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Green Synthesis of Silver Nanoparticles and their Applications: A Systematic Review

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Abstract

The field of nanotechnology has seen remarkable progress with the emergence of silver nanoparticles, which are recognised for their unique physicochemical properties and diverse applications. Among the various synthesis methods, green synthesis of silver nanoparticles has garnered significant attention due to its eco-friendly, cost-effective, and sustainable nature. This review provides a comprehensive analysis of the classification, properties, and various synthesis techniques for silver nanoparticles, with a particular focus on green synthesis approaches that employ biological sources such as plants, bacteria, fungi, and algae. It discusses the factors influencing synthesis and stability, as well as key characterisation techniques used to assess the properties of the nanoparticles. Additionally, the review explores the wide-ranging applications of silver nanoparticles, including their roles in biomedical fields, environmental remediation, the textile industry, and agriculture. It also identifies future challenges and examines the potential of silver nanoparticles in developing advanced drug delivery systems and their contributions to environmental conservation.

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1. INTRODUCTION

The research in the field of nanotechnology has witnessed a break through in the fields of materials and manufacturing, nanoelectronics, medicine, and information technology. It is believed by many that nanotechnology will be the next Industrial Revolution. When the dimension of the material is reduced to a smaller size, then its properties will still be the same but will get a few changes in comparison to bigger one. In quantum dots three dimensions are in the nano range. Three kinds of nanostructures have been called by quantum because their properties are changed by the quantum mechanical nature of physics in the domain of ultra small.[1]

The biotechnology has an endless opportunities for molecular diagnosis and therapy. The nano carriers can be designed in a way to facilitate them to act as imaging probes using a variety of techniques such as ultrasound (US), X-ray, computed tomography (CT), positron emission tomography (PET), magnetic resonance imaging(MRI), surface – enhanced Raman imaging (SERS). Nano particles such as magnetic nano particles (iron oxide), silver nano-particles, gold nano-particles, silver nano-particles, nano shells and nano cages have been modified for the use of diagnostic and therapeutic agents.[2]

2. GREEN SYNTHESIS OF SILVER NANOPARTICLES

One of the most extensively researched and applied nanoparticles includes silver nanoparticles (AgNPs), owing to their extraordinary ability to combat microbes and their vast application in diverse industries. While several nanoparticles, such as gold nanoparticles, magnetic nanoparticles, silica nanoparticles, titanium nanoparticles, and chitosan nanoparticles, among others, are used in different fields like biomedical engineering, catalysis, and environmental purification, the use of silver nanoparticles is highly preferred due to their outstanding antimicrobial capabilities that can combat various organisms like bacteria and viruses.[1]

Synthesis of silver nanoparticles using a green method has received considerable interest due to its sustainability and environmental friendliness, compared to the use of physical and chemical processes of synthesis. Silver nanoparticles have unique properties, which include high conductivity, stability, and high antibacterial properties where the metal is able to kill a variety of disease-causing microorganisms. Compared to the traditional process of nanoparticle synthesis, there are various benefits of using the green approach, which include low toxicity, minimal harm to the environment, cost-effectiveness, scalable, and high yield. Although microorganisms such as bacteria, fungi, viruses, and yeasts can be used in the production of nanomaterials, their use has been hindered by factors such as high costs, long incubation periods, and difficulty in cultivation and purification. In response to these limitations, plant-based synthesis is preferred. Plant-based extracts contain different phytochemicals such as alkaloids, flavonoids, phenolics, tannins, terpenoids, saponins, amino acids, proteins, and vitamins that can function as reducing and stabilising agents [3]

Chemical methods are widely used to make silver nanoparticles, but they often leave behind unwanted residues like solvents, reducing agents, and stabilisers. These leftovers can include ethylene glycol, sodium citrate, and liquid paraffin. Such residue buildup raises red flags about toxicity, especially since these particles might end up interacting directly with the human body in applications like drug delivery, antimicrobial treatments, tissue engineering, and diagnostics. What is more, relying heavily on hazardous chemicals doesn't sit well with the Sustainable Development Goals. Because of these drawbacks, people have started looking for safer and greener ways to do things. So now, there's growing interest in biological or "green" synthesis methods for creating silver nanoparticles.

This approach uses natural reducing and stabilising agents, cutting down on toxic chemicals and helping out the environment in the process. On top of that, these green methods tend to be cheaper, use less energy, and work great for biomedical purposes too.

