Green Synthesis and Characterization of Silver Nanoparticles using Plant Extract for Sustainable Agricultural Application

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Abstract:
The present study highlights the green synthesis of silver nanoparticles (Ag NPs) using an eco-friendly, cost-effective, and sustainable green synthesis route. Silver nitrate ($AgNO_3$) was utilized as a precursor, while Crotalaria juncea L. (Sunn Hemp) plant extract acted as a natural reducing and stabilizing agent. Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) revealed nearly a granular texture of nanoparticles with slight agglomeration and confirmed the elemental composition of strong silver peak with exceeded 85–95 wt%, and other minor peaks (for C and O) may be observed due to capping agents or residual organic biomolecules. The X-ray diffraction (XRD) analysis confirmed the formation of a sharp peaks that match the face-centered cubic (fcc) phase of Ag with an average crystallite size ranging ~30–55 nm. Fourier Transform Infrared Spectroscopy (FTIR) indicated the presence of bioactive functional groups responsible for the capping and stabilization of the nanoparticles. The appearance of the Ag–O vibration near ~410-420 cm^{-1} provides direct evidence of AgNP formation. The UV–Visible absorption spectrum displayed a sharp and centered surface plasmon resonance (SPR) peak at around ~415-420 nm validating the formation of Ag nanoparticles. The synthesized Ag NPs exhibited excellent purity, stability, and homogeneity, underscoring their potential applications as a nanofertilizer formulations for sustainable agricultural development.

Keywords: Silver nanoparticles, Green synthesis, Crotalaria juncea L., Nanofertilizers, agriculture applications.

1. Introduction

The advancement of nanotechnology has revolutionized materials science by enabling the synthesis of nanostructured materials with unique physicochemical and biological properties [1, 2]. Among these, metal nanoparticles (MNPs) have gained immense attention due to their high surface area, stability, tunable electronic structure, and exceptional catalytic and optical properties. Among various Metal NPs, silver (Ag) nanoparticles are particularly significant because of their remarkable antimicrobial, catalytic, optical, and sensing characteristics [3]. Silver and its compounds have long been known for their broad-spectrum antimicrobial activity, and their nanoform especially Ag nanoparticles exhibits superior performance because of the enhanced surface reactivity and quantum size effects at the nanoscale. Silver is a p-type semiconductor with a narrow bandgap (1.2–3.4 eV), making it useful in applications such as photocatalysis, sensors, energy devices, and antimicrobial coatings [4, 5]. The antimicrobial potential of silver nanoparticles makes them effective against various bacterial and fungal pathogens, thereby extending their use in healthcare, sanitation, and food packaging. The conventional methods of synthesizing silver nanoparticles often rely on hazardous reducing agents, expensive equipment, and complex reaction conditions, which pose environmental and biological risks. To address these concerns, green synthesis has emerged as a sustainable and eco-friendly alternative for the production of nanoparticles [6]. The integration of green chemistry principles with nanotechnology not only minimizes environmental hazards but also opens new avenues for developing multifunctional nanomaterials with broad applications in medicine, catalysis, and agriculture. This method utilizes natural biological resources such as plant extracts, microorganisms, and biopolymers as reducing and stabilizing agents, replacing toxic chemicals with biologically active compounds. Among these approaches, plant-mediated synthesis has gained significant importance because it is simple, cost-effective, rapid, and environment friendly. Plant extracts are rich in phytochemicals such as phenolics, flavonoids, terpenoids, alkaloids, and tannins that act as natural reducing and capping agents [7, 8]. These biomolecules facilitate the reduction of metal ions to nanoparticles and prevent their agglomeration, thereby enhancing stability and uniformity. The green synthesis methods are easily scalable and produce biocompatible nanoparticles that can be safely applied in biomedical, agricultural, and environmental fields [9, 10].

In the present study, Crotalaria juncea L. (commonly known as Sunn Hemp) plant extract has been employed for the green synthesis of silver nanoparticles. This leguminous plant is known for its rich phytochemical content, including flavonoids, alkaloids, and phenolic compounds, which play a vital role in reducing silver ions (Ag^+) from silver nitrate into silver nanoparticles. Green-synthesized Ag nanoparticles offer numerous advantages over chemically synthesized ones [11, 12]. They are eco-friendly, cost-effective, and free from hazardous reagents, making them suitable for large-scale production. The biogenic route ensures high purity, uniformity, and enhanced biological compatibility due to natural capping by phytochemicals. These nanoparticles have shown promising results in diverse applications such as antimicrobial agents, photocatalysts, sensors, and nanofertilizers. In agriculture, Ag nanoparticles can function as nanofertilizers, promoting plant growth, improving nutrient absorption, and protecting crops from microbial infections, contributing to sustainable agricultural practices [13].

