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Review Article

Design, Synthesis, Characterization and Optimization of Silver Nanoparticles Using *Jatropha curcas* Bark Extract and their Antibacterial, Antifungal and Antioxidant Applications

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ABSTRACT

Green synthesis of silver nanoparticles has emerged as a sustainable and eco-friendly alternative to conventional chemical and physical methods. Among various plant sources, Jatropha curcas has gained attention due to its rich phytochemical composition and diverse pharmacological properties. The present review highlights the design, synthesis, characterization, and optimization of silver nanoparticles using Jatropha curcas bark extract, along with their antibacterial, antifungal, and antioxidant applications. Phytoconstituents such as flavonoids, phenolic compounds, tannins, and terpenoids present in the bark play a crucial role in the reduction and stabilization of silver ions into nanoparticles. Various characterization techniques including UV–Visible spectroscopy, dynamic light scattering, zeta potential analysis, SEM, TEM, FTIR, and XRD are discussed to confirm nanoparticle formation and evaluate their physicochemical properties. Furthermore, the review summarizes reported antimicrobial and antioxidant activities of biosynthesized silver nanoparticles and explains their possible mechanisms of action. The integration of green nanotechnology with traditional medicinal plants offers a promising approach for developing novel therapeutic agents with enhanced biological efficacy and reduced toxicity. Overall, Jatropha curcas-mediated silver nanoparticles represent a potential candidate for future biomedical and pharmaceutical applications.

INTRODUCTION

Nanotechnology and Importance of Nanoparticles

Nanotechnology is an emerging field that deals with the design and application of materials at the nanoscale (1–100 nm). Nanoparticles exhibit unique physical, chemical, and biological properties due to their high surface area, quantum

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effects, and enhanced reactivity. These properties make nanoparticles highly useful in pharmaceuticals, medicine, electronics, and environmental applications.[1,2]

Silver Nanoparticles (AgNPs) and Their Biomedical Importance

Silver nanoparticles are one of the most widely studied metallic nanoparticles due to their strong antimicrobial, antifungal, antiviral, and anticancer properties. AgNPs have been extensively used in wound dressings, drug delivery systems, medical device coatings, and diagnostic applications. Their ability to generate reactive oxygen species and disrupt microbial cell membranes makes them effective against a wide range of pathogens.[2,4,5]

Green Synthesis Using Plant Extracts

Green synthesis is an eco-friendly, cost-effective, and sustainable method for nanoparticle production that utilizes biological sources such as plants, bacteria, fungi, and algae. Plant extracts contain natural reducing and stabilizing agents like phenolics, flavonoids, and proteins, which facilitate the reduction of metal ions and stabilize the formed nanoparticles. Green synthesis avoids the use of toxic chemicals and high-energy processes, making it suitable for biomedical applications.[3,4]

Jatropha curcas as a Medicinal Plant

Jatropha curcas is a medicinal plant belonging to the Euphorbiaceae family and is widely used in traditional medicine. Various parts of the plant, including bark, leaves, seeds, and latex, possess pharmacological activities such as antimicrobial, anti-inflammatory, antioxidant, and wound-healing properties. The bark of Jatropha curcas is rich in bioactive compounds that can act as natural reducing and capping agents in the synthesis of silver nanoparticles, enhancing their biological activities.[6,7,8]

2. Jatropha curcas Bark: Phytochemical and Medicinal Importance

Botanical Description

Jatropha curcas L. is a perennial shrub or small tree belonging to the family Euphorbiaceae. It is commonly known as physic nut and is widely distributed in tropical and subtropical regions. The plant has thick bark, green leaves, and produces seeds rich in oil. The bark is rough, greyish-brown, and contains various bioactive compounds, making it useful for medicinal and industrial applications.[9,10]

Traditional Medicinal Uses

Jatropha curcas has been widely used in traditional medicine for the treatment of various diseases. The bark has been used for treating wounds, skin infections, inflammation, and gastrointestinal disorders. Different parts of the plant are also used as antimicrobial, anti-inflammatory, analgesic, and purgative agents in folk medicine.[11,13,14]

Phytochemical Constituents (Phenolics, Flavonoids, Tannins, Alkaloids)