Green synthesis methods for making nanoparticles fall into three main groups. First, there's using microorganisms like bacteria, fungi, and yeasts. These tiny organisms convert silver ions using their natural enzymes and metabolic processes. Second, you can use stuff from plants – think extracts and phytochemicals. These work as reducing and capping agents when forming nanoparticles. Third, there's the use of biological templates like viral particles, DNA, and cell membranes. These help guide the nanoparticle creation and shape their form, too. These biological techniques have gained lots of interest because they make stable silver nanoparticles under milder conditions. They also cut down on the harmful risks that traditional chemical methods bring. So, it's all about creating something effective but safer for the environment and our health, too.[4]

2.1 Using Plants

Plant-mediated synthesis is now one of the most studied green methods for making silver nanoparticles. In this approach, plant extracts act as both reducing and stabilising agents, which means no dangerous chemicals or complicated microbial techniques are needed. Compared to using microorganisms, plant-based production is usually simpler, quicker, more budget-friendly, and easier to expand. Also, it's seen as environmentally friendly and great for applications that require biocompatible materials. Lots of metal nanoparticles, like those made of silver, gold, platinum, and titanium, have been created using plant extracts. These extracts come from various plant parts, such as leaves, roots, fruits, bark, flowers, seeds, and pericarps. Flavonoids, phenolic compounds, alkaloids, terpenoids, proteins, and sugars in these extracts help reduce metal ions and stabilise the nanoparticles formed.

First, gather the plant stuff you need and wash it well to get rid of dirt and extra plants that shouldn't be there. Then, dry it out in the shade and turn it into powder. To make an aqueous extract, boil the powder in deionised water and strain it. After that, combine the clear liquid with a 1 mM silver nitrate solution. When you mix these things in the plant extract turn the Ag^{+} from the silver nitrate into elemental silver, forming nanoparticles. This usually shows up as a color change because of something called surface plasmon resonance. UV-visible spectroscopy helps track all this – look for those special absorption peaks, which mean the nanoparticles did their thing. So, that's how you make silver nanoparticles with plants. Several plants have been found to be really good at making silver nanoparticles. Take Morinda citrifolia roots, Aloe vera, and Jatropha gossypifolia latex for example. Even Phyllanthus emblica fruit extracts and rosemary extracts work wonders. These plant-based nanoparticles can fight bacteria and other microbes pretty effectively too. Moreover, scientists found that nanoparticles made from Ocimum sanctum leaves wipe out bacteria; their sizes generally fall between 4 and 30 nanometers. Now, to make these particles, you have got to think about a bunch of stuff. Things like the plant extract's concentration and makeup, how much silver you start with, the reaction's pH, temp, and time really matter. All these factors shape the nanoparticles' chemical and physical traits – size, shape, stability, and functionality. So, tweaking them right is key to getting the perfect nanoparticles each time.[5]

2.2 Using bacteria

Bacteria are getting lots of attention for making silver nanoparticles in an environmentally friendly way. Still, not every bacterial type can turn metal ions into nanoparticles. Their ability depends on how well they resist and clean up metals inside their cells. When bacteria encounter silver ions, those ions go right in and latch onto important stuff inside the cells. These ions mess with the cell's DNA by attaching to it, which hinders its structure and replication. Plus, the silver ions love binding to sulfur in proteins, especially thiol groups. This binding zaps enzymes of their abilities, hindering normal cell functioning.

To counter the toxicity of silver ions, some bacteria have special systems that convert Ag^{+} into less reactive metallic silver (Ag^{0}). They do this using reductase enzymes which turn the ions into a form that's not so harmful for the cell. This happens when the enzymes, often relying on cofactors like NADH or NADPH, move electrons around and transform those silver ions into something less reactive – even starting the creation of silver nanoparticles. There is variation between different bacterial types in how good they are at this, thanks to differing amounts and effectiveness of the reductase enzymes. That's why certain bacteria are better at making these nanoparticles than others. These bacteria can reduce metal ions both inside and outside the cell. With the extracellular method, the bacteria send out their reductase enzymes and other stuff into the surrounding area. There, the ions get transformed into nanoparticles, all without the enzyme ever crossing the cell membrane. On the flip side, intracellular processes take the ions right into the cell where they're then turned into nanoparticles inside it. For both types of reactions, the end goal is protection. By changing the harmful ions into something less nasty, the bacteria survive metal exposure better.

Bacteria without good metal-reduction pathways usually can't handle high silver levels, often suffer cell damage or even die. So, having effective reductase systems is crucial for surviving metal-rich conditions. This also makes these systems perfect for the green synthesis of silver nanoparticles, which is explained in detail in reference sixty-eight.

