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RESEARCH ARTICLE

Synthesis and Characterization of Silver Nanoparticles Using *Elaeocarpus ganitrus* Leaf Extracts; A Sustainable Approach with Antimicrobial Activity

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Highlights

- This work reports on green synthesis of silver nAgNPs) using Rudraksha leaf extracts
- Biosynthesized AgNPs were characterized by XRD, FTIR, SEM and UV–vis analyses
- AgNPs showed strong antimicrobial potential for biomedical applications

Abstract

The current study reports the production of silver nanoparticles (AgNPs) with aqueous leaf extracts from Elaeocarpus ganitrus (Rudraksha). The synthesized NPs were characterized using FTIR, UV-vis spectroscopy, SEM, and XRD. The synthesis of AgNPs was proven by a characteristic peak in the UV-Vis spectra at 432 nm. Functional groups like hydroxyl and carbonyl were found via FTIR analysis. XRD examination confirmed the crystal structure and found their size to be 11.93 nm. XRD showed the crystalline NPs with diffraction patterns matched the face-centred cubic structure of silver. The SEM image exhibited primarily spherical, uniformly sized NPs with some aggregation. The effectiveness of the AgNPs against specific types of bacteria was determined using the agar-well diffusion method. These results highlight the potential of Rudraksha-mediated silver nanoparticles as potent antibacterial agents that are safe for application in biomedical and eco-friendly settings.

Keywords: *AgNPs, antimicrobials, Elaeocarpus ganitrus, green synthesis, phytochemicals*

Introduction

Nanoparticles (NPs), which are typically between 1 and 100 nm in size, exhibit unique physical, chemical, and biological properties that differ from bulk materials. They also have an extremely large surface area. Their unique properties make them useful in a variety of fields including electronics, biological, electronics, environmental remediation, biomedical and catalaysis

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(Darwish et al., 2024). AgNPs are among the most studied kinds of NPs because they are so effecting at eliminating bacteria, protecting cells from harm, and accelerating chemical reactions (Bhakya et al., 2016; Khan et al., 2019). However, traditional methods for synthesizing AgNPs usually require a lot of energy and harmful chemicals, which can be harmful to both the environment and human health (Makarov et al., 2014; Raveendran et al., 2003). Scientists have developed green synthesis methods utilizing plant extracts to solve these issues. These methods are less costly, safer, and more environment friendly (Alissa, 2025; Moradi et al., 2021). Conventional NPs synthesis includes numerous physical and chemical methods, such as sol-gel method, hydrothermal method, laser ablation, microemulsion, and coprecipitation (Salehirozveh et al., 2024). Although these techniques are effective, they usually results in high energy consuption, hazardous chemicals, and toxic waste (Afonso et al., 2024). Green synthesis, which utilizes natural resources such as microbes, plant extracts, and biopolymers to synthesize NPs in a way that is safer, more environmentally friendly, and economically viable, has appeared as a potential solution to these problems (Shrestha et al., 2025; Singh et al., 2023). Natural phytochemicals like flavonoids, phenolics, alkaloids, and terpenoids are used in the synthesis of NPs from plants to stabilize and reduce the particles. These biomolecules aid in the transformation of Ag^+ to Ag^0 and maintain the stability of NP (Ahmed et al., 2016). In this regard, several medicinal plants such as *Azadirachta indica*, *Eugenia roxburghii*, and *Hagenia abyssinica* have been assessed for their potential in the synthesis of NPs (Giri et al., 2022; Murthy et al., 2020).

In the present study, focuses has been placed on the environmentally friendly production of Ag NPs using an aqueous leaf extracts from *Elaeocarpus ganitrus*, widely known as Rudraksha, a plant highly valued for its religious and medicinal importance in South Asia. Rudraksha is a promising candidate for nanoparticle synthesis and biomedical applications owing to its well-documented antibacterial, antioxidant, and anti-inflammatory properties (Khanal et al., 2020). The structural and morphological features of Ag NPS were confirmed by using FTIR, UV-vis spectroscopy, SEM, and XRD. We evaluated their functional performance by testing their antibacterial activity against specific pathogenic microbes.

Materials and Methods

Materials

High-purity dimethyl sulfoxide (DMSO), silver nitrate, and methanol were utilised. In order to prepare extracts, Rudraksha leaves were gathered from the Patan Multiple Campus.

Preparation of Rudraksha Extracts

After being cleansed with distilled water, the Rudraksha leaves were kept in the dark for a few days. Then, it was powdered in a blender. The powder was boiled in distilled water (5 g in 200 mL) in a conical flask until its volume becomes one-fourth. The boiled extract was filtered. The heavy and solid particles present in the extract were removed by centrifuging the filtration. Then it was refiltered. Sterilized bottles were used to collect plant extracts, and they were stored.

