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Eco-friendly synthesis of silver nanoparticles: advances in green methods and biomedical potential

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A B S T R A C T

Our paper examines the environmentally sustainable production of silver nanoparticles utilizing renewable resources, including plant extracts. Green synthesis methods are a better option than traditional chemical processes because they utilize fewer harmful chemicals and are less environmentally hazardous. Different methods for characterization include UV-Vis double beam spectrophotometry, Fourier transform infrared spectroscopy (FTIR), and Scanning electron microscopy (SEM). To assess the dimensions, shape and stability of the synthesized AgNPs. The study mainly emphasizes the different applications of silver nanoparticles, particularly their remarkable antibacterial efficacy against a broad spectrum of pathogenic microbes. Using eco-friendly methods to make AgNPs with herbal extract is a more modern and safer way than traditional chemical synthesis. Eco-friendly methods make nanoparticles more durable and enhance their functional properties. Silver nanoparticles exhibit antibacterial properties that are highly beneficial in healthcare and industry, including illness treatment and environmental sanitation. It refers to their scalability and compatibility with biological systems. Further study is required to enhance the eco-friendly synthesis procedure, ensure manufacturing efficacy, and ensure the safety of nanoparticles for practical applications. This review demonstrates that eco-friendly nanotechnology can provide sustainable activities. Further research to find solutions to the challenges that come with scalability, biocompatibility, and sustainability. In this manner, these technologies can be employed safely and ethically in many domains.

Keywords: Eco-friendly Synthesis, Silver Nanoparticles, Antimicrobial Efficacy, Nanoparticle Characterization, Sustainable Synthesis, Nanotechnology

Introduction

Eco-friendly methods used to synthesize silver nanoparticles (AgNPs) are a safer and better option than traditional chemical methods. These methods are utilized to assess the antibacterial activity of different bacteria. Eco-friendly methods make nanoparticles more stable and increase their functional properties. It can be used in different fields, including medicine, industry and environmental science. Common ways to synthesize chemicals use hazardous solvents, toxic reducing agents and a lot of energy causes environmental pollution. Eco-friendly methods to synthesize nanoparticles, are sustainable option that use fewer harmful chemicals while still being highly effective and stable.[1] These limitations have promoted researchers to investigate green synthesis methods that uses biological resources as much safer and more sustainable alternative.[2] Nanotechnology, which involves manipulating matter at the nanoscale (1-100nm), has changed the field of medicine, material science and the environment by making materials with unique phytochemical properties that are not found in larger materials. NPs are very beneficial for catalysis, pharmaceutical management, and antimicrobial applications because they possess substantial dimension to volume ratio. Among all metal ions, AgNPs are one of the most well-known type of metal nanoparticles because they are stable, biocompatible and have high range of antimicrobial properties.[3] In past, the eco-friendly synthesis of silver nanoparticles (AgNPs) utilizing biological agents such as plant extracts, microbes, fungi, and algae has become a promising area of nanotechnology. In these methods, biomolecules that are found in nature, such as phenolics, antioxidants, aromatic compounds, proteins, and polysaccharides work as agents that lower and stabilize. This means that no external toxic chemicals are needed. Recent reviews have shown that these biosynthetic methods not only have low effect on environment, but also make nanoparticles more stable and useful.[4] Recent studies