2.3 Using Fungi

Fungi are pretty cool in the world of green nanoparticle creation, thanks to their awesome ability to make all sorts of bioactive stuff. Did you know that loads of biologically useful compounds come from filamentous fungi and other ascomycete buddies? Another neat trick is how tough they are withstanding heavy metals. This lets them grab, pile up, and change metal ions – perfect for churning out nanoparticles.

Fungi also grow pretty easy on a big scale, which makes producing these tiny particles in an eco-friendly way super simple and cheap. Plus, you get uniform shapes and sizes too. The coolest part about fungi compared to lots of other microorganisms is their huge output of extracellular proteins and enzymes. These do double duty as reducers and stabilizers, converting silver ions to those handy nanoparticles while stopping them from clumping too much. So not only is it good for the environment, but it also gives you nice, steady nanoparticles.

The biosynthesis of nanoparticles by fungi happens in one of two ways—either intracellularly or extracellularly. For intracellular processes, the metal precursor goes right into the fungal culture. Once there, the fungi absorb the metal ions which then get reduced inside the cells. After this, the tricky part begins; forming the nanoparticles requires them to be removed from the biomass. It involves breaking down the cells, applying chemical treatments, plus separating the particles via centrifugation and filtration.

On the flip side, during extracellular synthesis, you just add the metal precursor to a filtered solution that contains all the enzymes and proteins fungi secreted. This results in the reduction of silver ions and the creation of nanoparticles outside the cells. Because of this setup, the nanoparticles end up straight in the reaction medium. Most researchers actually prefer this method since it skips those complicated extraction steps and keeps things simpler downstream. That said, getting a clean batch of nanoparticles still demands purifying the suspension to weed out any leftover fungal stuff and other crud. Methods like regular filtration, membrane filtration, gel filtration, dialysis, and ultracentrifugation do the trick for getting those particles squeaky clean.

In contrast, extracellular synthesis adds the metal precursor to a cell-free fungal filtrate that contains enzymes, proteins, and other bioactive molecules. Here, the silver ion reduction and nanoparticle formation happen outside the fungal cells. As a result, nanoparticles end up directly in the reaction medium. This process is usually preferred because it avoids complex extraction procedures and makes downstream processing easier. Still, purification of the nanoparticle suspension is necessary to get rid of leftover fungal stuff and other junk. People use different methods like conventional filtration, membrane filtration, gel filtration, dialysis, and ultracentrifugation for this purpose.

Overall, fungi-based synthesis provides a sustainable and eco-friendly way to produce silver nanoparticles. They secrete a lot of useful biomolecules and are easy to grow. Plus, they can make nanoparticles with specific traits. That's why fungi are some of the most looked-at biological systems for nanoparticle biosynthesis.

Synthesis Mechanism

Even with lots of research into how fungi help create silver nanoparticles, we still don't fully get the exact biological processes behind it. From what we know, in systems outside of the cell, the enzymes and other stuff that fungi release seem to transform silver ions (Ag^+) into metallic silver (Ag^0). This makes nanoparticles form, and you can actually see the mixture changing colors. We figure out if those particles really formed by using something called UV-visible spectroscopy. When you do that, special bands known as surface plasmon resonance (SPR) show up, proving you've got silver nanoparticles. These appear usually around 400–450 nanometers. Changes in where and how strong the SPR band appears give us clues about the particles. If that peak shifts towards longer wavelengths, it suggests that the nanoparticles are getting bigger. Other factors also play into how big, shaped, and stable those particles end up being – like which type of fungus was used, the pH level, temperature, and ingredients in the mix that act as capping agents.

