Green Synthesis of Biocompatible Silver Nanoparticles Using Garlic Extract: A Sustainable Approach

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Abstract - This research presents an environmentally friendly method for synthesizing silver nanoparticles (AgNPs) by utilizing garlic extract in conjunction with a silver nitrate solution. The garlic extract acted as a reducing agent and a stabilizer in the synthesis process. The formation of AgNPs was first identified by the colored changes of the reaction mixture, from colorless to orange, and then eventually to a dark brown coloration. The confirmation of the synthesis and some properties of the resulting nanoparticles was made by various analytical techniques. The UV-Vis spectroscopic analysis exhibited a maximum absorption between 435 nm, which indicated AgNPs. FTIR analysis identified functional groups (hydroxyl, amide, and polysaccharides) involved in the reduction and stabilization of AgNPs. XRD confirmed a crystalline face-centered cubic (FCC) structure, while TEM revealed spherical particles sized 10–30 nm. This eco-friendly method offers a simple, efficient, and sustainable alternative for producing AgNPs with desirable properties for environmental applications.

Key Words: (Environmental remediation; climate action; biocompatible agent; nanotechnology; agriculture waste; silver nanoparticles: green chemistry.

1.INTRODUCTION

There is considerable interest in the scientific community regarding silver nanoparticles because they have distinct physical and chemical properties compared to their bulk material counterparts. Within the dimension range of 1-100 nanometers, such nanoparticles fabricated have outstanding properties, such as antimicrobial effectiveness, electrical conductivity, and even optical responsiveness. Their nanoscale dimensions create an extraordinarily high ratio of surface atoms to internal atoms, allowing a dramatic enhancement in their interaction with microbial cell membranes and catalyzing reactions [1-5].

recent years, green synthesis has emerged as a promising approach for the production of silver nanoparticles (AgNPs), offering a sustainable and environmentally friendly alternative to conventional chemical and physical methods. This method utilizes biological entities, such as plant extracts, bacteria, fungi, and even waste products, tomediate the reduction of silver ions into nanoparticles. Among these, the use of plant extracts has garnered significant attention due to its accessibility, cost-effectiveness, and the ability to scale up production processes [6].

Garlic (Allium sativum), in particular, has proven to be an effective reducing and stabilizing agent in the green synthesis of silver nanoparticles. Rich in bioactive compounds such as allicin, flavonoids, and thiol groups, garlic extract facilitates the reduction of silver ions and influences the particle size and shape of the synthesized nanoparticles. [7, 8]

Synthesis not only minimizes the use of harmful chemicals but also complements the global pursuit of sustainable development. The generated AgNPs exhibit unique physicochemical properties, offering a broad spectrum of applications.

The silver nanoparticles were characterized by various analysis techniques. The crystallographic structure of the synthesized nanoparticles was determined by XRD, while UV-Vis spectroscopy was used to obtain information on the optical characteristics. The elemental composition was studied by EDX, which provided a full profile of the chemical composition of the nanoparticles [9].

These analytical methods ensure the efficacy of the synthesis process, paving the way for their application in medicine, electronics, and environmental science.

Garlic plays a crucial role in the green synthesis of silver nanoparticles, offering an eco- friendly and sustainable alternative to conventional chemical methods. Its use in nanoparticle synthesis capitalizes on the rich organic compounds present in garlic, such as allicin, flavonoids, and sulfur-containing compounds, which act as natural reducing and stabilizing agents. These bioactive compounds facilitate the reduction of silver ions (Ag^{+}) to elemental silver (Ag^{0}), forming nanoparticles in the process.

This reduction process is not only efficient but also reduces the need for hazardous chemicals traditionally used in nanoparticle synthesis, minimizing environmental and health-related risks. Moreover, garlic's inherent biocompatibility and biodegradability make it an ideal candidate for medical and pharmaceutical applications of silver nanoparticles, as it enhances their antimicrobial and therapeutic properties.

This eco-friendly approach eliminates the need for hazardous chemicals typically employed in conventional nanoparticle synthesis processes, making it a favorable alternative in nanotechnological applications [12].