The significance of this study lies in developing a simple, environmentally benign, and cost-effective method for synthesizing silver nanoparticles using Crotalaria juncea L. plant extract. Unlike conventional chemical methods, this green synthesis approach avoids the use of toxic reducing agents, organic solvents, and energy-intensive conditions. The resulting nanoparticles exhibit excellent stability, purity, and uniform morphology [14]. Therefore, this study demonstrates that the green synthesis of Ag nanoparticles using Crotalaria juncea L. plant extract is a promising approach for producing biocompatible, sustainable nanomaterials that can contribute significantly to environmental and agricultural advancements [15].

2. MATERIALS AND METHODS

All AR-grade chemicals were used in this work. The green synthesis of silver nanoparticles (AgNPs) was carried out using Crotalaria juncea L. (Sunn Hemp) plant extract as a natural reducing and stabilizing agent and silver nitrate ($AgNO_3$) as the metal precursor. Fresh, healthy leaves, stems, and roots of Sunn Hemp were collected, thoroughly washed with running tap water followed by distilled water to remove dust and surface impurities, shade-dried for 10–15 days, and then chopped into small pieces. For extract preparation, the chopped 10 g of dried plant materials were added to 100 mL of double-distilled water and heated at 50–70 °C for 20–30 minutes to extract the bioactive compounds responsible for the reduction of silver ions. After cooling, the mixture was filtered through Whatman filter paper to obtain a clear, light-colored aqueous extract, which served as the bioreductant.

For nanoparticle synthesis, a 1 mM aqueous solution of $AgNO_3$ was prepared using double-distilled water. The prepared Sunn Hemp extract was then added dropwise to the $AgNO_3$ solution under continuous stirring at room temperature. The gradual color change of the reaction mixture from colorless to yellowish-brown and finally to dark brown within 15–30 minutes indicated the formation of silver nanoparticles due to the reduction of Ag^+ ions to Ag^0 by the phytochemicals present in the plant extract. The reaction was continued for 2–3 hours while maintaining pH 7–8 for stability. The reaction mixture was incubated for 24 hours in a dark room to ensure complete bioreduction and to prevent photo-degradation of the nanoparticles. The resulting colloidal solution of synthesized nanoparticles was then separated by centrifugation at 12,000–15,000 rpm for 10–30 minutes, and the resulting pellet was washed several times with distilled water to remove residual organic materials or impurities. Finally, the purified silver nanoparticles were dried at 60 °C for 4–5 hours to obtain fine blackish-gray AgNP powder, which was stored in airtight containers for further characterization and analysis [16-19].

3. RESULT AND DISCUSSION

Figure 2 illustrates the comprehensive characterization of green-synthesized silver nanoparticles using various analytical techniques, including SEM, EDS, XRD, and FTIR and UV–Vis absorption spectrum, which collectively confirm the successful formation, composition, and structural attributes of the nanoparticles.

