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HERBAL EXTRACT–BASED SILVER NANOPARTICLES: A COMPREHENSIVE REVIEW

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ABSTRACT

Herbal extract–based silver nanoparticles (AgNPs) have emerged as a promising and sustainable alternative to conventional chemical and physical synthesis methods due to their eco-friendly, cost-effective, and biocompatible nature. In this green synthesis approach, plant-derived phytochemicals such as flavonoids, phenolics, terpenoids, alkaloids, proteins, and polysaccharides act as both reducing and stabilizing agents, facilitating the conversion of silver ions (Ag^+) into metallic silver nanoparticles (Ag^0) while preventing aggregation. The physicochemical properties of biosynthesized AgNPs – including size, morphology, crystallinity, and surface charge – are influenced by parameters such as pH, temperature, extract concentration, and reaction time, and are characterized using techniques like UV–visible spectroscopy, FTIR, TEM, SEM, XRD, DLS, and zeta potential analysis. Herbal AgNPs exhibit significant biological activities, including antibacterial, antifungal, antiviral, antioxidant, and anticancer effects, primarily through mechanisms involving membrane disruption, reactive oxygen species generation, DNA damage, and apoptosis induction. Beyond biomedical applications such as wound healing, drug delivery, and medical device coatings, these nanoparticles also demonstrate potential in agriculture and environmental remediation. Despite their advantages, concerns regarding toxicity, reproducibility, large-scale production, and regulatory approval remain challenges for clinical and industrial translation. Overall, herbal extract–based silver nanoparticles represent a vital convergence of green chemistry and nanotechnology with substantial potential for sustainable therapeutic and technological applications.

KEYWORDS: *Silver Nanoparticles (Agnps); Green Synthesis; Herbal Extracts; Plant-Mediated Synthesis; Phytochemicals; Biosynthesis; Surface Plasmon Resonance; Antimicrobial Activity; Anticancer Activity; Nanobiotechnology; Sustainable Nanotechnology; Toxicity Assessment.*

INTRODUCTION

Overview of Nanotechnology

Nanotechnology is a multidisciplinary field that involves the design, synthesis, characterization, and application of materials at the nanoscale, typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. These properties include increased surface area, enhanced reactivity, improved optical characteristics, and superior mechanical strength. Nanotechnology has found widespread applications in various fields such as medicine, pharmacy, electronics, agriculture, environmental science, and energy. In the pharmaceutical sector, nanotechnology has revolutionized drug delivery systems by improving drug solubility, bioavailability, stability, and targeted delivery, leading to better therapeutic outcomes and reduced side effects.

Importance of Silver Nanoparticles (AgNPs)

Silver nanoparticles (AgNPs) are among the most extensively studied and widely used metallic nanoparticles due to their remarkable antimicrobial, antioxidant, anti-inflammatory, and anticancer properties. Silver has been used for centuries as an antimicrobial agent, and its nanoscale form significantly enhances its biological activity. AgNPs possess a large surface-to-volume ratio, which increases their interaction with microbial cells and enhances their effectiveness against a broad spectrum of pathogens, including bacteria, fungi, and viruses. Because of these properties, AgNPs are widely used in pharmaceuticals, wound dressings, medical devices, cosmetics, textiles, and water purification systems. Their multifunctional nature and strong biological activity make them highly valuable in biomedical and pharmaceutical applications.

Limitations of Conventional Synthesis Methods

Traditional methods for synthesizing silver nanoparticles generally involve physical or chemical processes. Physical methods, such as evaporation–condensation and laser ablation, require expensive equipment, high energy consumption, and complex procedures. Chemical synthesis methods often involve toxic reducing agents, organic solvents, and stabilizing chemicals that may pose environmental and biological risks. These methods can also generate hazardous by-products and may lead to residual toxicity in the final nanoparticle formulation. Additionally, chemical methods may require strict control of reaction conditions and may not always produce biocompatible nanoparticles suitable for medical applications. These limitations have created a demand for safer, more sustainable, and environmentally friendly synthesis approaches.

Need for Green Synthesis

Green synthesis of silver nanoparticles has emerged as an eco-friendly alternative to conventional physical and chemical methods. This approach uses natural biological resources such as plant extracts, microorganisms, and biomolecules to reduce silver ions into nanoparticles. Among these, plant-based synthesis is particularly attractive because it is simple, cost-effective, rapid, and does not require sterile conditions or complex procedures. Plant extracts contain various bioactive compounds such as flavonoids, phenolics, alkaloids, terpenoids, and proteins, which act as natural reducing and

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stabilizing agents. Green synthesis eliminates the use of hazardous chemicals, reduces environmental impact, and produces biocompatible nanoparticles suitable for pharmaceutical and biomedical applications.

