in industrial, commercial, agricultural, and biomedical sectors.

In pharmaceuticals, nanomaterials are increasingly explored, although many applications are still under development. In agriculture, the sector faces numerous challenges, including the need to enhance crop productivity and provide nutritionally adequate food for a growing global population. These challenges are exacerbated by climate change, water scarcity, land degradation, and environmental pollution. To address these issues, frontier technologies like nanotechnology offer promising strategies for sustainable development, enhanced resource-use efficiency, and environmental protection. Among nanomaterials, silver (Ag) has long been recognized for its therapeutic and antimicrobial properties. Silver ions and silver-based compounds have been used since ancient times to combat microbial infections (Slawson et al., 1992; Zhao and Stevens, 1998). Advances in nanotechnology have enabled the synthesis of silver nanoparticles (SNPs), further enhancing silver's biomedical potential. Several methods exist for SNP synthesis, including physical, chemical, and biological approaches. While physical and chemical methods are commercially viable, biological synthesis is more environmentally friendly (Hulkoti and Taranath, 2017).

SNPs are particularly valuable in nanomedicine due to their desirable physicochemical characteristics and broad biological functionality. These include potent antimicrobial and anticancer properties, the ability to form diverse nanostructures (Sohn et al., 2015), and cost-effective synthesis (Capek, 2004). Applications of SNPs extend to drug delivery systems, wound dressings, tissue engineering, and antimicrobial. Their large surface area allows for extensive ligand binding, enabling effective surface functionalization. Compared to free silver ions, SNPs exhibit superior antimicrobial performance due to enhanced microbial interaction via increased surface area. Moreover, their efficacy against antibiotic-resistant microbes has made them an important research focus (Hutchison and Greener, 2008). To date, SNPs have demonstrated potential in multiple domains, including food processing, agriculture, agro-industries, biomedical devices, diagnostics, orthopedics, cancer therapy, and infection control. This manuscript highlights the principal methods for SNP synthesis and their diverse roles in antimicrobial, antibiofilm, antitumor, dental, orthopedic, and wound healing applications.

Synthesis of Silver Nanoparticles

The synthesis of silver nanoparticles (SNPs) can be achieved through various physical, chemical, and biological methods, each offering distinct advantages in terms of scalability, cost, particle size control, and environmental impact. Chemical reduction is the most widely used method, where silver salts such as silver nitrate ($AgNO_3$) are reduced to elemental silver (Ag^0) using reducing agents like sodium borohydride or citrate, often in the presence of stabilizers to prevent agglomeration (Sharma et al., 2009). While effective, chemical methods may involve toxic reagents and byproducts, raising concerns about their environmental and biomedical safety. In contrast, green or biological synthesis methods have gained popularity due to their eco-friendliness and biocompatibility. These approaches utilize plant extracts, bacteria, fungi, or algae as reducing and capping agents, leveraging natural biomolecules such as phenolics, flavonoids, and proteins to facilitate the formation of SNPs (Iravani et al., 2011). Green synthesis not only minimizes the use of hazardous chemicals but also offers improved biocompatibility, making it particularly suitable for medical and environmental applications. However, challenges related to scalability, reproducibility, and precise control over particle characteristics remain areas of active research.

Physical Methods

Physical methods for the synthesis and analysis of nanoparticles (NPs), particularly silver nanoparticles (SNPs), involve high-energy techniques such as evaporation-condensation, laser ablation, and thermal decomposition. These methods focus on manipulating key physical parameters like shape, size, and surface morphology to produce nanoparticles with controlled characteristics. Nanoparticles are commonly introduced as aerosols (solid or liquid phases in air), suspensions (solid in liquid), or emulsions (two liquid phases), and their surface and interfacial properties can be tailored using surfactants or polyelectrolytes, which help prevent aggregation by modifying surface charge and stabilizing the outer molecular layer (Liufu et al., 2005). The complex developmental history of a nanoparticle, such as those generated through combustion processes, often results in diverse surface compositions due to the adsorption of various chemical agents during cooling and environmental exposure. These dynamic interactions with surrounding media, especially at the nanoparticle–liquid interface, make it difficult to predict nanoparticle behavior using simple models. The physical and chemical properties of nanoparticles, particularly at scales between the angstrom and micrometer levels, deviate significantly from those of bulk materials due to quantum mechanical effects. The electronic, optical, and reactive characteristics of nanoparticles often differ substantially from those of the same materials in their bulk forms, necessitating sophisticated quantum models to understand size-dependent behaviors and to compare experimental outcomes with theoretical predictions.

In the context of silver nanoparticle production, physical techniques have been extensively studied. Lee and Kang (2004) demonstrated the synthesis of monodispersed SNPs via the thermal decomposition of Ag^{+}-oleate complexes, while Jung et al. (2006) employed a small ceramic heater to produce metal nanoparticles through evaporation-condensation, noting that a stable temperature yielded non-agglomerated, polydisperse SNPs. Laser ablation has proven particularly versatile, offering size control through wavelength adjustment. Tsuji et al. (2002) reported that reducing laser wavelength from nanoseconds to femtoseconds significantly decreased particle size-from 29 nm to 12 nm-and further found that femtosecond laser pulses produced more uniform colloids, though with lower formation efficiency compared to nanosecond pulses (Tsuji et al., 2003). Kim et al. (2006) and Torras and Roig (2020) also showed that laser ablation in a polyol medium could yield spherical SNPs with a range of sizes. In another approach, Seigal et al. (2012) synthesized SNPs through direct physical deposition of silver into glycerol, providing an efficient and less chemically intensive alternative with good resistance to aggregation and narrow size distribution. Despite advantages such as rapid synthesis, the absence of hazardous reagents, and the use of radiation as a reducing agent, physical methods are also associated with drawbacks like high energy consumption, low yields, non-uniform particle distribution, and potential solvent contamination (Elsupikhe et al., 2015). These limitations continue to drive research toward refining physical synthesis strategies to enhance scalability, reproducibility, and environmental compatibility'

Chemical Method

Different strategies are accessible to synthesis of SNPs. Chemical techniques are helpful because the equipment required is more advantageous and less complex than that utilized in biological techniques.

Table 1: Chemical methods for the synthesis of monodispersed and quasi-spherical SNPs

Reducing Agent	Precursor Agent	Capping Agent	Experimental Conditions	Ref.
Trisodium citrate	Silver nitrate	Trisodium citrate	Diameter ≈ 10–80 nm; temperature ≈ boiling point	(Almatroudi, 2020)
Ascorbic acid	Silver nitrate	Daxad 19	Diameter ≈ 15–26 nm; temperature ≈ boiling point	
Alanine/NaOH	Silver nitrate	DBSA (dodecyl benzenesulfonic acid)	Diameter ≈ 8.9 nm; temperature ≈ 90°C; time ≈ 60 min	(Almatroudi, 2020)
Ascorbic acid	Silver nitrate	Glycerol/PVP	Diameter ≈ 20–100 nm; temperature ≈ 90°C	(Liu et al., 2020)
Oleic acid	Silver nitrate	Sodium oleate	Diameter ≈ 5–100 nm; temperature ≈ 100–160°C; time ≈ 15–120 min	(Almatroudi, 2020)
Trisodium citrate	Silver nitrate	Trisodium citrate	Diameter ≈ 30–96 nm; temperature ≈ boiling point; pH ≈ 5.7–11.1	(Almatroudi, 2020)
Trisodium citrate	Silver nitrate	Trisodium citrate/Tannic acid	Diameter ≈ 10–100 nm; temperature ≈ 90°C	(Ranoszek-Soliwoda et al., 2017)

It has proactively been accounted for that silver ions receive electrons from the decreasing agents and become changed over into the metallic structure, which at last totals to shape SNPs. Among the silver salts utilized in chemical synthesis of SNPs, AgNO3 is one of the most generally utilized because of properties like minimal expense (Table 1) (Ge *et al*., 2014, Calderon-Jimenez *et al.,* 2017). In 2002, Sun and Xia reported the synthesis of monodispersed silver nano cubes through reducing nitrate (Sun and Xia 2002). Agnihotri and Mukherji (2013) synthesized SNPs involving AgNO3 as a forerunner, and sodium borohydride and trisodium citrate as stabilizing agents. It has been accounted for that sodium borohydride is a decent decreasing agent for the synthesis of SNPs having a size scope of 5-20 nm. In correlation, trisodium citrate is the best-diminishing agent for the synthesis of SNP**s** of the size range 60-100 nm (Agnihotri and Mukherji 2013). Polyvinylpyrrolidone (PVP) as a size regulator and a capping agent, with ethylene glycol as a solvent and reducing agent, is accounted for to lead to SNPs with a typical size under 10 nm (Agnihotri and Mukherji, 2013). Patil *et al*. (2012) affirmed the synthesis of SNPs utilizing hydrazine hydrate as the reducing agent and polyvinyl liquor as the stabilizing agent. Their outcomes uncovered that the resultant NPs had a spherical morphology, and these particles showed huge applications in biotechnology and biomedical science (Patil *et a*., 2012). As per one more significant study, the synthesis of SNPs was found to be spherical with various sizes (Amirjani *et al*., 2020).