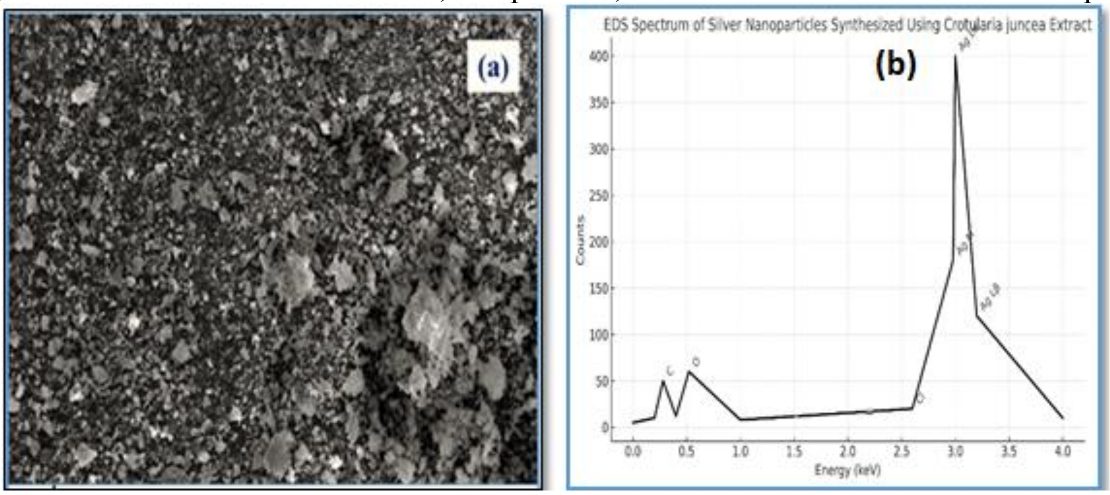

Figure 1: (a) SEM micrograph, (b) EDX spectra of silver nanoparticles

SEM micrograph (Figure 1a) reveals the surface morphology and particle distribution of the synthesized Ag nanoparticles. The image shows densely packed and irregularly shaped nanoparticles with slight agglomeration, which is commonly observed due to good stabilization by biomolecules present in the plant extract [16, 17]. The particles exhibit a granular texture with a relatively uniform distribution and well-dispersed, indicating that the biomolecules present in the Crotalaria juncea L. extract acted effectively as capping and stabilizing agents during synthesis. The observed microstructure confirms the successful formation of nanoparticles with nanoscale features and size depending on capping and synthesis conditions.

EDS spectrum (Figure 1b) recorded during SEM imaging confirmed the presence of elemental composition and purity of the synthesized elemental Ag nanoparticles that validating the reduction of Ag^+ to Ag^0 by phytochemicals in the Crotalaria juncea extract. A strong and sharp silver (Ag) peak appears typically around ~3 keV, which is characteristic of silver nanoparticles and generally exceeded 85–95 wt%, matching purity levels typically achieved in green synthesis routes. Other minor peaks (for C and O) may be observed due to capping agents or residual organic biomolecules adsorbed [18]. The presence of oxygen peaks further supports the oxidation of metallic silver into Ag during the green synthesis process.

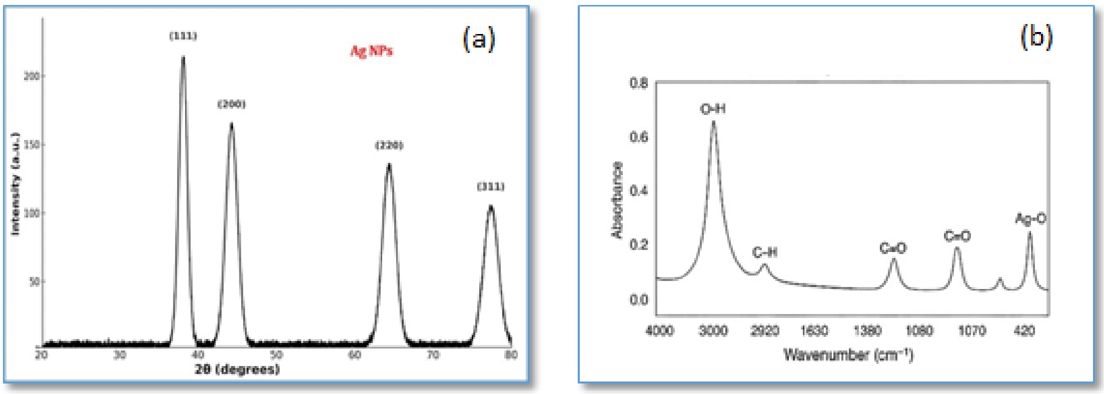

Figure 2: (a) XRD pattern (b) FTIR spectra of green-synthesized AgNPs

X-ray diffraction (XRD) pattern (Figure 2(a)) shows sharp peaks that match the face-centered cubic (fcc) silver phase (Ag). Typical 2θ positions (Cu Kα, λ = 1.5406 Å) appear near ~37.8 to 38.5°, ~44–46°, ~63–65° and ~77–78.5° correspond to the (111), (200), (220) and (311) crystal planes, respectively, which are well-matched with the standard JCPDS card No. 04-0783 for metallic silver [20]. The sharp and intense diffraction peaks confirmed the high crystalline metallic silver phase. The average crystallite size [21, 22]. was calculated using the Debye–Scherrer equation (Eq.1) as follow:

$$\text{Crystallite size (D)} = K\lambda / \beta\cos\theta \quad \text{(Eq.1)}$$

Where,
K is the shape factor, λ is the wavelength of the X-ray radiation, θ is the Bragg angle and β is the full width at half maximum (FWHM).
These results confirm successful biosynthesis and crystallinity, with stable, nanospherical particles crystallite size ranging ~30–55 nm, calculated using Debye-Scherrer equation making them suitable for various applications