Scope and Objectives of the Review

The primary objective of this review is to provide a comprehensive overview of herbal extract–based silver nanoparticles and their significance in modern nanotechnology. The review focuses on the principles of green synthesis, the role of plant phytochemicals in nanoparticle formation, and the methods used for their preparation and characterization. It also discusses the biological activities, pharmaceutical applications, advantages, limitations, and future prospects of herbal silver nanoparticles. By compiling and analyzing available research, this review aims to highlight the potential of plant-mediated silver nanoparticles as a sustainable and effective platform for biomedical and pharmaceutical applications.

Silver Nanoparticles: Fundamentals

Silver nanoparticles (AgNPs) are metallic nanoparticles composed of elemental silver with sizes typically ranging from 1 to 100 nanometers. At this nanoscale dimension, silver exhibits distinct properties that differ significantly from its bulk form. These nanoparticles possess a very high surface area-to-volume ratio, which enhances their reactivity and interaction with biological systems. Due to their small size, AgNPs can easily penetrate microbial membranes, interact with cellular components, and exhibit strong antimicrobial, antioxidant, and catalytic activities. Their size, shape, and surface characteristics play a major role in determining their biological effectiveness and physicochemical behavior.

The physicochemical properties of silver nanoparticles include high electrical conductivity, optical activity, catalytic efficiency, and thermal stability. One of the most important characteristics of AgNPs is their optical property known as surface plasmon resonance (SPR). SPR occurs when the conduction electrons on the nanoparticle surface oscillate in response to incident light at specific wavelengths. This phenomenon produces a strong absorption band in the visible region, typically around 400–450 nm, which is used as a key indicator for the formation and stability of silver nanoparticles. The SPR effect also gives AgNPs their characteristic yellowish-brown color in colloidal solutions.

Silver nanoparticles exhibit unique nanoscale behavior due to quantum size effects and increased surface reactivity. At the nanoscale, atoms on the surface have higher energy and reactivity compared to atoms within the bulk material. This leads to enhanced chemical interactions, improved catalytic performance, and increased biological activity. The small size also allows nanoparticles to interact more effectively with microbial cells, proteins, and DNA, making them potent antimicrobial agents. These unique properties make silver nanoparticles highly useful in medicine, pharmacy, electronics, textiles, and environmental applications.

Green Synthesis of Silver Nanoparticles

Green synthesis of silver nanoparticles is based on the principles of green nanotechnology and green chemistry. These principles emphasize the use of environmentally friendly materials, energy-efficient processes, and non-toxic reagents to minimize environmental impact. Green chemistry promotes safer synthesis routes, reduction of hazardous substances, and the use of renewable resources. In the context of silver nanoparticle synthesis, green methods avoid harmful chemical reducing agents and instead utilize natural biological materials such as plant extracts, microorganisms, and biomolecules. This approach reduces toxicity, lowers production costs, and enhances the biocompatibility of the nanoparticles.

Herbal extracts play a crucial role in the green synthesis of silver nanoparticles. Plant extracts contain various phytochemicals such as flavonoids, phenolic acids, terpenoids, alkaloids, proteins, and sugars, which act as natural reducing and stabilizing agents. These compounds donate electrons to silver ions (Ag^{+}), reducing them into metallic silver atoms (Ag^{0}). The reduced atoms then undergo nucleation and growth to form nanoparticles. Simultaneously, phytochemicals attach to the nanoparticle surface, acting as capping agents that stabilize the particles and prevent aggregation. This dual role of plant metabolites makes herbal extracts highly efficient and eco-friendly tools for the synthesis of stable and biologically active silver nanoparticles.

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Commonly Used Medicinal Plants in AgNP Synthesis

Neem (*Azadirachta indica*)



Azadirachta indica, commonly known as neem, is one of the most widely used medicinal plants for the green synthesis of silver nanoparticles. Neem leaves contain bioactive compounds such as azadirachtin, nimbin, flavonoids, and phenolic compounds. These phytochemicals act as reducing and stabilizing agents, converting silver ions into silver nanoparticles. Neem-based AgNPs exhibit strong antibacterial, antifungal, antiviral, and anti-inflammatory activities, making them useful in wound healing, antimicrobial coatings, and pharmaceutical formulations.

Tulsi (*Ocimum sanctum*)



Ocimum sanctum, also known as holy basil, is a highly valued medicinal herb in traditional medicine systems. Tulsi leaves are rich in eugenol, flavonoids, tannins, and essential oils. These compounds help reduce silver ions and stabilize the formed nanoparticles. Silver nanoparticles synthesized using tulsi extract show significant antimicrobial, antioxidant, and anticancer activities, making them promising for pharmaceutical and cosmetic applications.