Preparation of AgNPs

60 mL of the Rudraksha extract were added dropwise using a burette into 20 mL of $AgNO_3$ (0.1M) on a magnetic stirrer at neutral p^H at 25 °C (Adebayo-Tayo et al., 2019). The prepared $AgNO_3$ solution was stored in a beaker and fully wrapped with carbon paper to protect it from exposure to sunlight and prevent any photoreaction of silver (**Figure 1**). The conical flask was air tightly covered to avoid light penetration. The conversion of color of mixture into reddish brown was an indication of synthesis of AgNPs. After 48 hours of reaction, the content was centrifuged at room temperature and repeatedly splashed with DI water. Lastly, the solid mass was desiccated and collected for characterization and antimicrobial activity.

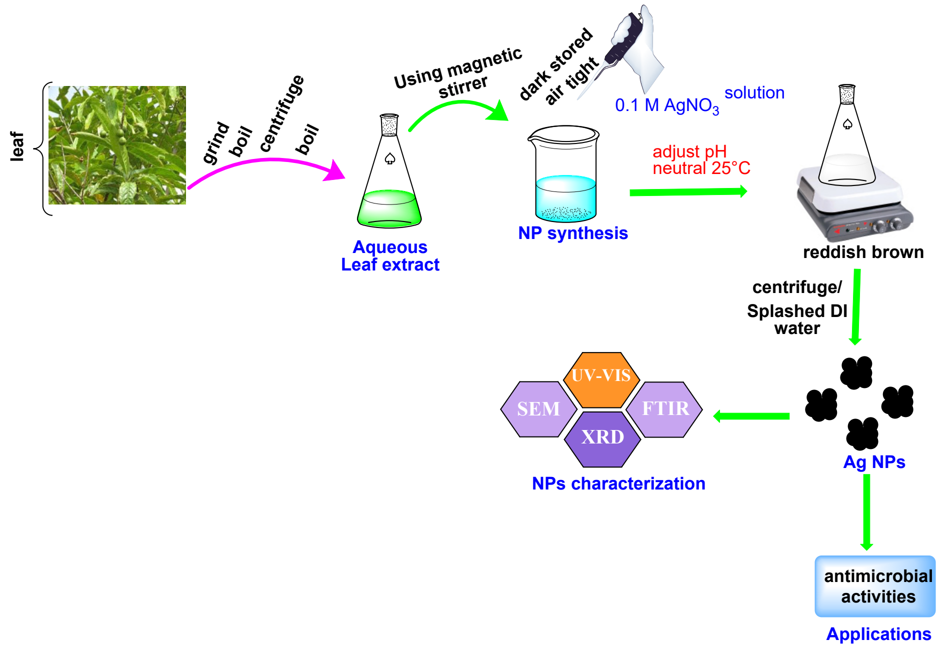

Fig. 1. Representing diagram of Rudrakshya leaf-AgNPs synthesis

Characterization of NPs

UV-vis Spectroscopy

A UV-visible spectrophotometer (Specord 200 Plus, Anaalytik Jena, Germany) was used to characterise the AgNPs synthesized using rudraksha extract. The UV-visible spectrum of the diluted suspension was obtained within the range from 300 to 700 nm wavelength.

XRD Analysis

The crystallographic properties were analyzed using a D2 phaser from Bruker, utilizing Cu Kα radiation, with measurements taken over a 2θ range from 30° to 90°. The NP size was calculated based on Scherrer's formula (**Equation 1)**, a standard method for determining crystallite dimensions (Dhungana et al., 2024; Poudel et al., 2025).

$$D = \frac{k.\lambda}{\beta cos\ \theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

In this case, λ stands for the wavelength of X-ray radiation, θ for Bragg's angle (in radians), β for full-width half maximum, D for crystal size, and K for dimensionless shape factor (= 0.9). Software called Origin 2024b was used to analyze the XRD data.

FTIR Analysis

A PerkinElmer Spectrum IR (version 10.6.2) was used for FTIR spectroscopy in order to detect the functional groups in extract responsible for synthesis of AgNPs. Absorption spectrum between 500 and 4000 cm^{-1} and Origin 2024b software were employed to analyze the obtained data.

Antimicrobial activity

The antimicrobial activity of synthesized NPs was studied by bioassay technique using bacteria (Murthy et al., 2020a).