Garlic (Allium sativum) is a highly efficient biological agent for the green synthesis of AgNPs. Garlic extract contains potent bioactive compounds such as allicin, flavonoids, polyphenols, and sulfur compounds (thiosulfates and thiol groups). These reduction and stabilization capabilities are critical in the process of nanoparticle formation. Bioactive components not only have the capability to reduce silver ions (Ag^+) to metallic silver (Ag), but also cap the formed nanoparticles to prevent agglomeration. Allicin, the principal active compound in garlic, contains sulfur-functional groups with energetic reducing properties, and the flavonoids and polyphenols also contribute reduction and stabilization functions.

Some of the existing challenges in the synthesis of AgNP from garlic include achieving fine size control, nanoparticle stability for long periods, standardization of synthesis protocols to achieve reproducible results, and a full comprehension of the complex reduction mechanisms. Advances have been made in the modification of reaction conditions, such as temperature, pH, extract concentration, and reaction time, to adjust nanoparticle shape and size distribution. Progress has also been made in hybrid methods where garlic is blended with other natural extracts to generate synergies that promote nanoparticle characteristics.

The rich phytochemistry of garlic not only aids in the reduction process but also stabilizes the resulting nanoparticles. Compounds such as thiosulfates, flavonoids, and polyphenols contribute to capping and prevent agglomeration, ensuring the stability and uniformity of the nanoparticles. This inherent stability is crucial for maintaining the functional properties of silver nanoparticles, which include antimicrobial, anti- inflammatory, and anticancer activities [13].

The use of garlic as a bioreductant is not only cost-effective but also efficient, as the process can often occur at room temperature and neutral pH, reducing energy consumption and minimizing the environmental impact of nanoparticle production. Moreover, the synthesis process is straightforward, allowing for simple scalability from laboratory to industrial levels. Overall, garlic provides a potent, natural, and sustainable option for the synthesis of silver nanoparticles, showcasing the potential for integrating traditional knowledge with advanced technological applications [14,15].

The primary objective of this study is to develop a green synthesis method for AgNPs using garlic extract and to evaluate their potential applications in environmental remediation.

In summary, garlic serves as a versatile and environmentally benign agent in the synthesis of silver nanoparticles, driving forward the field of green nanotechnology by marrying the benefits of nature with advanced material science, and leading to innovative solutions across a range of applications [16].

2. Materials and Experimental

2.1 Synthesis materials.

The major reagents and materials used during this work included analytical-grade silver nitrate provided by Merck and ethanol from the CHEM-LAB Company. Fresh garlic bulbs used for the extract were procured from the market. Throughout the experimental process, deionized water served as the primary solvent and cleaning agent. To ensure experimental integrity, all laboratory equipment underwent thorough cleaning with deionized water, followed by oven drying, prior to use.

2.2 Garlic Extract Preparation

The fresh garlic bulbs were cleaned with deionized water to remove the dirt on the surface, then air-dried to remove excess moisture. The extraction was done with 50 g of crushed garlic, which was subjected to Soxhlet extraction with 200 ml of ethanol in a 20:1 solvent-to-solid ratio under controlled heating at 50°C until the complete evaporation of ethanol yielded a concentrated crude extract. The product was transferred into amber glass bottles and stored at 4°C until further use in the synthesis of nanoparticles.

Fig -1: a) fresh garlic,b) garlic extract and silver nanoparticles.

2.3 Characterization of Silver Nanoparticles

2.4 UV-Vis spectroscopy

Spectroscopic analysis was used to describe silver AgNPs. The UV-visible spectrometer (T70+PGInstrument Ltd, United Kingdom) detects the reduction of silver ions from Ag^+ to Ag within wavelengths of 300–600 nm.

2.5 Infrared Spectroscopy FTIR

Measurements were made using a Bruker VERTEX 80 (Germany) spectrometer, with a platinum-diamond ATR accessory in the range of 4000-400 cm^{-1}. The measurements were performed at room temperature using a spectral resolution of 4 cm^{-1} and a refractive index of 2.4.

2.5.1 X-ray diffraction (XRD) Spectrum

X-ray diffraction was performed to determine the structure of the studied AgNPs. The samples were dried at 60°C, ground to pass a 75 µm sieve, and the prepared samples were analyzed by XRD technique using a Philips X-ray vertical diffractometer, type PW 1373, Holland. The analysis was conducted using a Ni-filter and Cu-Kα (λ=1.5405 Å) at 40 kV and 40 mA.