have shown that different plants, the part of the plant used (leaves, roots, flowers), the method of extraction (alcoholic and aqueous) and techniques (hot plate magnetic stirrer and rotary machine) all have a big effect on the dimension, form, stability, and biological activity of nanoparticles. This makes it possible to make nanoparticles that are perfect for certain uses.[5] Plant mediated synthesis has become a lot of attention among biological routes because it is cheap, fast kinetics reaction and can be done on large scale. Plant extract are the great source of secondary metabolities that can change silver ions into nanoparticles at low temperature. Research from last decade shows that reaction parameters like pH, ambient temperature, extract ratio and cation ratio have a huge effect on dimension, shape, and biological activity of nanoparticles.[6] Phytochemical capped AgNPs frequently demonstrate the improved antimicrobial properties interaction with silver and plant mediated.[7] Meanwhile, using bacteria and fungi has opened new possibilities for green nanofabrication. Microorganisms can use enzymes to lower the amount of Ag^+ ions inside or outside of cells, making nanoparticles with a controlled shape and small size range. Microbial synthesis may take longer and need to be done in sterile conditions, but it has benefits like being able to be repeated and possibly changing the genetic material to make nanoparticles in a controlled way.[8] Researchers focuses the biomedical uses of eco-friendly method to synthesize silver nanoparticles in past years. A lot of research has shown that these substances are very efficient against a wide variety of bacteria (gram +ve and gram –ve), even strains that are sensitive to multiple drugs (MDR). Also, biosynthesized AgNPs have been shown to be antifungal, antiviral, anti-inflammatory, antioxidant, anticancer and antibacterial are often less toxic to cells than chemically synthesized AgNPs.[9] Recent studies highlight the significance of chemical surface properties, and capping agents in impacting the biological behavior of silver nanoparticles. Phytochemical obtained from green synthesis effect cellular uptake, biocompatibility and antimicrobial mechanisms.[10] Along with antimicrobial treatment, green produced silver nanoparticles have demonstrated potential in healing process, drug management, bio-sensing, medical coatings and diagnostic applications. Nano-medicines because of their eco-friendly sources could be safe. Recent studies suggest that combining green synthesis with functionalization techniques can improve therapeutic efficacy while ensuring biosafety.[4] In this review, we thoroughly examine the advances in sustainable production of AgNPs over the past decade, focusing on plant and microbe based methods and their biomedical potential. By critically analyzing recent literature, this article highlights methodological developments, biological mechanisms, therapeutic applications and current challenges. Thereby, providing a consolidated framework for eco-friendly synthesized AgNPs.

2.1. Antibiotic Resistance

Antibiotic resistance has become a significant worldwide threat, caused by the over use of conventional antibiotics in humans. Multidrug-resistant (MDR) bacteria, such as *Escherichia coli, Staphylococcus aureus, Klbsiella pneumoniae* and *Pseudomonas aeruginosa,* are increasingly responsible for hospital and community acquired infections, increasing morbidity and mortality worldwide.[11] Enzymatic breakdown of antibiotics, alteration of drug targets, efflux machanism and biofilm formation are all ways that bacteria can become resistant to drugs. These mechanisms all work together to make drugs less effective.[12] In the past ten years, the number of infections that are resistant to antibiotics has grown alarmingly, particularly in moderate nation where there isn't much regulation. Research has indicated that MDR strains demonstrate resistance to β-lactams, fluoroquinolones, and carbapenems, which were formerly regarded as antibiotics.[13] Conventional antibiotics are progressively ineffective against resistant pathogens, prompting the exploration for innovative antimicrobial agents. Nanoparticles, especially silver nanoparticles made using green methods, have strong antibacterial properties against MDR bacteria because they work on many different targets.[14]

2.2. Nanotechnology

Nanotechnology refers to the scientific discipline that utilizes phenomena at the nanoscale(1-100nm) for the design, characterization, fabrication, and application of materials, structures, devices, and systems. The concept of nanotechnology was initially proposed in 1959 when physicist Richard Feynman delivered a lecture on manipulating matter at the quantum and the level of molecule. Nanotechnology is currently considered the rapidly advanced technology of the twenty-first century, and researchers have investigated it as an innovative method in medicine.[15]

2.3. Different Types of Nanotechnology

Computational, wet, and dry technologies are the main types of nanotechnology. These all together work in advanced nanotechnology to perform different functions. Wet methods are best for biomedical and environmental uses, dry methods are best for electronics and materials engineering, and computational tools help predict how to make nanomaterials more efficiently.[16]

2.4. Applications of Nanotechnology in various fields

Nanotechnology is rapidly expanding discipline that crosses many disciplines and has many uses in medicine, environmental science, agriculture, and energy. NPs are mainly involved in biomedicine for specific drug administration, diagnostic imaging, biosensors, and antimicrobial treatments because of their unique size dependent properties.[17]