The bark of *Jatropha curcas* contains several bioactive phytochemicals such as phenolic compounds, flavonoids, tannins, alkaloids, saponins, and terpenoids. These compounds possess strong antioxidant and antimicrobial properties. Phenolics and flavonoids act as natural reducing agents, while tannins and alkaloids contribute to antimicrobial and therapeutic effects.[12,15,16]

Role of Bark Extract in Nanoparticle Synthesis

The bark extract of *Jatropha curcas* plays a crucial role in the green synthesis of silver nanoparticles. The phytochemicals present in the extract act as reducing agents to convert silver ions into silver nanoparticles and also serve as stabilizing or capping agents to prevent nanoparticle aggregation. This makes the bark extract an eco-friendly and efficient medium for nanoparticle synthesis with enhanced biological activity.[16,17,19]

Conventional vs Green Synthesis Methods

Conventional methods for the synthesis of silver nanoparticles include physical and chemical techniques such as chemical reduction, thermal decomposition, and photochemical methods. These methods often require toxic chemicals, high energy input, and complex procedures, which may limit their biomedical applications due to environmental and safety concerns.
In contrast, green synthesis is an eco-friendly and sustainable approach that utilizes biological sources such as plant extracts, microorganisms, and enzymes. Green synthesis is cost-effective, simple, and avoids hazardous reagents, making it more suitable for pharmaceutical and biomedical uses.[18,20,21,23]

Role of Plant Extracts as Reducing and Stabilizing Agents

Plant extracts contain various bioactive compounds such as phenolics, flavonoids, tannins, terpenoids, and proteins. These phytochemicals act as natural reducing agents to convert silver ions (Ag^+) into metallic silver nanoparticles (Ag^0). Additionally, these compounds act as stabilizing or capping agents, preventing aggregation of nanoparticles and enhancing their stability and biological activity.[22,24,25]

Mechanism of AgNP Formation Using Jatropha curcas Bark Extract

The synthesis of silver nanoparticles using *Jatropha curcas* bark extract involves the reduction of silver ions from silver nitrate solution by phytochemicals present in the extract. Phenolic and flavonoid compounds donate electrons to Ag^+ ions, leading to the formation of Ag^0 nanoparticles. The biomolecules present in the bark extract adsorb onto the nanoparticle surface, acting as capping agents and stabilizing the nanoparticles. The formation of AgNPs is usually indicated by a color change of the reaction mixture and confirmed by spectroscopic and microscopic characterization techniques.[24,25,26,27]

Effect of pH

pH plays a crucial role in the synthesis of silver nanoparticles as it influences the reduction rate and stability of nanoparticles. Alkaline pH generally favors the formation of smaller and more stable nanoparticles, whereas acidic conditions may lead to aggregation or incomplete reduction of silver ions.[27,29,30]

Effect of Temperature

Temperature affects the kinetics of nanoparticle formation and growth. Higher temperatures increase the reduction rate of silver ions and promote faster nanoparticle synthesis, while lower temperatures may result in slower reaction rates and larger particle sizes.[28]

Effect of Silver Nitrate Concentration

The concentration of silver nitrate determines the availability of silver ions for nanoparticle formation. Higher silver nitrate concentrations can lead to increased nanoparticle yield but may also cause particle aggregation if not properly controlled.[31]

Effect of Extract Concentration

The concentration of *Jatropha curcas* bark extract influences the reduction and stabilization of nanoparticles. Higher extract concentrations provide more phytochemicals for reduction and capping, resulting in better stabilization and smaller particle sizes, whereas insufficient extract may lead to unstable nanoparticles.[31,32]

Reaction Time Optimization

Reaction time is an important parameter affecting nanoparticle formation and stability. Longer reaction times allow complete reduction of silver ions and growth of nanoparticles, but excessive time may lead to aggregation. Therefore, optimizing reaction time is essential to obtain uniform and stable silver nanoparticles.[33,34]

5. Characterization Techniques of Silver Nanoparticles

UV–Visible Spectroscopy

UV–Visible spectroscopy is commonly used to confirm the formation of silver nanoparticles by detecting the surface plasmon resonance (SPR) peak. AgNPs typically show a characteristic absorption peak in the range of 400–450 nm, indicating successful nanoparticle synthesis and providing information about particle size and dispersion.[35,37,40]