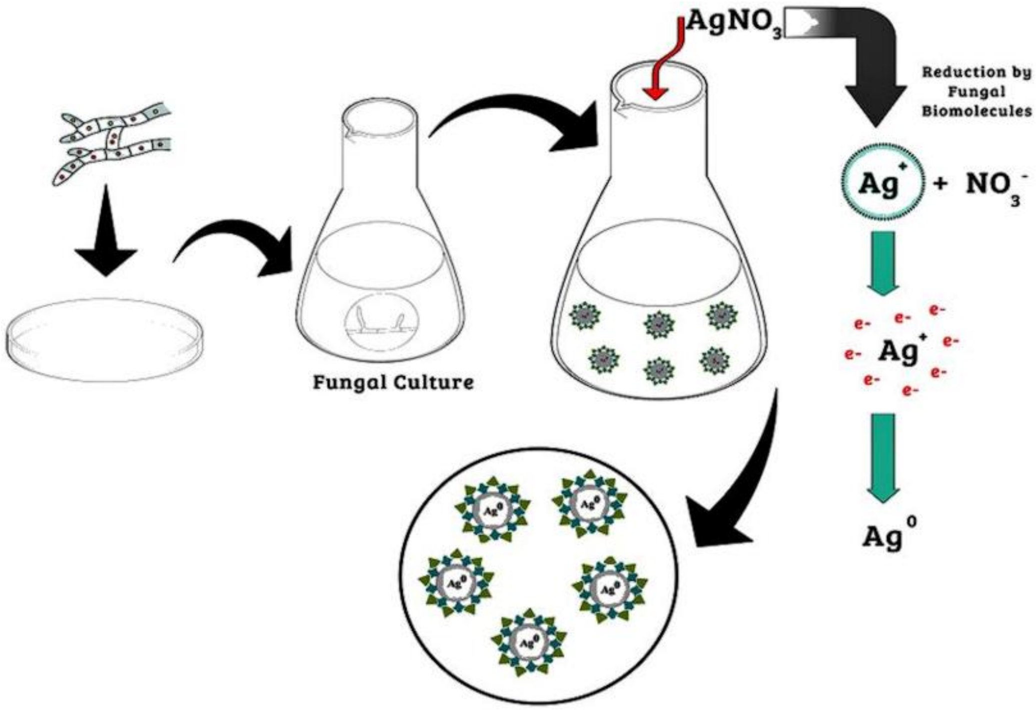

Figure 1: Mechanisms of synthesis of silver nanoparticles using fungi

Several fungal biomolecules help in the reduction process, mainly those in cellular electron-transfer pathways. The oxidation of NADPH/NADH to $NADP^+/NAD^+$ is thought to be crucial for turning silver ions into metallic silver. Molecules like NADH and NADH-dependent nitrate reductase enzymes do most of the work, often showing up in the creation of metallic nanoparticles. This is explained in Figure 1.[6]
New research has shed more light on how nanoparticles form. Some studies show that NADPH can make silver nanoparticles all on its own, even without nitrate reductase enzymes. That's huge because it means some organisms without those enzymes might still be able to make the nanoparticles. Still, other work with Fusarium oxysporum shows that for this particular fungus, the process needs both nitrate reductase enzymes and something called anthraquinone compounds to really work.[6]

2.4 Using Algae

Algae can make silver nanoparticles through a process called green synthesis; thanks to all the cool bioactive stuff they contain. Things like proteins, carbs, and pigments, among others, are really important here. These compounds help convert silver ions into little silver nanoparticles – tiny, in some cases uniquely shaped bits like spheres, rods, and wires. Many types of algae can do this too, whether they're red, brown, green, or blue-green. What's neat is that each kind produces nanoparticles with different sizes and shapes based on its specific mix of biomolecules. Proteins and amino acids, for instance, aren't just there to reduce silver ions; they also cap those nanoparticles naturally – making sure they stay stable and do not clump up. So not only is this method good for the environment, but it also lets us customize nanoparticles easily using what nature provides.
Algae-mediated synthesis has some big advantages over traditional chemical methods. It usually works at mild conditions—think room temp, regular air pressure, and a nearly neutral pH—and doesn't use any poisonous stuff. Also, it creates nanoparticles that are small, uniform, and really biocompatible. Because of these traits, algae seem great for making eco-friendly nanoparticles. But, there's a catch; the production rate is pretty slow, which could hold back large-scale industry use. When algae make nanoparticles, the process resembles their natural actions like photosynthesis, which boosts both environmental and economic perks. Microalgae soak up, gather, and detox heavy metal ions, fitting them perfectly for nanoparticle biosynthesis. By turning those ions into less harmful forms, they help build green production systems that check green chemistry boxes.
The way algae make nanoparticles is a lot like other natural biological processes, including photosynthesis. This method not

only helps the environment but could be economical too. Microalgae can soak up and clean heavy metal ions, which makes them great at creating nanoparticles in a bio-friendly way. By changing those metal ions into something less harmful, they help make production eco-friendlier – it fits right in with green chemistry. [7] When algae create nanoparticles, it happens either inside or outside their cells. Wherever the reducing action occurs, that's where you find the tiny particles. If it's happening intracellularly, silver ions move into the alga's cells and get turned into nanoparticles thanks to biomolecules produced during metabolic actions. Cells of algae have built-in defenses against the nasty side of those metal ions. They use stuff from processes like photosynthesis and respiration to strip electrons from the silver ions – NADPH, NADPH-dependent reductases, and nitrogenase enzymes do much of the work here. The result? Tiny particles form right inside the cells.[8]