Table 2: Physical and chemical syntheses of SNPs

Type	Reducing agent	Biological activity	Characterization	Ref.
PDLC and PMA capped SNPs	Methacrylic acid polymers	Antimicrobial	UV-Vis, reflectance spectrophotometry	(Dubas *et al*., 2006)
SNPs	Ascorbic acid	Antibacterial	UV-Vis, EFTEM	(Pal *et al*., 2007)
Chitosan-loaded SNPs	Polysaccharide chitosan	Antibacterial	TEM, FTIR, XRD, DSC, TGA	(Ali *et al*., 2011)
SNPs	Hydrazine, d-glucose	Antibacterial	UV-Vis, TEM	(Shrivastava *et al*., 2007)
PVP-coated SNPs	Sodium borohydride	—	UV-Vis, TEM, EDS, DLS, FIFFF	(Tejamaya *et al*., 2012)

Polydiallyldimethylammonium chloride-PDLC, Polymethacrylic acid-PMA, Silver nanoparticles-SNPs, UV-Vis – ultraviolet-visible spectroscopy, FIFFF – flow field-flow fractionation, DSC – differential scanning calorimetry, TEM – transmission electron microscopy, EDS – energy-dispersive spectroscopy, EFTEM – energy filtered TEM, FTI R – Fourier transform infrared, DLS – dynamic light scattering, XRD – X-ray diffraction, TGA – thermogravimetric analysis.

Biological Methods

The physical and chemical methods of producing SNPs are costly, time-consuming, and environmentally unfriendly. Therefore, it is critical to create a technique that is both economically and environmentally sustainable, eliminates the use of hazardous chemicals, and does not entail physical or chemical methods of manufacturing (Iravani, 2014). Biological approaches bridge these gaps and provide a wide range of uses in the management of health by controlling different biological processes. Utilizing supplies from plants as well as bacteria, yeasts, and fungus are examples of biological manufacturing techniques. These sources greatly increase the popularity of this method for using NPs in medicinal applications. According to reports, the use of microorganisms and plants in the manufacture of NPs is safe, cost-effective, and environmentally less hazardous than chemical synthesis (Makarov *et al*. (2014), Gowramma *et al*. (2015). Furthermore, inorganic metallic ions from the environment can be absorbed and accumulated by plants and microbes (Shah *et al*., 2015). Microorganisms and plant sources are the primary sources used in the biological production of SNPs (Figure 1) (Ahmad *et al*., 2019).

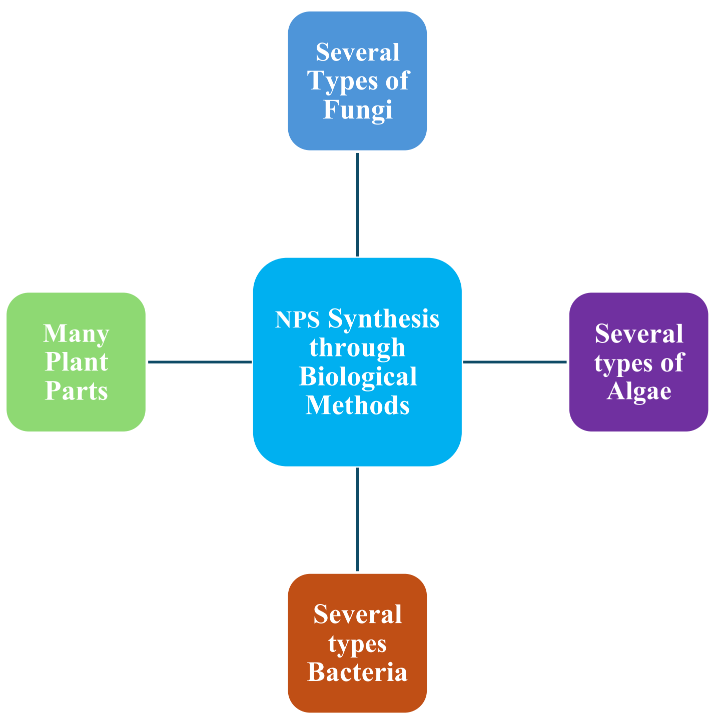

Figure 1: Different Biological Techniques for the synthesis of SNPs.

Controlled chemical reactions are the primary means of producing defined bottom-up nanoparticles in the liquid phase regarding particle size, chemical composition, surface, and charge characteristics (Frens, 1973). By regulating growth conditions, self-limiting self-assembly methods have also developed. In view of the ecological cycle of nanomaterials, attention needs to be paid in part to the existing state of knowledge about bulk material corrosion and disintegration (Oberdorster *et al*., 2005). Erosion and chemical breakdown of parent materials that are geological (such as clays) or organic (such as plant or microbe detritus) are naturally occurring processes that result in nanosized structures in the liquid phase. The surface characteristics of each of these disintegration processes, as well as how they alter chemically, are crucial in predicting whether individual NPs could develop in the appropriate media (Boyle *et al*., 2005).

The principal course of bottom development of NPs in the gas stage is by a chemical reaction prompting a non-volatile product, which undergoes through homogeneous nucleation followed by conduction and development. As of late, this has turned into a significant pathway for the industrial production of NP powders, which might be of metals, oxides, semiconductors, polymers and different types of carbon, and which might be as spheres, wires, needles, tubes, platelets or different shapes. This is additionally the accidental pathway by which NPs are formed following the oxidation of gas-progressively precursors in the atmosphere, in volcanic plumes, in normal and man-made combustion processes, or in exhaust related with any man-made process including volatilizable material at elevated temperature, like welding or smelting, polymer fabrication, or in any event, cooking. Similarly, as with the fluid stage case, disintegration processes of parent materials give a pathway which just prompts NPs to be suspended in the gas stage under extraordinary circumstances. While in the fluid stage the presence of emulsifying agents accompanying a disintegration or chemical process could uphold the suspension interaction, the scattering of NPs into a gas from fluid emulsions or dry powders is seriously restricted by major areas of strength for the powers between individual NPs. In this manner, any precisely prompted weight on the parent material generally prompts particles in the micrometer reach or more. Just under unintentional circumstances, for example on account of uncontrolled arrival of a powder or an emulsion from an exceptionally compressed vessel could solid shear powers conquer these adhesive forces (Reeks, 2001). Conversely, the spraying of liquids containing NPs or dissolvable material at exceptionally low concentration, trailed by drying of the solvent, can prompt the resuspension of NPs or the formation of new NPs from the solutes. This can prompt the rearrangement of NPs, biological material or harmful substances into nanoparticulate airborne structures.

As of late, a study was performed to create SNPs through the decrease of aqueous Ag^+ ions utilizing the culture supernatants of different bacteria. This approach was exhibited to be quick and the association of SNPs with the cell filtrate produced SNPs within 5 min. Besides, this concentrate additionally announced that piperitone somewhat hindered the decrease of Ag^+ to metallic SNPs (Shahverdi *et al*., 2007). It is vital to take note that the nitro decrease action of Enterobacteriaceae is hindered by the natural product piperitone. It is expected that the bio decrease of silver ions to SNPs may be to some degree repressed by various types of Enterobacteriaceae, for example, *Klebsiella pneumoniae*. Korbekandi *et al*. (2012) concentrated on the enhancement of SNP production by *Lactobacillus casei subspecies casei*, affirming the bio-reductive synthesis of SNPs (Korbekandi *et al*., 2012). Liu *et al*. (2000) showed the formation of NPs from dried cells of *Bacillus megaterium.* Das *et al*. (2014) have portrayed the extracellular synthesis of SNPs through a bacterial strain. The study showed that the treatment of *Bacillus* strain CS 11 with AgNO3 brought about the development of SNPs extracellularly.