FTIR Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy is used to identify functional groups present in the *Jatropha curcas* bark extract and on the surface of AgNPs. FTIR helps to confirm the involvement of phytochemicals such as phenolics, flavonoids, and proteins in the reduction and stabilization of nanoparticles.[36,39]

Particle Size and Zeta Potential Analysis

Dynamic Light Scattering (DLS) is used to determine the hydrodynamic particle size and size distribution of silver nanoparticles. Zeta potential analysis provides information about the surface charge and stability of nanoparticles, where higher absolute zeta potential values indicate better colloidal stability.[38,41]

6. Antibacterial Activity of *Jatropha*-Based AgNPs

Mechanism of Antibacterial Action

Silver nanoparticles exhibit strong antibacterial activity through multiple mechanisms. AgNPs attach to the bacterial cell wall and membrane, causing structural damage and increased membrane permeability. They also generate reactive oxygen species (ROS), which damage cellular proteins, lipids, and DNA. Additionally, AgNPs can penetrate bacterial cells and interfere with enzymatic activities and DNA replication, leading to cell death.[42,43]

Gram-Positive and Gram-Negative Bacteria Studies

Jatropha curcas–mediated AgNPs have shown significant antibacterial activity against both Gram-positive and Gram-negative bacteria. Gram-negative bacteria such as *Escherichia coli* and *Pseudomonas aeruginosa* are often more susceptible due to their thinner peptidoglycan layer, while Gram-positive bacteria like *Staphylococcus aureus* and *Bacillus subtilis* also show sensitivity to AgNP treatment. The antibacterial efficacy depends on particle size, concentration, and surface properties of the nanoparticles.[44,45,47]

Comparison with Crude Extract and Standard Drugs

Studies have reported that AgNPs synthesized using *Jatropha curcas* bark extract exhibit higher antibacterial activity compared to the crude plant extract alone, due to enhanced surface area and nanoparticle-mediated mechanisms. When compared with standard antibacterial drugs, AgNPs demonstrate comparable or synergistic effects, suggesting their potential as alternative or adjunct antimicrobial agents.[46]

Antifungal Activity

Mechanism of Antifungal Action

Silver nanoparticles exhibit antifungal activity by disrupting the fungal cell membrane and cell wall integrity. AgNPs interact with membrane proteins and lipids, leading to increased membrane permeability and leakage of intracellular contents. They also generate reactive oxygen species (ROS), which cause oxidative stress and damage fungal DNA and enzymes, ultimately resulting in fungal cell death.[47,48]

Activity Against Pathogenic Fungi

Jatropha curcas bark-mediated AgNPs have shown significant antifungal activity against various pathogenic fungi such as *Candida albicans*, *Aspergillus niger*, and *Aspergillus fumigatus*. The antifungal efficacy depends on nanoparticle size, concentration, and surface chemistry. Smaller nanoparticles generally exhibit stronger antifungal activity due to their higher surface area and enhanced interaction with fungal cells.[49,50,52]

Potential Biomedical Applications

Due to their strong antifungal properties, *Jatropha*-based AgNPs have potential applications in the treatment of fungal infections, wound dressings, and biomedical coatings. They can also be incorporated into pharmaceutical formulations and medical devices to prevent fungal contamination and improve therapeutic outcomes.[51,52,53]

8. Antioxidant Activity

Free Radical Scavenging Assays (DPPH, ABTS, FRAP)

The antioxidant activity of *Jatropha curcas*–mediated silver nanoparticles is commonly evaluated using in vitro assays such as DPPH, ABTS, and FRAP. The DPPH assay measures the ability of nanoparticles to scavenge stable free radicals, while the ABTS assay evaluates radical cation scavenging capacity. The FRAP assay determines the reducing power of nanoparticles by measuring their ability to reduce ferric ions to ferrous ions. These assays collectively provide insight into the antioxidant potential of AgNPs.[53,54,57]

Role of Phytochemicals and Nanoparticles

The antioxidant activity of *Jatropha* bark-based AgNPs is attributed to the presence of phytochemicals such as phenolics, flavonoids, and tannins, which act as natural antioxidants. During green synthesis, these phytochemicals remain adsorbed on the nanoparticle surface and enhance the free radical scavenging activity. Additionally, the nanoscale size and high surface area of AgNPs contribute to improved antioxidant efficiency compared to crude plant extracts.[55,56]