Preparation of Liquid Broth (LB) media

One litre of water was mixed with 13 g of liquid broth LB powder to prepare culture media. It was autoclaved for 25 minutes at 15psi and 121°C for about half an hour. It was chilled to 50 °C. It was then put into sterile 15 mL falcon tubes, each holding 5 mL. The bacteria seed culture was co-cultured in each tube of media individually and then incubated.

Preparation of MHA media and antimicrobial study

The MHA plate was prepared by dissolving 39 g of MH agar powder in one litre of water. The content was autoclaved for 25 minutes. It was chilled and then transferred into Petri plates (25 mL each). Following plate labelling, a swab was used to blow out 150 µL of liquid bacterial seed over the plate's surface. The wells were made on the media and the sample powder (about 30 mg of provided sample, in case of AgNP; 100 mg/mL dissolved in DMSO in case of rudhrakshya extract; and 15 mg: 15 mg of AgNP: Rudhrakshya sample (1:1 ratio) and in each well, 10 µL of kanamycin (5 mg/mL) was added. The media was incubated at a temperature of 37 °C. The antimicrobic outcomes were evaluated for the next 24 hrs. Every antimicrobial test was carried out in triplicate. The mean ± standard deviation (n=3) is used to express the data.

Results and Discussion

Plant-mediated synthesis mechanism of AgNPs

Elaeocarpus ganitrus (Rudraksha) leaf extract is used through a redox-driven process where phytochemicals function as stabilizing and reducing agents at the same time. Phenolics, flavonoids, alkaloids, tannins, and proteins are abundant in the extract. These substances have functional groups (-OH, -NH, -C=O) that can donate electrons and chelate Ag ions. Upon addition of the aqueous extract to AgNO3 solution under continuous stirring, phytoconstituents undergo oxidation, reducing Ag^+ to elemental silver (Ag^0) nuclei. These nuclei function as a substrate for NP growth via atomic addition and regulated aggregation. Proteins and tannins are examples of high molecular weight biomolecules that adsorb to the surface of developing particles at the same time. They act as capping agents that control the size and shape of the particles and keep the colloid stable (Tariq et al., 2022). The overall change can be shown by the simple redox step:

$$Ag^+ + \text{(reducing phytochemical)} \longrightarrow Ag^0 + \text{(oxidized phytochemical)}$$

When surface plasmon resonance (SPR) is stimulated in AgNPs, the colour changes from pale yellow to reddish brown, which clearly shows that the reaction has taken place (Tariq et al., 2022).

UV-Vis Analysis

Figure 2 (a) shows the UV-visible spectrum of AgNPs made from Rudraksha extracts. There was a distinct surface plasmon resonance (SPR) band at 432 nm, which demonstrated that AgNPs had created well. The sharp and strong absorption peak shows that the NPs are stable and uniform. The existance of this band indicates that the phytochemicals found in Rudraksha extracts function as natural capping and reducing agents. This accelerating the transition from Ag^+ to Ag^0 and maintains the stability of NPs. Based on the previous studies, the peak position we observed is within the typical SPR range for AgNPs (400–450 nm) (Bogireddy et al., 2016; Chand et al., 2020; De Aragão et al., 2019). The size, shape, and the dielectric medium surrounding the synthesised NPs are the primary characteristics that show up in the peak's location (Zhang et al., 2016). The band at 432 nm indicates that the NPs are mostly nanosized and have a shape that is close to a sphere.

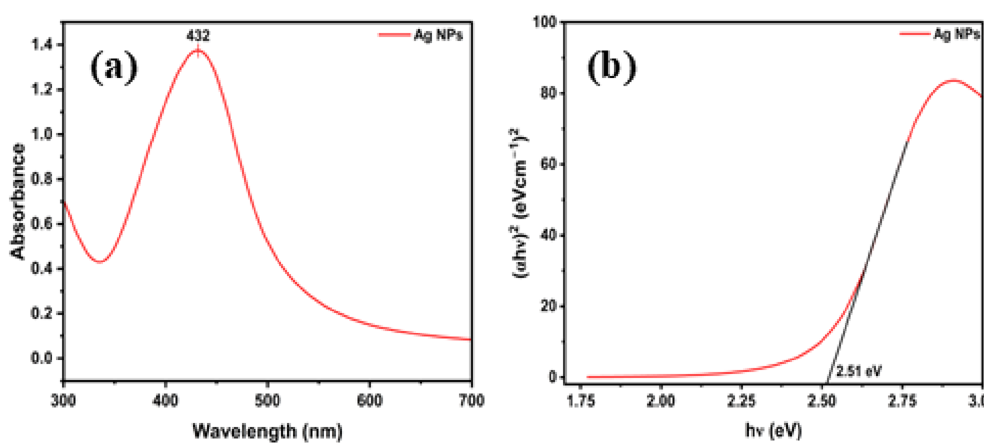

Fig. 2. UV–visible spectrum of Rud-AgNPs **(a)** showing the absorption peak at 432 nm and **(b)** Tauc plot indicating a band gap of 2.51 eV.