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Aloe vera



Aloe vera is a well-known medicinal plant widely used for its soothing, healing, and antimicrobial properties. The gel of aloe vera contains polysaccharides, vitamins, enzymes, amino acids, and phenolic compounds. These biomolecules act as natural reducing and capping agents in silver nanoparticle synthesis. Aloe vera-mediated AgNPs are commonly used in wound dressings, skin care products, and antimicrobial formulations due to their enhanced healing and antibacterial effects.

Green tea (*Camellia sinensis*)



Camellia sinensis is rich in polyphenols, especially catechins such as epigallocatechin gallate (EGCG). These compounds are powerful antioxidants and effective reducing agents for nanoparticle synthesis. Green tea extract facilitates rapid formation of silver nanoparticles and provides strong stabilization. AgNPs synthesized using green tea show potent antimicrobial and antioxidant activities and are widely explored for biomedical and food-related applications.

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Turmeric (*Curcuma longa*)



Curcuma longa contains the active compound curcumin, along with other phenolics and essential oils. These phytochemicals act as both reducing and stabilizing agents in the formation of silver nanoparticles. Turmeric-based AgNPs exhibit strong antimicrobial, anti-inflammatory, and anticancer properties. They are widely studied for applications in wound healing, drug delivery, and anticancer therapy.

Moringa (*Moringa oleifera*)



Moringa oleifera, often called the drumstick tree, is rich in proteins, flavonoids, phenolic acids, and vitamins. These compounds enable efficient reduction of silver ions and stabilization of nanoparticles. Moringa-mediated AgNPs have demonstrated antimicrobial, antioxidant, and anticancer activities. Due to its nutritional and medicinal value, moringa is frequently used in green nanotechnology for biomedical and environmental applications.

Factors Influencing Biosynthesis of Silver Nanoparticles

Several parameters affect the size, shape, stability, and yield of silver nanoparticles during green synthesis.

pH

The pH of the reaction medium significantly influences nanoparticle formation. At higher (alkaline) pH values, reduction of silver ions occurs more rapidly, leading to smaller and more uniformly distributed nanoparticles. In acidic conditions, the reaction rate is slower, and larger or aggregated particles may form.

Temperature

Temperature affects the reaction kinetics and nucleation rate. Higher temperatures generally accelerate the reduction process and produce smaller nanoparticles due to rapid nucleation. However, excessively high temperatures may cause instability or aggregation of particles.

Silver Ion Concentration

The concentration of the silver precursor, usually silver nitrate, determines the number of ions available for reduction. Higher concentrations may increase nanoparticle yield but can also lead to particle aggregation or irregular shapes if not properly controlled.

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Extract Concentration
The amount of plant extract influences the availability of phytochemicals acting as reducing and capping agents. Higher extract concentrations usually promote faster reduction and better stabilization, resulting in smaller and more stable nanoparticles.

Reaction Time
The duration of the reaction affects nanoparticle growth and stability. Short reaction times may produce incomplete reduction, while longer reaction times allow particle growth and stabilization. Excessive reaction time may lead to aggregation or changes in particle size.

Plant Species Variation
Different plant species contain varying types and concentrations of phytochemicals. These differences influence the reduction efficiency, particle size, morphology, and biological activity of the synthesized nanoparticles. Therefore, the choice of plant species plays a crucial role in determining the properties of the final silver nanoparticles.

Characterization Techniques
Characterization of herbal silver nanoparticles (AgNPs) is essential to determine their size, shape, structure, stability, surface chemistry, and optical properties. These parameters directly influence their biological activity and applications. Various analytical techniques are employed to confirm nanoparticle formation and to evaluate their physicochemical properties. Characterization helps in understanding particle morphology, crystallinity, dispersion, and interaction with biological systems. It also ensures reproducibility, stability, and quality control of the synthesized nanoparticles, which is important for biomedical, agricultural, and environmental uses.

Pectroscopic and Microscopic Techniques
Spectroscopic and microscopic methods are commonly used to analyze herbal AgNPs. UV–Visible spectroscopy is used to confirm nanoparticle formation by detecting the surface plasmon resonance (SPR) peak, typically between 400–450 nm for silver nanoparticles. Fourier Transform Infrared Spectroscopy (FTIR) helps identify functional groups from plant extracts that are responsible for reduction and stabilization of nanoparticles. Microscopic techniques provide direct visualization of nanoparticles. Transmission Electron Microscopy (TEM) gives detailed information about particle size, shape, and internal structure. Scanning Electron Microscopy (SEM) is used to observe surface morphology and particle distribution. Atomic Force Microscopy (AFM) provides three-dimensional surface topography and particle size measurements at the nanoscale. Structural and surface analysis techniques such as X-ray Diffraction (XRD) confirm the crystalline nature of nanoparticles. Dynamic Light Scattering (DLS) determines particle size distribution in colloidal systems, while zeta potential analysis evaluates surface charge and stability of the nanoparticles.