2.5.2 Transition Electron Microscope (TEM)

TEM was measured using HR-TEM, JEM-2100, Jeol, Japan, operated at 200 kV.

3. Results and Discussions

3.1 Characterization of Silver Nanoparticles

3.1.1 UV-Vis spectroscopy

UV-Vis spectroscopy reflected the plasmonic properties of the silver nanoparticles. The SPR of silver nanoparticles is characterized by a clear absorption peak in the region of 435 nm, as depicted in Figure 2. The exact position and shape of this peak depend on various factors, such as the size, shape, and distribution of the silver nanoparticles, and the dielectric constant of the surrounding medium. [17]

The UV-visible spectral analysis confirmed the successful synthesis of silver nanoparticles using garlic extract and silver nitrate, as indicated by the presence of a characteristic absorption peak in the UV-visible spectrum.

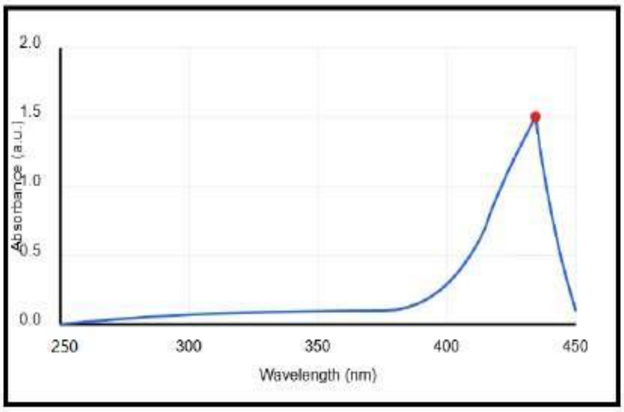

Fig -2:UV-Vis absorption spectra of silver nanoparticles using garlic extract..

3.1.2 Infrared Spectroscopy FTIR

Fourier transform infrared spectroscopy was used for the identification of the functional groups present on the synthesized silver nanoparticles, as shown in Fig. 3. Characteristic absorption bands were seen to occur at the concerned wavenumber positions in the spectrum. Strong spectral features at 3417.24 and 2924.72 cm^{-1} confirmed the presence of hydroxyl groups from phenolic and carboxylic acids. We noticed a sharp peak at 1604.48 cm^{-1}, which we can attribute to the presence of the amide I group in peptide structures. Further spectral analysis revealed a band at 1384.64 cm^{-1}, characteristic of in-plane O-C-H bending within carbohydrate and flavone structures. Other peaks, at 1076.08 cm^{-1} and 613.25 cm^{-1}, showed the presence of C-O stretching and C-H bonding in aromatic structures. This spectral profile, therefore, provides evidence for the involvement of phytochemicals in plant extract both for the reduction and surface stabilization steps during the synthesis [18].

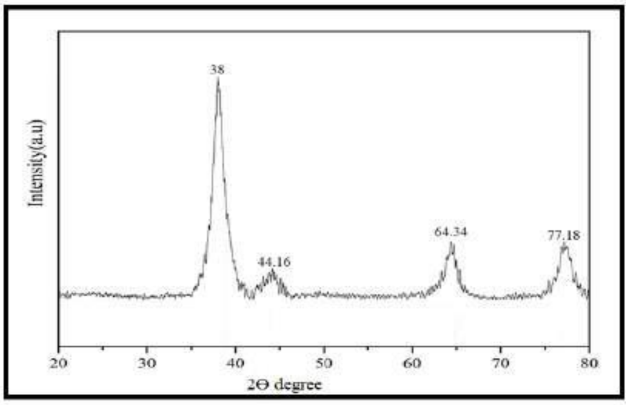

Fig -3: FTIR of silver nanoparticles using garlic extract.

3.1.3X-ray diffraction (XRD) Spectrum

XRD analysis showed four characteristic diffraction peaks at about 2θ = 38.00°, 44.16°, 64.34°, and 77.18°, which are typical for the FCC structure of silver. Thus, the relatively broad nature of these peaks signifies the nanoscale dimensions of these particles, as expected for small crystalline nanoparticles, while the crystallographic plane corresponding to (111) relates to the strongest intensity peak observed in the recorded diagram, inferring that the AgNPs produced are crystalline FCC [19].