Different sorts of fungi have been accounted for to be associated with the production of SNPs (Guilger-Casagrande and de Lima, 2019). The production of SNP by fungi has been viewed as extremely fast. Numerous scientists have concentrated on the biosynthesis of SNPs by fungi exhaustively (Iravani *et al*., 2014). One study has shown the extracellular biosynthesis of spherical SNPs by cooperation of *Fusarium solani* with silver nitrate (Ingle *et al*., 2008). Syed and associates have detailed the biosynthesis of SNP by the *Humicola sp*. It was shown that a precursor solution was diminished by the interaction between *Humicola sp*. Also, Ag+ ions and extracellular NPs were produced (Syed *et al*., 2013). Owaid *et al.* (2015) have detailed the development of SNPs by the bio-reduction of silver nitrate initiated by the concentrate of *Pleurotus cornucopiae*. Xue *et al*. (2016) led an examination to biosynthesize SNPs with antifungal properties utilizing *Arthroderma fulvum*. Vigneshwaran *et al*. (2007) detailed that the connection of silver nitrate arrangement with the fungus Aspergillus flavus brought about the aggregation of SNPs on the outer layer of its cell wall. Besides, Bhainsa and D'Souza (2006) explored the extracellular biosynthesis of SNPs utilizing *Aspergillus fumigatus*. The outcomes demonstrated that the cooperation of silver ions with the cell filtrate produced SNPs in an extremely brief time frame. In any case, utilizing *Fusarium oxysporum* brings about an extracellular production of SNPs with a size of 5-50 nm (Ahmad *et al*., 2003). Also, the incubation of *Phanerochaete chrysosporium* mycelium with silver nitrate solution delivered SNPs (Vigneshwaran *et al*., 2006). Korbekandi *et al*. (2013) and colleagues showed the bio-reductive production of SNPs by utilizing *Fusarium oxysporum.*

Algal method is a plausible substitute for physical and compound techniques for NPs production since it is financial and eco-accommodating (Hamouda *et al*., 2019). Besides, algal growth has a high limit concerning metal take-up. It has been seen that those biological sources, for example, marine green growth can catalyze explicit responses. This limit is vital to current and practical biosynthetic plans (Govindaraju *et al*., 2009). A study considering the green growth remove has shown that the difference in variety from yellow to brown can demonstrate the decrease of silver particles to SNPs. Furthermore, Rajeshkumar *et al*. (2014) observed the profound earthy colored shade of SNPs at 32 h and it was detected that the time of incubation was straightforwardly connected with the expansion in variety power. SNPs were incorporated through the decrease of watery arrangements of silver nitrate with powder and dissolvable concentrates of *Padina pavonia.* Furthermore, the accomplished NPs showed high stability, quick development and small size (AbdelRahim *et al*., 2017). Salari *et al*. (2016) detailed the production of SNPs through the bio-reduction of silver particles (SPs) instigated by *Spirogyra varians*. It has been observed that yeasts can produce SNP. Furthermore, yeast-based techniques for producing SNPs are economical and environmentally friendly. Niknejad *et al*. (2015) conducted a study utilizing *Saccharomyces cerevisiae* in this context. It was observed that after adding Ag+ ions to the yeast culture, the colourless sample gradually became reddish-brown with longer incubation times. In addition, the solution's color becomes a deep reddish-brown. Kowshik *et al*. (2002) observed that soluble silver interacting with a yeast that is tolerant to silver during its log phase of development results in the extracellular creation of NPs. Similar other biological techniques, manufacturing in plants is superior to chemical and physical techniques because it does not require high temperatures, energy, or hazardous chemicals, and it is also more economical and environmentally beneficial (Dhuper *et al*., 2012). Aloe vera leaves contain a multitude of active ingredients. These components, which have been demonstrated to play a definite part in the reduction of silver ions, include lignin, hemicellulose, and pectin's (Emaga *et al*., 2008). In a recent work, an aqueous solution of Saudi Arabian plant extract (*Origanum vulgare L.*) was used to produce SNPs. The outcome showed that Ag+ ion reduction was the process used to produce SNPs. The reaction mixture's hue changed from light brown to dark brown during this procedure. Conversely, under the identical circumstances, no color change was noted in the absence of plant extract (Shaik *et al*., 2018). According to the findings of another investigation, adding various amounts of aqueous leaf extracts of *Azadirachta indica* caused the color of the aqueous silver nitrate solution to shift from faint light to yellowish brown (Ahmed *et al*., 2016). Using plant extract from Tamarix gallica, Lopez-Miranda *et al*. (2016) quickly produced SNPs by biosynthesis. An extract from the *Bauhinia purpurea* flower has been used by Chinnappan *et al*. (2018) to synthesize SNPs quickly and easily. The use of aqueous pomegranate juice extract as a reducing agent was reported by Ibraheim *et al*. (2016) for the synthesis of SNPs from silver nitrate. Their findings demonstrated that the use of juice extract results in the rapid synthesis of SNPs from AgNO3 solution. It was found that the variety changed from light yellow to ruddy brown with the development of SNPs after openness to microwaves for a couple of moments. Lakshmanan *et al*. (2018) used the extract of the *Cleome viscosa* plant to make SNPs. The study found that the plant's extract can effectively convert silver nitrate into metallic silver. Prasad *et al*. (2011) utilized aqueous leaf extracts of *Moringa oleifera* to develop a straightforward and fast technique for bio-reduction of SNPs. According to their findings, *Moringa oleifera* had strong potential to rapidly reduce silver ions to produce SNPs, which could lead to the synthesis of SNPs. In this regard, another finding indicated a quick and easy method for the synthesis of SNPs using Ficus benghalensis leaf extract, and the reduction of silver ions into SNPs occurred without the use of hard conditions within a short period of time (five minutes) of reaction time (Saxena *et al*., 2012). Besides, the treatment of aqueous solution of AgNO3 and chloroauric acid with neem leaf prompts the quick blend of stable silver and gold NPs at high fixations (Shankar *et al*., 2003). Prior specialists are responsible for spearheading NPs combination through utilizing plant separates (Shankar *et al*., 2003; Rai *et al*., 2006; Rai *et al*., 2007; Chandran *et al*., 2006). Ponarulselvam et al. (Panarulselvam *et al*., 2012) concluded that SNPs with antiplasmodial activity against *Plasmodium falciparum* could be made from extracts of the leaves of *Catharanthus roseus*. A few examinations have detailed that Ag particles are diminished extracellularly within the sight of organisms to create stable SNPs in water (Duran *et al*., 2007). Zarghar *et al*. (2011) have shown the arrangement of spherical SNPs by utilizing methanolic leaf extracts of *Vitex negundo* and exhibited the antibacterial movement of these SNPs against both Gram-positive and Gram-negative bacteria.

Characterization of Silver Nanoparticles

Characterization is a vital step in the green synthesis and overall production process of nanoparticles (NPs), including silver nanoparticles (SNPs). This phase provides critical information about the physical, chemical, and structural properties of the synthesized nanoparticles. Proper characterization is essential to understand and control nanoparticle behaviour, optimize synthesis conditions, and tailor them for specific applications such as antimicrobial activity, drug delivery, sensing, and catalysis. In the context of green synthesis, where biological methods are used, characterization becomes especially important. This is because the properties of the nanoparticles-such as morphology (shape and size), surface chemistry, surface area, particle distribution, and stability-can be significantly influenced by the biological agents and the conditions under which the synthesis occurs. Several advanced techniques are employed to analyse and characterize SNPs.