Biological Activities of Herbal AgNPs
Herbal silver nanoparticles exhibit a wide range of biological activities due to their small size, high surface area, and presence of bioactive phytochemicals. Their antimicrobial properties arise from their ability to disrupt microbial cell membranes, generate reactive oxygen species (ROS), and interfere with DNA and protein synthesis. Herbal AgNPs show strong antibacterial activity against both Gram-positive and Gram-negative bacteria. They also demonstrate antifungal effects by damaging fungal cell walls and inhibiting spore formation. Antiviral activity occurs through inhibition of viral attachment and replication. In addition, herbal AgNPs possess antioxidant properties by scavenging free radicals. Their anticancer activity is associated with induction of apoptosis, mitochondrial damage, and ROS-mediated cytotoxicity, leading to selective destruction of cancer cells.

Biomedical Applications
Due to their antimicrobial, anti-inflammatory, and biocompatible properties, herbal AgNPs are widely used in biomedical applications. They are incorporated into wound dressings to accelerate healing and prevent infections. In drug delivery systems, AgNPs act as carriers that enhance drug stability and targeted delivery. They are also used in tissue engineering for scaffold coatings to prevent microbial contamination. Medical devices such as catheters, implants, and surgical instruments are coated with AgNPs to reduce infection risk. Additionally, silver nanoparticles are being explored for diagnostic imaging due to their optical and electronic properties.

Agricultural Applications
In agriculture, herbal AgNPs are used as eco-friendly alternatives to chemical pesticides and fertilizers. They help control plant pathogens, including bacteria and fungi, thereby reducing crop losses. AgNPs are also used in nano-fertilizers to improve nutrient absorption and utilization by plants. Their small size enables better penetration into plant tissues, promoting growth and enhancing yield. These applications contribute to sustainable agriculture by reducing chemical usage and environmental pollution.

Environmental Applications
Herbal AgNPs play an important role in environmental protection. They are used in water purification systems due to their strong antimicrobial activity against waterborne pathogens. AgNPs also help in the degradation of toxic dyes and organic pollutants in wastewater through catalytic reactions. Additionally, they are used for removal of heavy metals from contaminated water by adsorption or reduction mechanisms. These properties make herbal AgNPs useful in environmental remediation and pollution control.

Toxicity and Safety Concerns
Despite their beneficial applications, herbal AgNPs may pose toxicity risks depending on their size, concentration, and exposure duration. Cytotoxicity studies have shown that high concentrations of AgNPs can damage healthy cells by inducing oxidative stress and inflammation. Genotoxic effects may occur due to DNA damage caused by reactive oxygen species. Environmental concerns include accumulation of nanoparticles in soil and water ecosystems, which may affect microorganisms, plants, and aquatic life. Therefore, toxicity is generally dose-dependent, and careful evaluation of safe concentration levels is necessary before large-scale use.

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Comparison with Chemically Synthesized AgNPs

Herbal-synthesized AgNPs offer several advantages over chemically synthesized nanoparticles. They are more environmentally friendly because plant extracts act as natural reducing and stabilizing agents, eliminating the need for toxic chemicals. The synthesis process is cost-effective and simpler compared to chemical methods. Herbal AgNPs often show enhanced biological activity due to the presence of phytochemicals on their surface. In contrast, chemically synthesized AgNPs may involve hazardous reagents, higher production costs, and potential toxicity issues. Therefore, green synthesis is considered safer and more sustainable.

Challenges and Limitations

Although herbal AgNPs have many advantages, several challenges remain. One major issue is the lack of standardization in plant extract composition, which leads to variations in nanoparticle size, shape, and stability. Scale-up of green synthesis methods for industrial production is also difficult due to process variability. Stability concerns, such as aggregation or oxidation over time, can affect nanoparticle performance. Regulatory challenges exist because nanoparticle-based products require extensive safety and efficacy evaluations before approval.

Future Perspectives

Future research on herbal AgNPs is expected to focus on controlled size and shape engineering to enhance their biological activity and safety. Functionalization of nanoparticles with targeting ligands or drugs may improve their therapeutic potential. Clinical trials are needed to confirm their safety and effectiveness in humans. Industrial-scale production methods must be developed to ensure consistency and cost-effectiveness. The use of artificial intelligence and machine learning may help optimize synthesis parameters, predict nanoparticle behavior, and accelerate product development.

CONCLUSION

Herbal silver nanoparticles represent a promising and sustainable approach to nanotechnology-based applications. They combine the advantages of green synthesis, biological activity, and environmental compatibility. Research has demonstrated their effectiveness in biomedical, agricultural, and environmental fields. However, challenges such as toxicity concerns, lack of standardization, and regulatory barriers still need to be addressed. Further studies, particularly clinical and large-scale production research, are required to fully realize their potential. With continued advancements, herbal AgNPs are likely to play a significant role in future nanotechnology-based solutions across multiple industries.

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