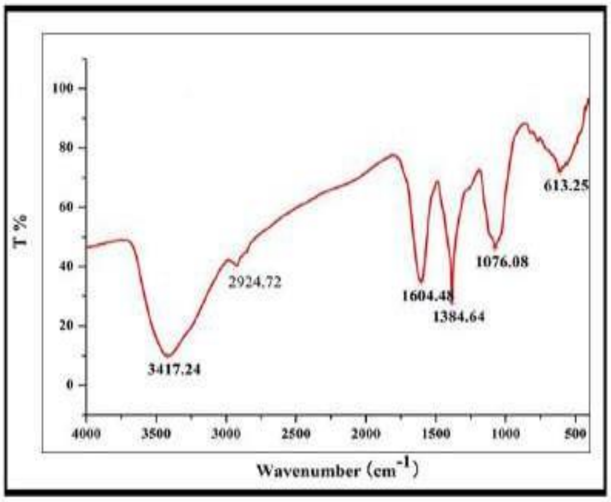

Fig -4: XRD of silver nanoparticles using garlic extract

3.1.4Transition Electron Microscope (TEM)

The TEM analysis consistently showed that the silver nanoparticles synthesized using garlic extract and silver nitrate were in the nanoscale range, with spherical shapes and nanoparticles size grow in the range of 10 to 30 nm. These characteristics are important for determining the properties and potential applications of the synthesized silver nanoparticles, as shown in Figure 5 [20].

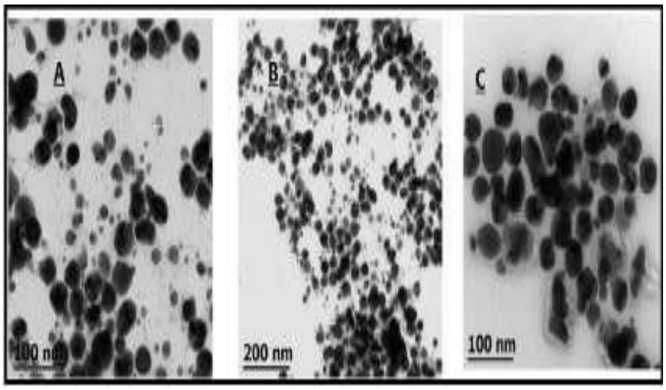

Fig -5: TEM of silver nanoparticles using garlic extract

Together, these characterization techniques confirm the successful synthesis of silver nanoparticles with the desired properties using garlic extract [21,22].

To better contextualize our findings, we have compiled a comprehensive summary of the key characterization results in Table 1, which illustrates the essential properties of the garlic-mediated AgNPs synthesized in this study.

Table 1: Summary of Key Characterization Results for Garlic-Mediated Silver Nanoparticles

Analysis	Key Findings	Significance
UV-Vis Spectroscopy	**Absorption peak at 435 nm**	**Confirms formation of AgNPs through surface plasmon resonance**
FTIR Spectroscopy	**Peaks at 3417.24, 2924.72, 1604.48, 1384.64, 1076.08, and 613.25 cm⁻¹**	**Indicates involvement of hydroxyl, amide, carbohydrate, and aromatic functional groups in reduction and capping**
XRD Peaks	**at 2θ = 38.00°, 44.16°, 64.34°, and 77.18°**	**Confirms face-centered cubic crystalline structure of AgNPs**
TEM	**Spherical particles with size range 11 nm**	**Reveals morphology and size distribution suitable for environmental applications**
pH	**5.6**	

Compared to other plant-mediated synthesis methods reported in the recent literature, our garlic-extract method has several advantages. As can be seen from Table 2, garlic-mediated synthesis produces AgNPs with comparable or superior properties to those synthesized using other plant extracts.