UV-Visible Spectroscopy (UV-Vis)

UV-Visible Spectroscopy (UV-Vis) is commonly used to confirm the formation of silver nanoparticles (SNPs) by detecting the surface plasmon resonance (SPR) peak, which typically appears around 400–450 nm. Fourier Transform Infrared Spectroscopy (FTIR) helps identify the functional groups present on the surface of SNPs, offering insights into the biomolecules responsible for their reduction and stabilization. X-Ray Diffraction (XRD) is employed to determine the crystalline structure and phase purity of the nanoparticles. It confirms the formation of elemental silver (Ag^0) and can be used to estimate the average particle size through the Debye-Scherrer equation. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) provide detailed images that reveal nanoparticle morphology, shape, and size distribution. TEM, in particular, delivers high-resolution images at the nanoscale. Dynamic Light Scattering (DLS) is used to measure the hydrodynamic diameter and size distribution of SNPs in solution, which is critical for assessing their colloidal stability. These characterization techniques, whether used individually or in combination, offer a comprehensive understanding of the physical and chemical properties of SNPs. This information is vital for ensuring consistency in synthesis, optimizing functionality, and meeting safety standards, particularly in biomedical and environmental applications (Figure 2). This strategy is generally used to describe metallic nanoparticles (MNPs) by checking their strength and synthesis (Saad et al., 2015; Sadeghi et al., 2015). A distinctive peak with strong visible absorptions is produced when a particular salt is used to synthesize MNPs (Li and Chin, 2012). According to several studies (Vanden Bout, 2012), the most effective absorption band for the characterization of particles between 200 and 100 nm in size is the 200-800 nm wavelength. In SNPs, the valence and conduction bands are very close to one another. A surface plasmon resonance absorption band is created because of the free movement of electrons in these bands. The chemical environment, dielectric medium, and particle size all play a role in the absorption of the SNP. The surface plasmon peak has been extensively studied for several MNPs ranging in size from 2 to 100 nm. Strength of SNPs produced through biological techniques was inspected for around a year and a surface plasmon reverberation top at a similar frequency was found utilizing UV-Vis spectrophotometry (Zhang *et al*., 2016). The application of EDX to nanotechnology has been documented. EDX is an important method for analyzing a sample's elemental composition. Any nanoparticle's elemental composition can be determined by looking at the peaks in the X-ray spectrum that are produced by each element's distinct atomic structures (Noruzi, 2015).

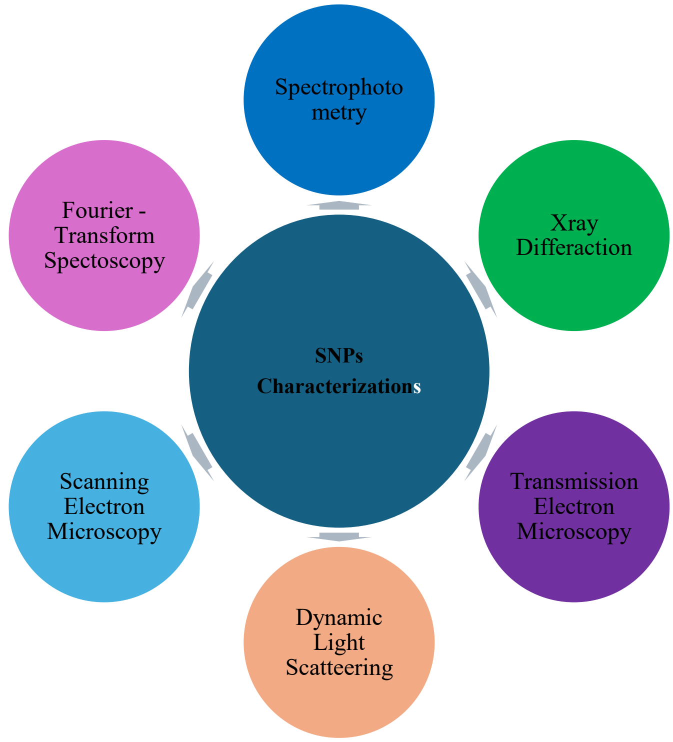

Figure 2: Numerous Techniques Apply for Characterization of SNPs

Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM)

TEM is an extremely helpful technique for the characterization of NPs, which gives information on the size and morphology of NPs (Rajeshkumar *et al*., 2017; Ghosh *et al*., 2012). TEM has a 1,000-fold higher resolution contrasted and SEM and its pictures give more exact information connected with size, shape and crystallography of the NPs (Vijayaraghavan *et al*., 2017). SEM can be used to observe the topography and morphology of NPs and to calculate their sizes at the micro- (10-6) and nano-(10-9) scales (Noruzi et al., 2011; Sundararajan and Gowri, 2011). A high-energy electron beam, produced by SEM, is aimed at the outer layer of the sample NPs and the backscattered electrons produced give the characteristic features of the sample (Hudlikar *et al*., 2013). Electron microscopy examination is utilized to analyze the progressions in the morphology of the cell when nanoparticle treatment. A few examinations have revealed that the noticeable changes in cell shape and holes of NPs in the cell wall have been utilized as signs of the antimicrobial activity of nanoparticles (Rahimi-Nasrabadi *et al*., 1969; Zhang *et al*., 2014). Utilizing SEM, control bacterial cells showed smooth and unharmed structures, while cells treated with SNPs for 60 min were fundamentally harmed, with clear morphological changes to the cell membrane prompting loss of membrane integrity (Roy *et al*., 2019).

X-ray Diffraction (XRD)

X-ray diffraction (XRD) is a common analytical method for observing the structure of crystalline metallic nanoparticles through the penetration of X-rays into the material (Rajeshkumar and Bharath 2017; Vijayaraghavan and Ashok Kumar 2017). The subsequent diffraction pattern affirms the development of NPs with crystalline structure (Alexander and Klug, 1950). To compute the molecule size from the XRD information, the Debye-Scherrer condition is applied by deciding the width of the Bragg reflection regulation as indicated by the situation: $d = K\lambda/\beta \cos \theta$, where d is the molecule size (nm), K is the Scherrer consistent, λ is the frequency of X-beam, β is the full-width half greatest and θ is the diffraction point (a big part of Bragg point) that compares to the lattice plane (Noruzi, 2015). Subsequently, the underlying elements of different materials, for example, biomolecules, polymers, glasses and superconductors, can be analyzed by XRD (Zhang *et al*., 2016).

Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR can be used to investigate the surface chemistry of synthesized metal nanoparticles and to notice the contribution of biomolecules in nanoparticle synthesis (Rajeshkumar and Bharath, 2017) and can be utilized for dissecting different covering specialists. In FTIR, infrared rays are passed through the sample, some are consumed by the sample and the excess passes through it. The subsequent spectra demonstrate the ingestion and transmission that are normal for the sample material (Rohman and Man, 2010). The function of biological molecules in the reduction of silver nitrate to silver can be determined using the cost-effective, appropriate, simple, and non-invasive FTIR method (Zhang *et al*., 2016).

Dynamic Light Scattering (DLS), Zeta Potential and Low-Energy Ion Scattering (LEIS)

DLS is a well-recognized procedure for measuring the size and size distribution of molecules. It has been utilized to measure the size of NPs, and it is commonly utilized to characterize NPs. In addition, DLS has been broadly utilized for sizing magnetic NPs in the liquid stage (Phenrat *et al*., 2009; Goon *et al*., 2009) and its role in characterization of different sorts of NPs has been reported. The size of NP decided by DLS is generally larger than TEM because of the Brownian movement. AES is a surface-sensitive explanatory technique that determines from the interaction of an electron beam and atoms in residence at the surface of a sample (Niehus *et al*., 1993) and is an exceptional expository strategy for nanotechnology (Brongersma *et al*., 2007). The oxidation state of Ag as a component of a hybrid substance can be probed by AES (Al-Hada *et al*., 2020). Assesses the surface charge of nanoparticles, indicating their stability in suspension. A higher zeta potential (positive or negative) suggests better stability due to electrostatic repulsion between particles. LEIS is a commonly utilized surface analytical method, which is well recognized for its incomparable surface sensitivity. With the help of this procedure, the structure and the elemental composition of a given sample can be found (Goebl *et al*., 2015; Rafati *et al*., 2013; Ecke *et al*., 2007). In addition, high affectability LEIS is a profitable surface analytical technique for the characterization of SAM-functionalized nanomaterials (Mogk,1990).