Extracellular synthesis happens outside cells and uses things like cell-free extracts or culture supernatants. For this process, you dump in proteins, pigments, and enzymes. These then interact with silver ions, reducing to metallic nanoparticles in the surrounding medium. One big plus for extracellular synthesis is that it makes nanoparticle recovery way easier. Since the particles from outside the cells, there's no need to break open cells or go through a ton of extra extraction steps. Because of this, extracellular methods are typically favoured when making silver nanoparticles on a large scale. In all, algae-mediated synthesis offers a sustainable approach for producing silver nanoparticles. Algae naturally have loads of reducing and stabilizing agents. Plus, the mild reaction conditions and the variety of nanoparticle shape they produce make algae really valuable in the world of green nanotech.

3. FACTORS AFFECTING SILVER NANOPARTICLES SYNTHESIS AND THEIR STABILITY

There are some factors that affect silver nanoparticles synthesis and their stability as illustrated in

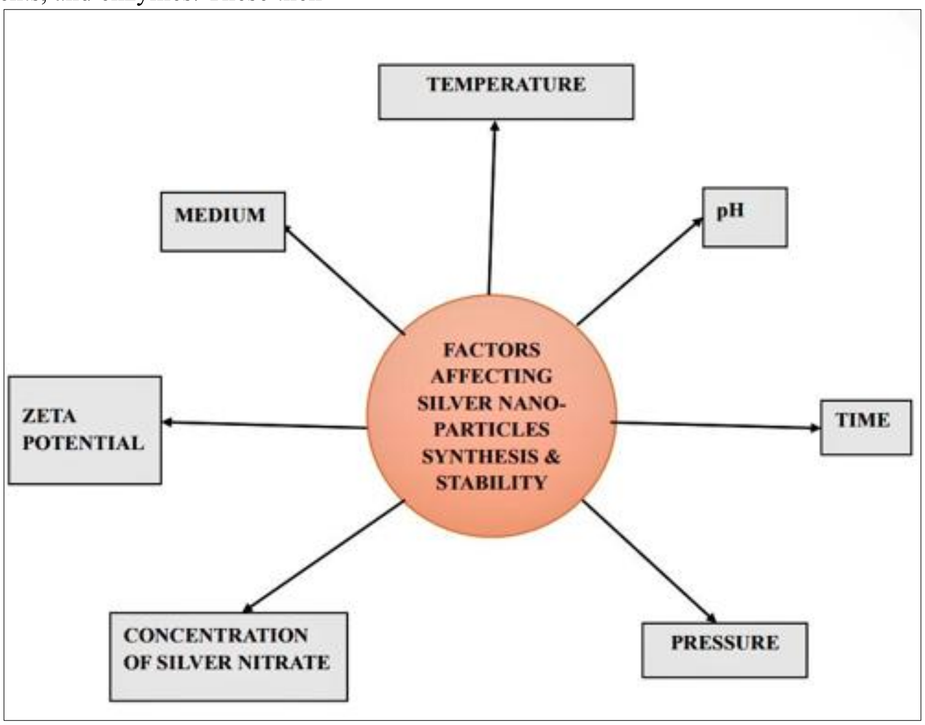

Figure-2: Factors affecting silver nanoparticles synthesis & their stability

3.1 Temperature

Temperature plays a big role in how silver nanoparticles form because it impacts how fast the reactions happen and how particles grow and stay stable. When you crank up the heat, it speeds up the process of turning silver ions into nanoparticles. Yet, if it gets too hot, the particles can clump together and unwanted reactions might happen, messing up their quality. Experiments show that changing the temperature really alters what the nanoparticles look like. At around 50°C, the mixture rapidly turns brown, showing that nanoparticles are forming. If you let the reaction continue, it might even turn black due to particle clumping. Also, when you bump the temperature up from 90°C to between 110-120°C, you see sharper absorption peaks on SPR tests. That means more neat and tidy nanoparticles formed. But run the reaction at a chilly 10°C? It drags on for hours with barely any change because everything slows down so much. While higher temps usually speed up synthesis, they don't always produce nanoparticles with the best properties. Lots of research highlights the need to balance reaction speed with quality. Some fungi make more nanoparticles at higher temps due to increased thermal energy, which helps in transferring electrons from biomolecules like amino acids to silver ions. Yet, super-high temps, say 80–100°C or more, can screw up proteins and other biomolecules acting as reducing, capping, or stabilizing agents. This damage wrecks nucleation and growth, creating bigger particles and wilder size ranges. So, finding the sweet spot for reaction temp is key—to crank out nanoparticles fast while keeping their size, shape, and stability just right.[9]