Table 2: Comparative Analysis of AgNPs Synthesized Using Different Plant Extracts

Plant Extract	Particle Size (nm)	Morphology	Reference
garlic (current study)	11	Spherical	Current work
Aloe vera	15-30	Spherical	Vanlalveni et al. (2021)
Neem	10-35	Spherical, irregular	Devi et al. (2020)
Lemon	25-50	Spherical, irregular	Zheng et al. (2023)
Green tea	20-40	Quasi-spherical	Laib et al. (2023)

The mechanistic pathway for the green synthesis of AgNPs using garlic extract involves some of the crucial bioactive constituents in coordination. Allicin (diallyl thiosulfinate), the primary bioactive component present in garlic, plays a crucial role in the reduction process. The thiosulfinate group (-S(O)-S-) in allicin possesses strong reducing properties, which catalyze the reduction of Ag^+ ions to Ag^0. The reaction can be represented as:

R-S(O)-S-R' + Ag^+ → R-S-S-R' + Ag° + oxidation product

Furthermore, organosulfur compounds, such as diallyl disulfide and diallyl trisulfide, also contribute to the reduction process through their sulfhydryl (-SH) groups, which have a strong metal ion affinity. Flavonoids and polyphenols in garlic extract are accountable for both the reduction and stabilization processes. These molecules contain hydroxyl (-OH) groups that are capable of donating electrons for silver ion reduction while simultaneously forming coordinating bonds with the surface of freshly synthesized silver nanoparticles.

Stabilization is brought about primarily due to the capping of the nanoparticles by proteins and polysaccharides in garlic extract. Capping is aided by FTIR analysis, as the band at 1604.48 cm^{-1} signifies involvement by proteins through amide linkages, whereas the band at 1076.08 cm^{-1} signifies involvement by polysaccharides through C- O linkages. This multi-layer organic shell prevents agglomeration through steric and electrostatic repulsion, resulting in the astonishing stability of the AgNPs synthesized.

The temperature-dependent synthesis kinetics observed in our research (optimum temperature 80°C) could be attributed to an increased frequency of collisions between the silver ions and reducing agents at elevated temperatures, and to the enhanced extraction of bioactive compounds from the garlic matrix. The color transition from colorless to orange and, finally, dark brown is a visible indication of the progressive reduction of the silver ions and the formation of more stable and concentrated AgNPs.

This mechanistic understanding describes not only the green synthesis mechanism but also the synergistic action of more than one bioactive compound contained in garlic extract, which is responsible for the controlled synthesis of stable AgNPs with a preferred morphology and size distribution for environmental applications.

4. CONCLUSIONS

This study successfully demonstrated the green synthesis of silver nanoparticles (AgNPs) using garlic extract, with comprehensive characterization confirming their nanoscale size, spherical morphology, crystalline structure, and surface-functionalized stability. The use of garlic extract as both a reducing and capping agent offers an eco-friendly and cost-effective approach to nanoparticle synthesis.

The synthesized AgNPs exhibit properties that make them highly promising for a range of practical applications, including antimicrobial coatings, catalytic processes, and environmental cleanup efforts such as water purification and pollutant degradation. Their small size and stable surface chemistry enhance their functionality in these fields.

Further studies should focus on evaluating the antimicrobial efficacy of these AgNPs under real-world conditions, particularly in environmental remediation and healthcare settings. In addition, it is crucial to investigate their potential cytotoxicity and ecological impact on non-target organisms to ensure safe deployment. Long-term stability, scalability of the synthesis process, and integration into composite materials should also be explored to expand their industrial and environmental applications.

Future research in the following significant areas must be undertaken:

1- Comprehensive assessment of the antimicrobial properties of these AgNPs against a wide range of pathogens, including multidrug-resistant bacteria.

2- Acritical evaluation of their performance in real environmental remediation conditions, particularly regarding the degradation of emerging contaminants in wastewater.

3- Investigating their potential toxicity to non-target organisms is crucial for their safe application in environmental systems.

4- Optimization of the synthesis conditions to achieve a controlled size distribution and enhanced stability for target applications.

5- Synthesis of composite materials incorporating these AgNPs is proposed for enhanced functionality in catalytic and antimicrobial applications.

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BIOGRAPHIES

Over ten-years of scientific career in Sanitary & environmental Institute (SEI) at Housing and Building National Research Center (HBRC) with academic excellence and scientific success certificate. Experience gained from several projects in field of water and wastewater analysis and water quality assessment, Lecturer director in different training courses. The research interests cover treatment of water and wastewater using different eco-friendly and law cost environmental materials including biological, chemical, physical and mathematical modeling