The shape, size and morphology of NPs depend on physical and chemical factors that affect the synthesis of SNPs. In general, the basic parameters affecting the formation of SNPs are methods of production, temperature, pH, timeline, shape and size. There are numerous techniques to produce NPs, counting physical and chemical methods and biological protocols. Different organic or inorganic chemicals as well as living organisms are utilized for the synthesis of NPs in these techniques (Patra and Baek, 2014). It has as of now been discussed that green synthesis is preferable to other strategies since it is eco-friendly and cost-effective. The production of NPs has been discovered to be significantly influenced by temperature. The synthesis of spherical nanoparticles occurs at high temperatures. On the other hand, nanotriangle production generally takes place at lower temperatures (Rahimi-Nasrabadi *et al*., 1969). Research has demonstrated that raising the temperature to a range between 30°C and 90°C increases the frequency of synthesis (Hudlikar *et al*., 2012; Dankovich and Gray, 2011) and may also promote the creation of smaller silver nanoparticles (Mohammed Fayaz *et al*., 2009). According to several research, room temperature, preferably 25-37°C, is ideal for the biogenic production of metal nanoparticles. According to most of the research, basic media increase NP stability more than acidic ones (Roopan et al., 2013; Routray et al., 2016). Nevertheless, it was shown that extremely high pH (pH >11) has several disadvantages, including the formation of agglomerated and unstable SNPs (Tagad *et al*., 2013). Consequently, it may be said that the pH affects the size and form of NPs. Another aspect influencing the reduction of ions to a bulk metal with different forms is decreasing the reaction time (minutes to hours). High absorbance peaks suggest the medium has larger quantities of NPs within the optimal period. It was ascertained by using diverse growth circumstances and the production of NPs in a range of sizes, including spherical, triangular, hexagonal, and rectangular (Rai *et al*., 2007). The characteristics of NPs are largely dependent on their size and shape. It has been found that the shape and size of the NP dictate its optimum activities and that most of its attributes depend on its size.

Mechanisms of Action of AgNPs

SNPs have appeared to have antifungal activity towards distinctive fungi (Bankar et al., 2010; Raut *et al*., 2014), but the mechanism behind it has not been completely caught on. SNPs tend to disturb the structure of the cell membrane. This harming impact on the membrane and restraint of the budding process has been recommended as the component for the antifungal activity of SNPs against *Candida albicans* species (Kim *et al*., 2009). In a study of antibacterial and antifungal activity, nano-Ag sepiolite fibres containing monodispersed SNPs were utilized as the source of silver. Low-melting soda lime glass powder containing NPs had great antibacterial and antifungal activity (Esteban-Tejeda *et al*., 2009). A study illustrated that fluconazole in combination with SNPs appeared the most noteworthy restraint against *Candida albicans*. In this study, *Alternaria alternata* fungus was utilized for the extracellular biosynthesis of SNPs (Gajbhiye *et al*., 2009). *Trichoderma harzianum* cell filtrate was connected in the generation of SNPs which brought about in their generation inside 3 h and TEM investigation illustrated ellipsoid and spherical nanoparticles having a size range of 19-63 nm and an average size of 34.77 nm (Abdelghany *et al*., 2018).

SNPs play a critical role as antibacterial agents. Silver nano formulations have moreover been found to have a great capability for repressing the growth and development of microorganisms such as bacteria (Figure 4) (Du et al., 2019). SNP-based devices are commonly utilized in dental and cardiovascular implants since they do not cause diseases. It has been reported that SNPs have an effective antibacterial action against both Gram-negative and Gram-positive bacteria (Faghri Zonooz and Salouti 2011; Mukunthan *et al*., 2011). A few considerations have detailed that Gram-negative bacteria are more sensitive than Gram-positive bacteria to SNPs (Mukunthan *et al*., 2011), Dehnavi et al., 2013). Moreover, it was reported that the antibacterial activity of different sorts of antibiotics was expanded in the presence of SNPs (Allahverdiyev et al., 2011). The antimicrobial exercises of SNPs against diverse pathogenic organisms were explored by Nanda and Saravanan (Nanda and Saravanan, 2009). The greatest antimicrobial action was examined against methicillin-resistant Staphylococcus aureus (Nanda and Saravanan, 2009). Qasim *et al.* (2018) were examined the antimicrobial exercises of SNPs encapsulated in poly-N-isopropylacrylamide-based polymeric nanoparticles. The study uncovered that the bacteriostatic exercises of polymeric nanoparticles were decided by the estimate of nanoparticles as well as the amount of AgNO3. SNPs have been found to have larvicidal activities against the dengue vectors *Aedes aegypti* (Suresh *et al*., 2014) and *Culex quinquefasciatus* (Tarannum *et al*., 2019). Allahverdiyev *et al*. (2011) conducted a study to assess the impact of SNPs on the biological parameters of *Leishmania tropica*. Saad *et al* (2015) synthesized silver and copper NPs and tried their antiparasitic activity, finding that SNPs essentially decreased the oocyst reasonability of *Cryptosporidium parvum*. NPs provide an alternative to drugs for treating and controlling the growth and development of viral pathogens. Biosynthesis of SNPs may result in strong antiviral agents to restrict virus functions. Suriyakalaa *et al*. (2013) considered bio-SNPs to persuade anti-HIV activities at an early stage of the reverse translation mechanism. Biosynthesized metallic nanoparticles have numerous binding destinations for gp120 of the viral membrane to control the function of the virus. SNPs have been illustrated to exert antiviral action against HIV-1 at non-cytotoxic concentrations. These SNPs were assessed to illustrate their mode of antiviral activity against HIV-1 utilizing a board of distinctive in vitro assays (Lara *et al*., 2010). Uncovering the Tacaribe virus to SNPs before infection facilitated virus uptake into the host cell, though it was taken note that the silver-treated virus appeared a critical decrease in viral RNA production and this finding illustrated that SNPs could restrain arenavirus infection *in vitro* (Speshock *et al*., 2010).

It is known that biofouling is one of the major challenges confronted by the water industry and public health. SNPs of *Rhizopus oryzae* fungal species have been tested on contaminated water. SNPs determined by utilizing *Lactobacillus fermentum* cells were found to control biofilm formation and were affirmed to have antifouling properties (Zhang *et al*., 2014). In addition, SNPs are too connected to several sorts of natural concerns such as air disinfection, water cleansing and surface sanitization. A later consideration illustrated that productive management of biofouling can be accomplished by a direct deposition of SNP coatings on environmentally friendly surfaces (Ren *et al*., 2014). Around the world, the food industry and community are subject to microbial biofilm challenges. Johani *et al.* (2018) conducted a ponder to assess purified endoscope channels for residual bacterial contamination and biofilm nearness. Due to the fast emergence of antimicrobial resistance and the constrained impact of anti-microbials on bacterial biofilm, alternative methodologies such as green silver nanotechnology are gaining consideration due to the unique size, shape and structure of NPs produced by this strategy. Recently people have begun utilizing SNPs for hindering biofilm formation, but the correct component of the inhibitory activity of SNPs is not clearly understood. Chen et al. (2013) categorized antibiofilm methodologies into two groups: (i) treatment that inhibit biofilm formation particularly and (ii) Prevention and utilization of altered biomaterials in biomedical devices to make them safe to biofilm formation. In consideration of the antibiofilm activity of SNPs against multidrug-resistant Gram-negative bacterial isolates, they viably limited biofilm formation (Ramachandran and Sangeetha, 2017). Palanisamy *et al*. (2014) conducted a study to check the impact of SNPs on the formation of biofilm. Another recent study was made to assess the contacts of SNPs with Pseudomonas putida biofilms (Fabrega *et al*., 2009). Kalishwaralal *et al*. (2010) explored the antibiofilm activity of SNPs against biofilms formed by *Pseudomonas aeruginosa* and *Staphylococcus* epidermidis and observed these living organisms appeared inhibition of biofilm formation. The information supported the previous studies that the biofilm formation was irritated by SNPs. Besides, antibacterial activity was achieved to be progressed, compared to a human cationic antimicrobial peptide (Mohanty *et al*., 2012).

Applications in Agriculture

Nano-silver is the most read-up and used NP for bio-system. Having solid inhibitory and bactericidal impacts as well as an expansive range of antimicrobial activities has been known. SNPs, which have a high surface area and a high part of surface atoms, have a high antimicrobial impact when contrasted with mass silver. Also, SNPs have notable acknowledgement for their cancer prevention agent, antibacterial, antifungal, against viral and calming properties. It is profoundly referenced that the utilization of SNPs in agribusiness is generally hypothetical yet soon scientists will get assorted uses of SNPs.

Antimicrobial and Antifungal Agent

SNPs have numerous properties making them helpful materials for different industries, for example, agribusiness, agriculture, antibacterial and optical properties, accessibility and low production, handling and stockpiling costs. Besides, SNPs with a measurement of around 100 nm are vital for huge scope industries because of their little molecule size, high surface area, quantum restriction and spread without agglomeration (Verma and Maheshwari, 2019). Consequently, SNPs are utilized as options in the production of generally utilized goods and industries. These days, SNPs are being investigated in different industries like pesticide, medication, biotechnology, material science and energy sectors, and especially restorative goods such as injury dressings, drug conveyance, biosensors and clinical diagnostics, orthopaedics, health, food and textile industries and water sanitization systems. Besides, SNPs are frequently utilized for commercial products, for example, cosmetics and food products processing as a fundamental added substance.