3.2 pH

The pH level is super important for making efficient silver nanoparticles because it affects how biomolecules act, how silver ions get reduced, and how stable the nanoparticles stay after that. Lots of studies show that a pH ranges from 7.0 to 7.6, which is slightly alkaline, works best for making these particles. In this sweet spot, not only does the reduction process improve, but the nanoparticles also stay stable better. This leads to more of them being produced and having top-notch properties. Another big deal is how pH levels change the way silver ions interact with the functional groups found in bio-materials. Things like amino, sulfhydryl, hydroxyl, and carboxyl groups hang out on biomass surfaces, and these help in binding and reducing metals. Altering the pH changes the charges and protonation states of these groups. If the pH gets too low, these groups can get protonated, changing how they interact with metal ions and messing with the reduction process. Silver ions really like attaching to soft ligands, such as amino and sulfhydryl groups in proteins and other bio-molecules. These groups can grab onto silver ions and help turn them into metallic silver. Plus, carboxyl groups, which are common in biological systems, join in too—especially when the environment is acidic. This is because protons affect how they work. So, these groups' ability to bind metals influences how nanoparticles form and grow.

3.3 Time:

Incubation time really matters when it comes to making silver nanoparticles. It shapes how silver ions get reduced, how particles form, and grow over time. Usually, if you let the reaction go on longer, more silver builds up on what's already there, and you end up with bigger particles. Studies show that as reaction time grows, so do the optical properties of the silver nanoparticle mixtures. One clear change? The surface plasmon resonance (SPR) absorption peak shifts towards the red part of the spectrum in UV–visible readings. That means it moves to longer wavelengths, which usually happens when particles get bigger and start clustering together. Also, giving the reaction more time typically boosts absorbance levels, telling us there are more particles floating around in the solution.[10]

3.4 Pressure:

Pressure plays a key role in making nanoparticles. Usually, when creating silver ones, increasing the pressure leads to bigger particles. But changing pressure also affects their shape. For instance, under more pressure, they might shift from being spherical to cubic, then to cauliflower-like blobs. However, studies using high-pressure chambers found mixed results. Sometimes, there wasn't a clear link between nanoparticle size and gas pressure. One theory is that higher pressure speeds up the argon gas flow, cutting down how long nanoparticles stay in the reaction chamber. This brief time means the particles do not get a chance to grow as much as expected from the pressure increase alone. While pressure should make the particles bigger, the quickened process cancels out that effect.

3.5 Concentration of Silver Nitrate:

The concentration of silver nitrate, $AgNO_3$, really affects the size of the silver nanoparticles made. Experiments show that when you go from 0.5 mM to 0.7 mM and then to 0.9 mM, the particle size grows too, going from 23.87 nm to 24.51 nm and 25.16 nm. This means there's a straight-up link between how much silver ions you start with and how big your final nanoparticles end up being. More metal ions mean there are more building blocks around for the particles to form, making them get bigger during the process.[11]

3.6 Zeta Potential:

The zeta potential is the measure of electrical potential at the slipping plane around a nanoparticle in a liquid. People use it to gauge how stable a colloid is and to learn about the surface charge of nanoparticles. Typically, if the zeta potential is less than ±20 mV, the system is seen as unstable because the particles aren't repelled strongly enough to stay separated. On the flip side, when you see potentials from ±40 mV to ±60 mV, that means there's good stability due to robust repulsive forces which stop particles from clumping together. Both positive and negative nanoparticle suspensions can show these ideal zeta potential values, giving us an idea of their increased stability.

3.7 Medium:

The long-term stability of silver nanoparticles is greatly affected by the environment around them. Properties of that environment influence how the nanoparticles interact chemically and with each other, affecting how they clump together, as well as their size, shape, and durability over time. This becomes super important in water-based systems, where aging changes their physical and chemical traits. Therefore, keeping inorganic nanoparticles stable mainly relies on good surface treatment techniques that improve dispersion and stop unwanted alterations during storage and use.

4 CHARACTERIZATION OF SILVER NANOPARTICLES:

Nano particles are generally characterized by their size, morphology, and surface charge using advanced microscopic techniques such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM); Dynamic light Scattering (DLS), Fourier Transform Infrared (FTIR) Spectroscopy, X-ray Diffraction (XRD), as shown below Figure-2.