Therapeutic Relevance

Antioxidants play a crucial role in preventing oxidative stress-related diseases such as inflammation, cancer, neurodegenerative disorders, and cardiovascular diseases. *Jatropha*-based silver nanoparticles with strong antioxidant properties may have potential applications in pharmaceutical formulations, wound healing, and

biomedical therapies, offering synergistic therapeutic benefits.[57,58]

9. Biomedical and Pharmaceutical Applications

Wound Healing

Silver nanoparticles synthesized using *Jatropha curcas* bark extract have significant potential in wound healing applications due to their strong antimicrobial and antioxidant properties. AgNPs help in preventing microbial infection, reducing inflammation, and promoting tissue regeneration. They can be incorporated into wound dressings, hydrogels, and topical formulations to enhance healing efficiency.[59]

Drug Delivery

AgNPs can be used as nanocarriers for drug delivery due to their small size, high surface area, and ability to bind with therapeutic molecules. *Jatropha*-based AgNPs may improve drug stability, targeted delivery, and controlled release of drugs, making them promising candidates for advanced pharmaceutical formulations.[60,62]

Coatings for Medical Devices

Silver nanoparticle coatings are widely used on medical devices such as catheters, implants, and surgical instruments to prevent microbial biofilm formation. *Jatropha*-mediated AgNPs can serve as eco-friendly antimicrobial coatings, reducing the risk of hospital-acquired infections.[61,63]

Environmental and Food Packaging Applications

AgNPs synthesized using plant extracts are also applied in environmental and food packaging fields. They can be incorporated into packaging materials to prevent microbial contamination and extend shelf life of food products. Additionally, AgNPs can be used in water purification systems and antimicrobial surfaces due to their strong biocidal properties.

10. Toxicity and Safety Aspects

Cytotoxicity Studies

Although silver nanoparticles exhibit promising biomedical properties, their cytotoxic effects must be carefully evaluated. Cytotoxicity studies using cell lines and in vivo models have shown that AgNP toxicity depends on particle size, concentration, surface coating, and exposure duration. At higher concentrations, AgNPs may induce oxidative stress, DNA damage, and cell apoptosis, highlighting the need for dose optimization.

Biocompatibility Issues

Biocompatibility is an important factor for biomedical applications of AgNPs. Green-synthesized AgNPs using plant extracts generally show improved biocompatibility compared to chemically synthesized nanoparticles due to the presence of natural capping agents. However, long-term biocompatibility and interaction with biological systems require further investigation before clinical applications.

Environmental Concerns

The increasing use of silver nanoparticles raises concerns about their environmental impact. AgNPs released into the environment may affect aquatic organisms, soil microorganisms, and ecosystems. Green synthesis methods reduce environmental toxicity during production, but proper disposal, risk assessment, and regulatory guidelines are essential to minimize potential environmental hazards.[62,63,64]

CONCLUSION:

In recent years, green synthesis of silver nanoparticles has emerged as a promising and sustainable approach in nanotechnology. The use of plant-based materials for nanoparticle synthesis offers several advantages, including eco-friendly processing, cost-effectiveness, and improved biocompatibility compared to conventional chemical and physical methods. Among various medicinal plants, Jatropha curcas has gained significant attention due to its rich phytochemical composition and diverse pharmacological activities. The phytoconstituents present in Jatropha curcas bark, such as flavonoids, phenolic compounds, tannins, and terpenoids, play a crucial role in the reduction and stabilization of silver ions during nanoparticle synthesis. These naturally derived compounds not only facilitate the formation of stable nanoparticles but also enhance their biological activities. Characterization techniques such as UV–Visible spectroscopy, particle size analysis, zeta potential measurement, SEM, TEM, FTIR, and XRD are essential for confirming nanoparticle formation and evaluating their physicochemical properties. Several studies have demonstrated that plant-mediated silver nanoparticles exhibit significant antibacterial, antifungal, and antioxidant activities. The enhanced surface reactivity and nanoscale size of these particles contribute to their ability to interact effectively with microbial cells and free radicals. As a result, green synthesized silver nanoparticles show great potential for applications in antimicrobial therapy, drug delivery systems, wound healing, and other biomedical fields.

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