Table 3: Utilization of SNPs in different Activity in Industries (Verma and Maheshwari, 2019)

S. No.	Industry/ Applications	Application of SNPs
1	Pharmacological uses	Larvicidal, Antimicrobial, Wound healing, UV-ray Blocking
2	Textile Industry	Medicinal devices and textiles
3	Water treatment	Potable water, Ground water disinfection, Wastewater disinfection
4	Food Industry	Food processing, Food packaging
5	Agriculture and Biomedical Industry	Antibacterial, Antifungal, Antiviral, Anti-inflammatory, Anticancer

In the farming area, the use of NPs adds to tending to the food security challenges raised by environmental change. In the field of medication (Mishra *et al*., 2017), SNPs have acquainted another aspect with wound dressing and counterfeit inserts and the anticipation of post-operation microbial defilement. SNPs are pertinent as antibacterial agents in the material, wellbeing, farming and food industries. As an antibacterial agent, SNPs have different applications such as in water treatment, application in home and sanitizing clinical equipment. Besides, SNPs are utilized in various textile products (Table 3).

SNPs have been utilized as a potential candidate to increase crop yield by upgrading seed germination and plant growth and development. Figure 1 illustrates the different applications of nanotechnology to the agriculture field. The concentration of SNPs influences the development reaction of plants with positive or negative impacts. The impact of SNPs with diameters of 20 nm on seeds of Fenugreek (*Trigonella foenum-graecum*) has been carried out (Sathishkumar *et al*.,2012). Distinctive concentrations of SNPs (0, 10, 20, 30 and 40μg mL^{-1}) were utilized and showed that greatest seed germination (76.11%), speed of germination (4.102), root length (76.94 mm), root new weight (2.783) and root dry weight (1.204) at a concentration of 10 μg mL^{-1}. The introduction of plants to concentrations of SNPs might promote plant growth and development as compared to non-exposed plants, while higher and lower concentrations could have an inhibitory impact on plant growth and development (Roopan *et al*., 2013; Sharma *et al*., 2012). The growth and development response of SNPs utilizing diverse concentrations (0, 25, 50, 100, 200 and 400 ppm) in Brassica juncea and it is methodically concluded that 50-ppm treatment has been decided to be ideal with a positive impact on fresh weight, root and shoot length (Joshi et al., 2019). Moreover, the concentration of SNPs is capable of the observed impacts for both cowpea and Brassica. In cowpea, 50 ppm concentration brought about in growth and development promotion and expanded root nodulation by implication (Pallavi, 2016). It has about uncovered that the application of SNPs may be utilized to essentially upgrade seed germination potential, mean germination time, seed germination index, seed vigour index, seedling fresh weight and dry weight.

Nano Fertilizers and Plant Growth Promoters

Nano fertilizers and plant growth promoters play a significant role in enhancing agricultural productivity by positively influencing various stages of plant development. These nanomaterials can improve seed germination and seedling vigor by facilitating faster water absorption and activating essential enzymes involved in early plant growth. Additionally, nano fertilizers enhance nutrient uptake efficiency due to their high surface area and targeted delivery, ensuring that essential macro- and micronutrients are readily available to plants. This improved nutrient availability supports better root development and overall plant health. Moreover, certain nanoparticles have been shown to boost photosynthetic activity by increasing chlorophyll content and enhancing light absorption, thereby improving energy conversion efficiency in plants. Collectively, these effects contribute to more robust plant growth, higher yields, and better stress tolerance, making nano fertilizers and growth promoters valuable tools in sustainable agriculture.

Pest Control and Plant Disease Management

Utilization of SNPs and Nanotechnology in Agriculture in various ways is mentioned in Figure 3. Plant disease management in food crops and fruit plants is financially vital and a required investigation area. The well-scattered and stabilized, colloidal AgNPs are more adhesive on bacterial and fungal cell surfaces and subsequently act as way better bactericides and fungicides (Ocsoy *et al*., 2013). Scientists formulated momentous accomplishments in Plant disease management with the utilization of SNPs. DNA-directed SNPs developed on graphene oxide and examined the antibacterial activity against *Xanthomonas perforans*, a causative agent of bacterial spot in Tomatoes (Polash *et al*., 2017). The antimicrobial activity of plant extrication is due to the nearness of secondary metabolites such as tannin, saponin, and glycosides (Kim *et al*., 2012). The in vitro antifungal action of SNPs against nineteen distinctive plant pathogenic parasites is explored (Mout *et al*., 2017). Cationic arginine gold nanoparticles (ArgNPs) gathered Cas9En (Etag)-RNP (ribonucleoproteins) conveyance of sgRNA gives approximately 30% viable cytoplasmic/nuclear gene editing in cultured cell lines, which would enormously encourage future investigate into crop improvement (Elamawi *et al*., 2018). The antifungal action of SNPs synthesized by *Trichoderma longibrachiatum*, against nine fun isolates such as *Aspergillus alternate* and others (Nadaf and Kanase, 2015). Bacterial diseases are one more cause of noteworthy misfortune in crop yield around the world. SNPs are demonstrated to be dynamic against plant pathogenic microbes.

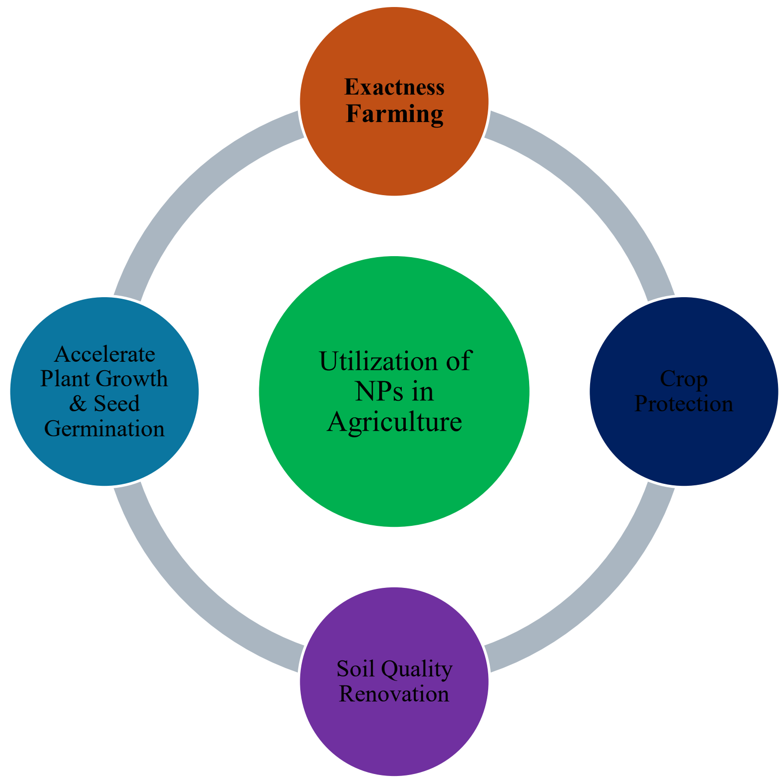

Figure 3: Utilization of SNPs and Nanotechnology in Agriculture

It has been uncovered that SNPs have higher antibacterial activity against *Erwinia cartovora, E. than* generic antibiotics Nadaf NY (Alloway, 2008). They moreover examined the antifungal activity of AgNPs against pathogenic fungi viz. *Fusarium oxysporum, Alternaria alternata* and *Aspergillus flavus* and obtained promising results. Anti-fungal adequacy of colloidal nano silver (1.5 nm normal diameter) against rose powdery mildew caused by *Sphaerotheca pannosa var rosae*. It is an exceptionally broad and common disease of both nursery and outdoor grown rosae. It causes leaf distortion, leaf twisting, early defoliation and decreased blooming. Twofold capsulized nano silver was prepared by a chemical reaction of silver ions with the help of physical methods, reducing agents and stabilizers. It dispenses with undesirable microorganisms in grower soils and hydroponics systems. In addition, silver is a great plant growth and development stimulator.