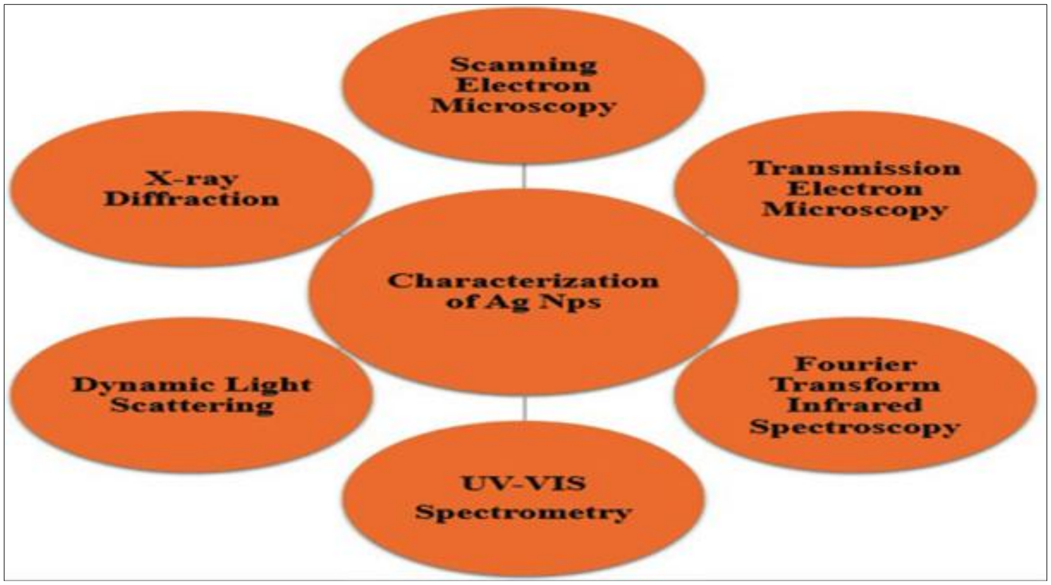

Figure-3: Various Characterisation Techniques

5. APPLICATIONS OF SILVER NANOPARTICLES

Silver nanoparticles exhibit a variety of physical properties, such as size, shape, morphology, and surface area, in addition to their magnetic, electrical, and optical characteristics. These features facilitate their widespread applications, such as:

5.1 Biomedical Applications

5.1.1 Antiseptic

Researchers have recognized the function of silver nanoparticles (Ag NPs) as effective antimicrobial agents against both fungi and bacteria, building on the historical application of silver metal as an antiseptic in wound healing. Silver nanoparticles exhibit considerable promise in addressing multi-drug-resistant strains of bacteria and fungi, with their antibacterial efficacy differing among species, which also affects their vulnerability. Notably, methicillin-resistant Staphylococcus aureus, methicillin-resistant Staphylococcus epidermidis, and Streptococcus show the highest antibacterial activity. Research indicates that the chitosan-silver colloid possesses enhanced bactericidal properties against Escherichia coli, while demonstrating limited effectiveness against C. albicans, a difference attributed to variations in cell wall structure and the presence of functional groups on the bacterial surface. Additionally, Ag NPs have been shown to improve the effectiveness of commonly used antifungal agents such as Amphotericin B, Nystatin, and Fluconazole.[12]

5.1.2 Drug Delivery Systems

Silver nanoparticles hold significant promise for use in sunscreen formulations and can also facilitate burn recovery, enhance dental devices, and improve the aesthetics of stainless-steel products. The optimal size range for Ag NPs in drug delivery applications is between 10 and 100 nm, with their smaller dimensions and larger surface area providing notable benefits. When compared to other metal-based nanomaterials, Ag NPs exhibit greater efficacy in extermination processes and display blue-shifting plasmon resonance peaks. This characteristic positions them as an excellent choice for a variety of applications, including surface-enhanced light chemistry with confined materials such as nitro benzyl adjuncts and photo-controlled drug delivery. Furthermore, nanobots offer advancements over traditional drug delivery methods, featuring faster metabolism, extended plasma half-life, and targeted delivery of drugs facilitated by endothelial cells to tumours locations.[13]