2.5. Nanoparticles

Nanoparticles are smaller in diameter (1-100nm) in size with a spherical shape and uniformly sized particles. Nanoparticles often act differently from bulk materials because they require high surface area. Nanoparticles are small in diameter due to this property it covers requires small surface area and high efficacy. These materials are valuable in different fields such as herbal medicine, industrial, electronic, and bio-science, where they are used for different applications such as drug management, biomedical, imaging, sensors, and advanced materials.[18]

2.5.1. Different methods of Nanoparticles synthesis

NPs produced by using three main methods, such as physical, biological, and chemical methods. Biological methods include green synthesis. It is a more advanced and safer method than chemical due to containing less harmful materials. In the physical method, a uniform size of particles is not found. Eco-friendly methods can make more stable, uniformly sized nanoparticles.[19]

2.5.2. Applications of Nanotechnology & Nanoparticles

Nanotechnology used in various fields due to their advanced technology. Commonly incorporate industrial, medical and electronic uses. In biomedical field, used for the diagnosis process including, drug delivery etc. In electronics, faster chips, sensors, and highly displays. Used in consumer products mainly in food packaging, textile, and cosmetics. In household goods, used as antibacterial coatings for appliances. Nanofiltration are advanced field in nanotechnology used in water purification processes.[17]

2.6. Green Synthesis

Green synthesis is the environmentally friendly way to make NPs by utilizing herbal products like herbal extracts, microbe, fungi, algae, or biomolecules as decreasing and stabilizing particle. Green synthesis is safer for biomedical and environmental uses non-toxic chemicals and minimizing energy consumption, or dangerous by-products like traditional methods do. Eco-friendly method is especially popular because phytochemicals like flavonoids, terpenoids, alkaloids, and phenolic compounds can lower metal ions and stabilize nanoparticles. They can also make them more biologically active. Nanoparticles made from green materials have shown strong antimicrobial, antioxidant, anticancer, and catalytic properties. This makes them good candidates for use in medicine, agriculture, environmental cleanup, and industry.[19]

2.6.1. Factors affecting Green Synthesis

There are the number of factors that effects the size and shape of nanoparticles includes, temperature, pH, incubation period. On higher temperature, more stable and smaller nanoparticles are formed. pH effects the reduction potential of biomolecules and morphology (size and shape). Reaction time large particles takes maximum time vice-versa. Light can also have influenced the rate of reaction and makes unstable. [2]

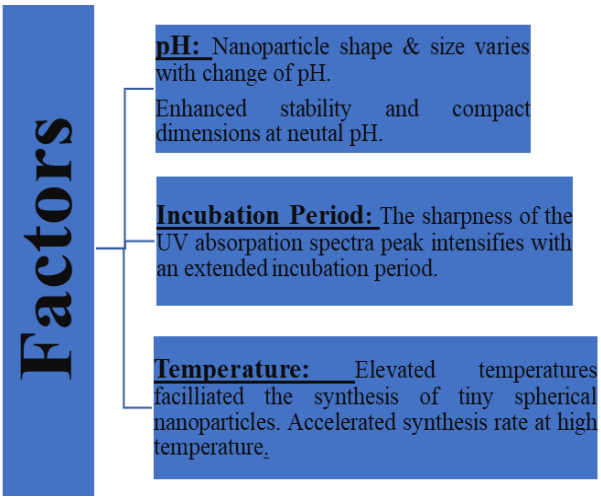

Figure.2.4. Factors affecting plant assisted synthesis (green synthesis) of nanoparticles

Table. 2.1. Factors affecting green synthesis of AgNPs.

Factor	Effect on AgNPs	Reference
pH	Alkaline pH favors smaller, more uniform nanoparticles; acidic pH may slow reduction	[19].
Temperature	Higher temperature accelerates reduction and produces uniform nanoparticles; too high can cause aggregation	[2].
Incubation Time	Longer time increases particle growth; very long can cause aggregation	[20].
Plant Extract Concentration	Higher concentration enhances reduction and stability; excessive can cause aggregation	[21].
Metal Salt Concentration	Higher Ag^+ can increase yield but may affect size and shape	[22].