SNPs have been tested with pesticides to decrease the burden of pests on crops. It has a demand for pest protection and dietary enhancement. This decreases the frequent utilizes of chemical fertilizers in conventional cultivating. It can devastate undesirable microorganisms in soil and hydroponics systems. SNPs are being utilized as a foliar spray to stop fungi, Molds, rot and various other microbial-associated plant infections (Babu *et al*., 2014; Rai *et al*., 2014). Aqueous silver solution, utilized to treat plants, is detailed to display fabulous preventive impacts on pathogenic microorganisms causing powdery mildew or downy mildew in plants. Additionally, it advances the physiological movement and development of plants and actuates disease and stress resistance in plants. It is conceivable to control pests by incorporating NPs into them. SNPs serves as a productive pest control agent that is non-toxic, secure and an improved pest management tool and the SNP-based pesticide too also provide high dose of pesticides to the target plants (Lamsal *et al*., 2011; Ragaei and Hasaan, 2014). The pesticide activity of SNPs can help a lot in the control of pests, since in the green method of preparation of SNPs. The biological agents for their synthesis may be microbes or plants and the flavonoids present in the plants prove to be poisonous to the plants (Zahir *et al*., 2012). Utility of SNPs in insect pest control has been detailed (Routray *et al.,* 2016). SNPs are utilized in the control of diseases in rice weevils and grasserie. SNPs treated with stored rice remained uninfected after 2 months of treatment, so it is proposed that SNPs can moreover be utilized as a fabulous seed protecting agent.

Soil and Environmental Impact

Silver nanoparticles widely recognized for their antimicrobial properties, can significantly affect soil health and ecosystem dynamics when released into the environment. One of the primary concerns is their impact on soil microbial diversity. SNPs can disrupt microbial communities by inhibiting the growth of beneficial bacteria and fungi involved in critical soil processes such as nitrogen fixation, organic matter decomposition, and nutrient cycling (Kumar et al., 2018). This disturbance can lead to imbalances in soil fertility and reduced efficiency of nutrient transformation, ultimately affecting plant growth and soil sustainability. Moreover, the environmental persistence and low biodegradability of SNPs raise concerns about their long-term ecological effects. Their small size and high reactivity allow them to interact with various soil components, potentially leading to bioaccumulation and toxicity in non-target organisms, including earthworms and aquatic species through runoff (Tourinho et al., 2012). Ecotoxicological studies suggest that even at low concentrations, SNPs can cause oxidative stress, DNA damage, and membrane disruption in soil and aquatic organisms. These findings highlight the need for regulated use and thorough environmental risk assessments of SNPs to ensure their safe application in agricultural and industrial practices

Applications in Biomedicine

SNPs play an important role in the modulation of various activities such as antiviral, antifungal antimicrobial, antibiofilm, antiparasitic, antifouling, anticancer, antiviral and drug-delivery systems. Applications of SNPs are presented in Figure 4.

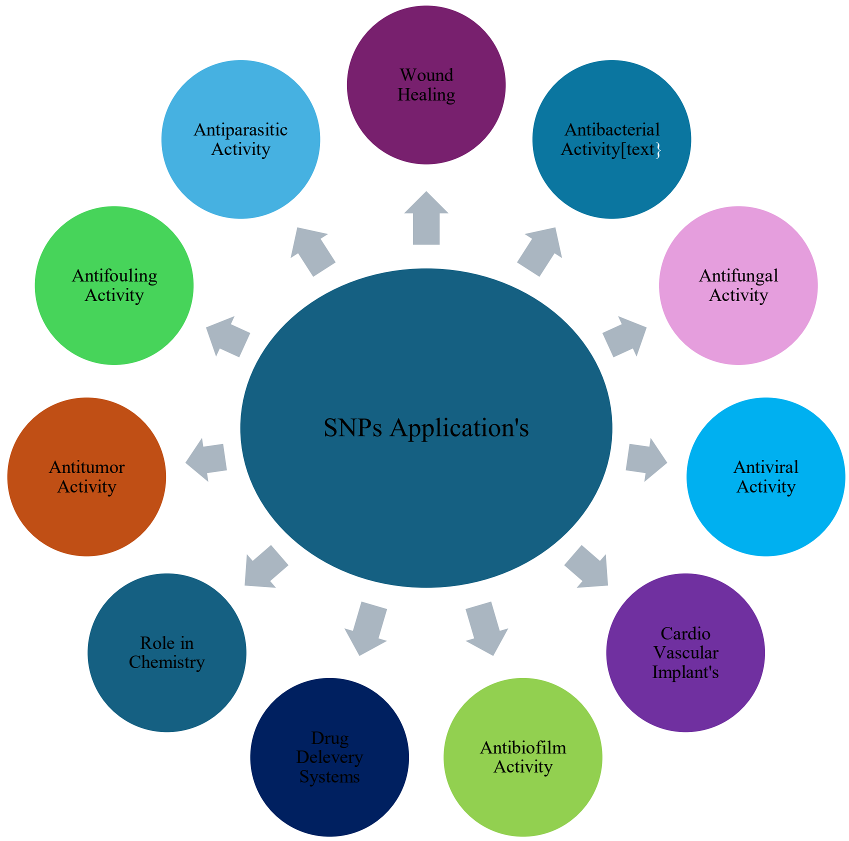

Figure 4: Utilization of Several Behaviors of SNPs

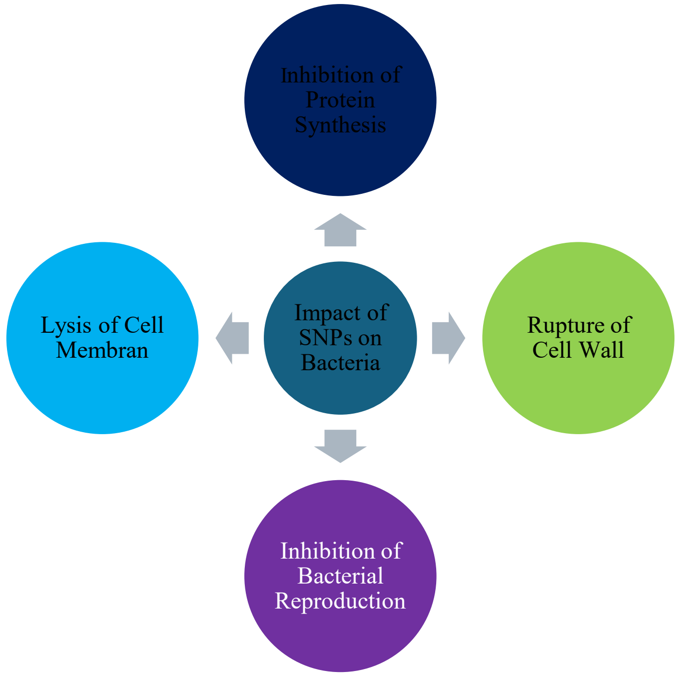

Figure 5: Sketching of Antibacterial Activity Mechanisms of SNPs.

Antimicrobial and Antiviral Properties

Silver nanoparticles exhibit potent antimicrobial and antiviral properties, making them valuable in a variety of medical and healthcare applications. Due to their ability to disrupt microbial cell membranes, generate reactive oxygen species (ROS), and interfere with DNA replication, SNPs are highly effective against a broad spectrum of bacteria, including both Gram-positive and Gram-negative strains (Rai et al., 2012). These properties have led to their incorporation into wound dressings, bandages, and topical ointments, where they help prevent infections, accelerate healing, and reduce inflammation. The nanoscale size of SNPs allows for better penetration and interaction with microbial cells, enhancing their antimicrobial efficacy even at low concentrations. In addition to their antibacterial action, SNPs are increasingly being explored for their antiviral potential. Studies have shown that SNPs can inhibit viral entry and replication by binding to viral surface proteins or interfering with host-cell interactions (Galdiero et al., 2011). This is particularly significant in the context of growing antibiotic resistance, as SNPs offer an alternative or complementary strategy to conventional antibiotics. Their use in coatings for medical devices, hospital surfaces, and personal protective equipment further highlights their role in infection control and public health. However, careful evaluation of their cytotoxicity and environmental impact is essential for safe and sustainable application.