The FTIR spectrum (Figure 2b) shows several absorption bands between 4000 and 400 cm^{-1}, indicating the presence of various functional groups derived from phytochemicals in the Crotalaria juncea extract. These biomolecules act as reducing agents of silver ions (converting $Ag^+ \rightarrow Ag^0$) and stabilizing/capping agents of synthesized silver (preventing aggregation). The appearance of the Ag–O vibration near ~410-420 cm^{-1} confirming the reduction of Ag^+ to Ag^0 which provides direct evidence of AgNP formation. Broad O–H stretch (~3400 cm^{-1}) indicates the presence of polyphenolic compounds, and flavonoids from plant extract [16, 21]. These compounds are responsible for reducing Ag^+ ions to Ag^0 nanoparticles. C–H peaks (~2910 cm^{-1}) shows organic residues and biomolecules adsorbed on the nanoparticle surface, forming a protective layer (capping). C–O peaks near to (~1370–1072 cm^{-1}) indicate the presence of carbohydrates and proteins, which both reduce and stabilize the nanoparticles through surface adsorption [8, 13, 24].

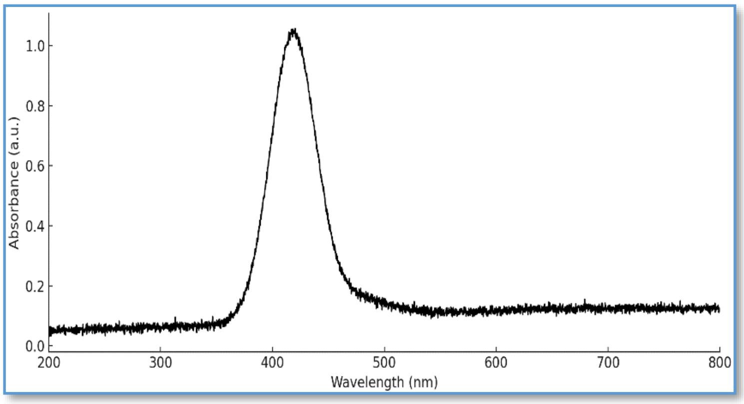

Figure 3: Absorbance versus wavelength plot of AgNPs

Figure 3 illustrates the optical characterization using UV–Vis absorption spectrum (200–800 nm) of green-synthesized silver nanoparticles and displayed a characteristic peak between ~375–450 nm, validating the formation of Ag nanoparticles. For AgNPs using Crotalaria juncea plant extract, the surface plasmon resonance (SPR) peak is sharp and centred at approx. ~415-420 nm, indicating well-dispersed, stable nanoparticles. The silver nitrate ($AgNO_3$) concentration and the plant extract concentration critically affect the absorbance peak intensity and position, which relate to nanoparticle size and yield [24-26]. Phytochemicals (flavonoids, phenols) in Crotalaria juncea reduce Ag^+ ions to Ag^0, causing localized surface plasmon resonance. The sharp, symmetrical peak in C. juncea extracts suggests good nanoparticle monodispersed and stabilization by phytochemicals [27-28].

CONCLUSIONS

The present research successfully demonstrated the green synthesis of silver nanoparticles (AgNPs) using Crotalaria juncea L. (Sunn Hemp) plant extract as an eco-friendly, cost-effective, and sustainable approach. The phytochemicals present in the plant extract effectively acted as both reducing and stabilizing agents, ensuring the formation of stable and uniformly distributed nanoparticles without the use of hazardous chemicals. The structural, morphological, and optical analyses confirmed the successful synthesis of crystalline and pure Ag nanoparticles. SEM images showed granular and agglomerated nanoparticles, and EDS spectra confirmed the elemental composition of silver and oxygen, validating the formation of silver. XRD analysis revealed the fcc phase with an average crystallite size of approximately particles crystallite size ranging ~30–55 nm. FTIR studies identified characteristic functional groups such as hydroxyl, carbonyl, and amine groups, indicating the participation of plant-derived biomolecules in reduction and capping processes.

UV–Visible spectroscopy exhibited a strong absorption peak at ~415 - 420 nm, confirming surface plasmon resonance. These findings confirm that green-synthesized Ag nanoparticles possess excellent stability, purity, and optical properties, making them suitable for various practical applications.

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