2.7. Silver Nanoparticles

AgNPs are one of the most studied type of metallic nanoparticles because they have unique properties that make them beneficial against antibacterial, antiviral, anticancer, and as catalysts. AgNPs are tiny particles of silver nitrate. Sizes ranges from 1 to 100 nanometers. Due to its small size, it shows the best antimicrobial activities against different bacteria. They can be synthesized physically (top and bottom methods), chemically, and biologically (green synthesis). Due to this property, it shows high effectiveness against bacteria, fungi, and viruses which makes it majorly important in healthcare and environmental applications.[19]

2.7.1. Synthesis & Characterization AgNPs

Eco-friendly method is gaining attention because it is economically efficient and biocompatible.[19] Silver ions (Ag^+) are turned into metallic silver nanoparticles (Ag^+) during synthesis. This is done by reducing agents found in plant extracts, which also work as stabilizers to keep the nanoparticles from clumping together. There are a number of analytical methods used to characterize AgNPs, UV–Vis double beam spectroscopy verifies nanoparticle synthesis through surface plasmon resonance. Fourier-transform infrared spectroscopy (FTIR) finds the functional groups that are responsible for reduction and capping. X-ray diffraction (XRD) finds the crystalline structure. Scanning electron microscopy (SEM) shows the size and shape of the particles, and dynamic light scattering (DLS) shows the dimension distribution and particle stability. To improve the characteristics of NPs for use in biomedicine, environmental cleanup, and industry, it is important to do the right synthesis and characterization.[23]

Table 2.2. Green-synthesized silver nanoparticles: plants, characterization and activity.

Plant used	Synthesis Process	Characterization	References
Mentha	Eco-friendly	EDX, UV-Vis, FTIR, SEM, XRD,	[6].
Acacia nilotica	Eco-friendly	UV-Vis, FTIR, SEM, XRD, EDX	[22].
Onosma bracteatum	Eco-friendly	UV-Vis, FTIR, XRD, SEM	[24].
Ipomoea batatas	Eco-friendly	UV-Vis, FTIR, XRD, SEM, EDX	[25].
Punica granatum	Eco-friendly	UV-Vis, EDX, FTIR, XRD, SEM	[26].
Azadirachta indica	Eco-friendly	UV-Vis, FTIR, EDX, XRD, SEM	[27].

2.8. Antibacterial potential of silver nanoparticles

AgNPs have high antibacterial efficacy that work against microbes, fungi, and viruses. This makes them good candidates for use in medicine and the environment. Because they are small and have a lot of surface area, they can get very close to microbial cell membranes. This can cause structural damage, stop cellular processes, and make reactive oxygen species (ROS), which eventually kill cells. AgNPs are highly effective in eliminating microbes that exhibit resistance to many bacteria, like *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, because they attack many cellular pathways at once. The antibacterial efficacy of AgNPs is affected by variables including material dimension, form, concentration, and surface chemistry, with smaller nanoparticles generally demonstrating greater activity. Green synthesized AgNPs made from plant extracts not only make the nanoparticles more biocompatible, but they also often have stronger antimicrobial effects because phytochemicals cover them. These qualities make AgNPs a good choice for use in wound bandage, for medical devices, water treatment, and as other antimicrobial potential in the fight against antibiotic resistance.[28]

Conclusion

Making silver nanoparticles (AgNPs) using plant extracts is a green way to synthesize particles. This one is better for the environment, cost-effective and duarable due to eco-friendly. It uses phytochemicals like flavonoids, terpenoids, and phenolics rather than harmful chemicals. Function as natural stabilizing and decreasing agents, Different methods are employed to define the NPs, includes UV-Vis double beam spectrophotometer, FTIR, XRD, SEM which demonstrate that the nanoparticles have stable size and form. Eco-friendly methods offer a lot of potential for use in medicine. Eco-friendly produced silver nanoparticles show antimicrobial, antioxidant, anti-inflammatory, and anticancer activities. These nanoparticles have applications in wound healing, drug delivery, medical coating, diagnostics, and tissue engineering.

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