5.2 Catalytic Converter

The catalytic efficiency of silver nanoparticles (Ag NPs) was evaluated by determining the reduction of dyes in conjunction with silica spheres; it was observed that dye reduction did not take place without the presence of silver nanoparticles. The textile materials used in the apparel and footwear sectors incorporate silver nanoparticles. Regarding chemical luminescence, silver nanoparticles demonstrate greater catalytic activity compared to gold and platinum emulsions. Furthermore, silver nanoparticles display photocatalytic properties that differ from those of color compounds such as naphthol orange (NO) and malachite green (MG).[14]

5.3 Chemical Sensor

Colourimetric techniques that employ silver nanoparticles and gold nanoparticles have shown remarkable accuracy and efficiency in environmental studies, especially in the detection of metal ions and biomolecules. Research has revealed that silver nanoparticles effectively sense lead (Pb) II ions through their interaction with dithizone. These nanoparticles are produced using the leaves of Aconitum violaceum, a biennial plant native to areas including Pakistan, Nepal, India, and the Himalayas. Furthermore, silver nanoparticles have been used to identify contaminants in water. They can detect trace amounts of hydrogen peroxide (H_2O_2), a recognized hazardous substance, and are also employed in the identification of heavy metal pollutants.[15]

5.4 Environmental Remediation

Silver nanoparticles are utilized in various environmental applications, such as air, soil, and drinking water purification, along with the treatment of biological waste. The presence of Ag NPs and their composite materials can effectively diminish or remove colorants, aiding in the reduction of environmental contaminants. Furthermore, silver nanoparticles have significant agricultural applications, as they impact soil bacteria. Membranes composed of nanocomposites that include silver nanoparticles demonstrate a strong capability to detoxify salts. Reports indicate that twenty percent of retail products are manufactured using nano-silver, which is found in half of all retail items.[16]

5.5 Textile Application

The antifungal properties of two varieties of silver-coated natural cotton fabric, created using a supercritical carbon dioxide ($scCO_2$) solvent, were examined. Scanning electron microscopy demonstrated that the $scCO_2$ technique can yield cotton fabric textiles with uniform silver nanoparticle coatings. The ability of these textiles to inhibit fungal growth was assessed using a modified Kirby-Bauer disc diffusion test. The cotton fabric samples treated with Ag(hepta) and Ag(cod)(hfac) displayed significant zones of inhibition, while the untreated fabric did not exhibit any inhibitory effect.[17]

5.6 Agricultural Applications

The synthesis of nanoparticles is highly significant due to the unique properties that can be integrated into composite fibers, biosensor materials, cryogenic superconductors, cosmetic products, and electronic components. The production silver nanoparticles (AgNPs) from plant extracts, particularly from agricultural waste, is a crucial area of research that promotes sustainable development in agro-industrial practices, especially in light of climate change and the depletion of natural resources. The resulting nanoparticles, characterized by their low toxicity, can be utilized in various agro-industrial applications, ranging from soil enhancement to the food supply chain, as plants play a vital role in this eco-friendly synthesis. In terms of the direct application of AgNPs in agriculture, numerous studies have focused on aspects such as seed germination, root growth, and plant responses to metal nanoparticles, including cellular oxidative stress and cytotoxic effects.[17]

5.7 As electron transfer

The ability of silver nanoparticles to facilitate high-intensity electron transport is noteworthy. Due to the substantial size of proteins, which are large and bulky molecules, silver nanoparticles can enhance the movement of electrons from a protein's redox center to the electrode surface. In this research, silver nanoparticles were positioned within the 1 V potential range on the surface of a graphite carbon electrode. The presence of silver nanoparticles, measuring between 70 and 150 nm in diameter, on the graphite electrode was confirmed using transmission electron microscopy (TEM).[17]

6. CONCLUSION

In recent years, there has been a notable increase in research dedicated to the environmentally sustainable production of nanoscale metals. Nanoparticles have demonstrated their utility across a wide array of industries, including micro-wiring, electronics, energy harvesting, food production, agriculture, and medicine. These nanoparticles can be synthesized through various methods, including physical, chemical, and biological techniques. Among these, green synthesis methods have shown superior effectiveness and success when compared to conventional techniques. The green synthesis approach is distinguished by its commitment to environmental safety, non-toxicity, and cost efficiency. The evidence gathered from these studies strongly supports the transition towards green synthesis methods for the production of metal and metal oxide nanoparticles, which have been shown to perform better in both environmental and therapeutic contexts. Our research team is dedicated to developing a broad spectrum of green nanoparticles in the future, targeting applications in diverse fields such as pharmaceuticals, healthcare, environmental science, aquaculture, and agriculture. The results of this research will facilitate further investigations into the creation of green nanoparticles for use in environmental and biomedical applications.

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