Drug Delivery Systems of AgNPs

Silver nanoparticles have emerged as promising nanocarriers in drug delivery systems due to their unique physicochemical properties, including high surface area, ease of surface functionalization, and strong antimicrobial activity. Their nanoscale size allows them to penetrate biological barriers and deliver therapeutic agents directly to target cells or tissues. AgNPs can be functionalized with ligands, polymers, or antibodies to enable controlled and targeted drug release, thereby minimizing systemic toxicity and enhancing treatment efficacy (Franci et al., 2015). This targeted delivery is particularly valuable in cancer therapy, where AgNPs can be designed to release chemotherapeutic agents selectively at tumor sites, reducing damage to healthy tissues. Controlled drug release from AgNPs can be achieved through stimuli-responsive systems that respond to pH, temperature, or enzymatic activity, allowing precise spatiotemporal release of the drug payload (Marambio-Jones & Hoek, 2010). Additionally, the intrinsic antimicrobial properties of silver further enhance the therapeutic effect, making AgNPs particularly useful in treating infections or wounds while simultaneously delivering drugs. Despite these advantages, challenges such as potential cytotoxicity, long-term biocompatibility, and regulatory approval remain areas of active research to ensure safe clinical applications.

Diagnostic and Therapeutic Uses

Silver nanoparticles have shown significant potential in both diagnostic and therapeutic applications due to their unique optical, electrical, and antimicrobial properties. In diagnostics, SNPs are utilized in biosensors and imaging systems where their strong surface plasmon resonance (SPR) enhances signal detection, allowing for highly sensitive and specific identification of biomolecules, pathogens, or disease markers. For example, SNPs have been incorporated into colorimetric assays and lateral flow devices for rapid detection of infectious agents and biomarkers, including those relevant in cancer and viral infections (Lee & El-Sayed, 2006). Their ability to be easily functionalized with antibodies, DNA probes, or aptamers makes them versatile tools in point-of-care diagnostics. Therapeutically, SNPs are being explored for applications ranging from antimicrobial coatings to cancer treatment. Their ability to induce oxidative stress and disrupt cellular functions in pathogens and cancer cells makes them effective agents for killing harmful cells while sparing healthy ones, especially when targeted delivery systems are used. Moreover, SNPs can be combined with other therapies, such as photothermal or photodynamic therapy, to enhance treatment efficacy against tumors (Gurunathan et al., 2014). These dual diagnostic and therapeutic ("theranostic") capabilities highlight the promise of SNPs in advancing precision medicine, though careful evaluation of their safety, biodistribution, and long-term effects is essential for clinical translation.

Toxicity and Biocompatibility

The toxicity and biocompatibility of silver nanoparticles (SNPs) are critical concerns that must be addressed before their widespread application in biomedical and environmental fields. While SNPs exhibit powerful antimicrobial and therapeutic properties, their small size and high reactivity also raise the potential for cytotoxic, genotoxic, and oxidative stress-related effects in mammalian cells. Studies have shown that SNPs can penetrate cell membranes, accumulate in organelles, and induce the generation of reactive oxygen species (ROS), leading to mitochondrial damage, DNA fragmentation, and apoptosis (AshaRani et al., 2009). The severity of these effects depends on various factors such as particle size, concentration, surface coating, and exposure duration. Despite these concerns, SNPs can be engineered for improved biocompatibility through surface modification with biocompatible polymers, proteins, or other stabilizing agents. Such modifications reduce agglomeration, control release kinetics, and mitigate toxic interactions with healthy cells. In vivo studies have demonstrated that low concentrations of well-coated SNPs can exhibit minimal toxicity while retaining therapeutic efficacy (Lansdown, 2010). However, comprehensive toxicological assessments, including long-term exposure studies and environmental impact analyses, are essential to ensure their safe use in medical and consumer applications.

Challenges and Concerns

Despite their wide-ranging applications, silver nanoparticles (SNPs) present several challenges and concerns that must be carefully considered, particularly regarding safety, environmental impact, and regulatory oversight. One of the primary concerns is the potential cytotoxicity and genotoxicity associated with SNP exposure, especially at high concentrations or with prolonged use. SNPs can accumulate in various organs, such as the liver, lungs, and kidneys, and may induce oxidative stress, inflammation, and DNA damage (Chen and Schluesener, 2008). These effects raise significant questions about their long-term biocompatibility and potential risks to human health, particularly in clinical and consumer products. Environmental concerns also play a crucial role, as SNPs released into soil or water systems can adversely affect microbial communities, disrupt nutrient cycles, and bioaccumulate in aquatic organisms (Gottschalk et al., 2009). Moreover, the lack of standardized synthesis protocols, inconsistent characterization methods, and limited toxicological data hinder the development of comprehensive safety guidelines. Regulatory frameworks for nanoparticle use are still evolving, making it difficult to ensure consistent monitoring and safe integration of SNPs into commercial products. Addressing these challenges requires interdisciplinary research, robust risk assessments, and the development of safer, more sustainable nanoparticle designs.

Future Perspectives and Research Directions

The future of silver nanoparticles in agriculture and biomedicine holds great promise for transforming traditional practices, driven by ongoing advancements in nanotechnology. As research progresses, AgNPs are expected to play critical roles in enhancing crop productivity and improving healthcare outcomes. Key to realizing this potential will be the development of sustainable, green, and scalable synthesis methods, such as biosynthesis using plant extracts, microorganisms, or waste materials, which offer cost-effective and environmentally friendly alternatives. Innovations in microfluidic systems, continuous flow reactors, and AI-assisted production are likely to streamline manufacturing processes further. Simultaneously, advanced characterization techniques will enable real-time, in-situ monitoring of nanoparticle behavior, facilitating the design of application-specific AgNPs with optimized size, shape, surface charge, and functionality to maximize benefits while minimizing toxicity. In agriculture, AgNPs are poised to revolutionize precision farming through controlled-release nano-fertilizers and pesticides, nano-enabled biosensors for real-time environmental monitoring, antimicrobial coatings, and even as carriers for CRISPR-Cas9 systems to enhance crop resilience. In medicine, next-generation applications include targeted drug delivery, antimicrobial coatings for medical devices, theragnostic that integrate therapy and diagnostics, and innovations such as AgNP-based vaccines, nanorobotics, and portable biosensors for point-of-care diagnostics, especially in underserved regions.

However, the widespread deployment of AgNPs must be balanced with careful consideration of potential risks to human health and the environment. Comprehensive toxicological studies, the development of biodegradable or self-degrading nanoparticles, and standardized safety regulations will be essential to ensure responsible use. Life cycle assessments and nano-safety-by-design principles will guide sustainable application, while global regulatory frameworks must evolve to define safe usage levels in both agricultural and biomedical contexts. Public engagement, transparency, and ethical guidelines will also be crucial to foster trust and ensure equitable access to nano-enabled technologies, particularly in low-resource settings. Moving forward, interdisciplinary collaboration among nanotechnologists, biologists, chemists, agronomists, and clinicians, combined with the integration of artificial intelligence and big data analytics, will be vital for advancing predictive modeling, the design of novel nanostructures, and personalized solutions. If environmental, regulatory, and ethical challenges are proactively addressed, silver nanoparticles have the potential to become powerful, sustainable tools for addressing global challenges in food security, healthcare, and environmental stewardship

Conclusion

Silver nanoparticles play a significant role in health management due to their wide range of applications, including use as antimicrobial and antitumor agents, in food packaging, agriculture, and the healthcare sector. However, the overuse and misuse of conventional antimicrobial agents have led to resistance, resulting in reduced effectiveness. This is especially concerning in the case of biofilm-forming bacteria, which pose a serious challenge. To address the growing problem of antibiotic resistance, global attention has shifted toward alternative treatment strategies. Among these, the application of SNPs-particularly through surface coatings or impregnation with nanomaterials-has emerged as a promising antibiofilm strategy. Furthermore, SNPs are among the most extensively studied and applied nanoparticles for managing various health conditions, including cancer, wound healing, dental implants, and other therapeutic applications aimed at enhancing biological performance. With advancing knowledge and improved technologies, the use of SNPs in medicine is expected to establish a robust platform for the prevention and treatment of multidrug-resistant pathogens and biofilm-associated infections. While nanotechnology is a rapidly growing field with extensive applications in electronics, energy, the environment, and health, its potential in agriculture remains underutilized, especially in India and other countries. Despite its promise as a novel and effective tool for addressing persistent agricultural challenges, research in this domain is still in its early stages and often remains at the conceptual level. Indian farmers and agricultural stakeholders should be encouraged to adopt such innovative approaches in farming practices. Doing so will enable the broader societal benefits of nanotechnology to be realized. Researchers and scientists in the nanotechnology field have ample opportunities to explore the intelligent application of engineered nanoparticles in agriculture and horticulture, unlocking their full potential for sustainable and smart farming solutions.

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Author contribution: Author Dr. KP collected the necessary data and literatures for first draft of the manuscript which was written. Finally, KP read, corrected and finalized the final shape of manuscript.

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