UV-Vis spectroscopy was employed to determine the optical energy gap (Eg) of the AgNPs synthesised from Rudraksha extracts. The band gap, indicating the energy difference between the valence and conduction bands, directly influences the optical and electrical properties of nanomaterials; thus, this method is commonly employed to evaluate their electronic structure. A reduced band gap is generally linked to improved charge carrier mobility (Hlapisi & Ajibade, 2025). The Eg was determined using the Tauc equation (**Equation 2)** (Baral et al., 2025) Fourier-transform infrared (FTIR).

$$(\alpha h\nu)^{\frac{1}{2}} = C(h\nu - Eg) \qquad \text{.......................... (2)}$$

Where, for direct band gap semiconductors, α is the absorbance coefficient, C is a constant, h is Planck's constant, v is the photon frequency, and m is half.

Tauc's approach, which produced a graph of (αhv)2 versus hv, was used to determine the band gap (Figure 2(b)). The optical band gap was determined by extrapolating the linear part of the curve to the point where $(\alpha h\nu)^2$ equals zero (Hlapisi & Ajibade, 2025). The determined band gap energy for the AgNPs generated from Rudraksha was 2.51 eV.

XRD Pattern of AgNPs

XRD characterization investigate the crystal structure of AgNPs . AgNPs of obtained from *Rudrakshya* extract observed diffraction peak in XRD at 2θ= 38.21°, 44.34°, 64.54°, 77.50° and 81.61°. After comparision with the reference code, silver file no. 01-087-0719, these discovered XRD peaks revealed that biosynthesised AgNPs were crystalline in structure , with the peak matching the standard (**Figure 3**). The face-centered cubic (FCC) crystalline of silver crystal planes (111), (200), (220), (311), and (222) are represented by the XRD peaks, respectively (Ali et al., 2023). Based on XRD data, the size of Ag-NPs were determined using the Scherrer formula (**Equation 1**), yielding an average crystallite size of 11.93 nm.

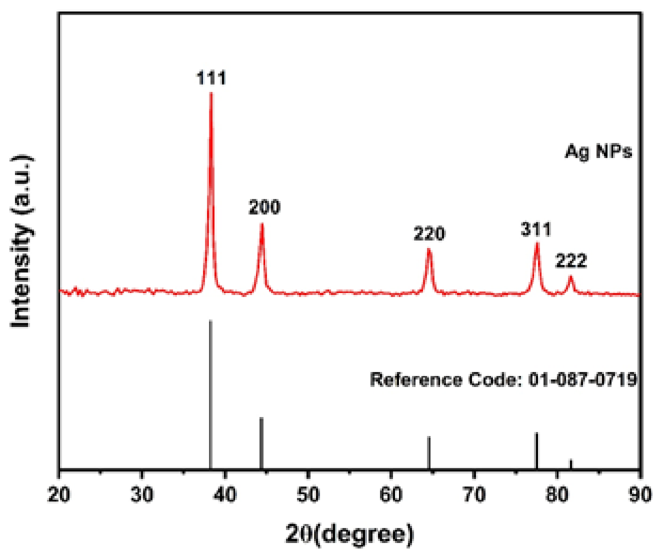

Fig. 3. AgNPs'XRD pattern of synthesized from *Rudrakshya* leaf extract.

FTIR Spectroscopic Analysis

The active functional groups of the biomolecules that plays vital role in the bioreduction of silver ions and in the capping of AgNPs were determined by analysing the FTIR data of Rudrakshya leaf extract and AgNPs. O-H vibrations of the phenolic and alcoholic groups were responsible for the large peak at 3450 cm^{-1} in the extract's FTIR spectra **Figure 4(a)** The carbonyl group was located at 1647 cm^{-1}. The presence of a carbonyl group was revealed by the band at 1670-1630 cm^{-1}, while the bands at 3410-3710 cm^{-1} are due to the presence of a -OH group. These functional groups were primarily involved in the creation of AgNPs and the bio-reduction of Ag^+ ions. In the alcoholic and phenolic groups of Rudrakshya synthesis AgNPs, the peak **Figure 4(b)** recorded the band at 3283 cm^{-1} due to O-H vibration, while the band at 1616 cm^{-1} indicated the presence of a carbonyl group.

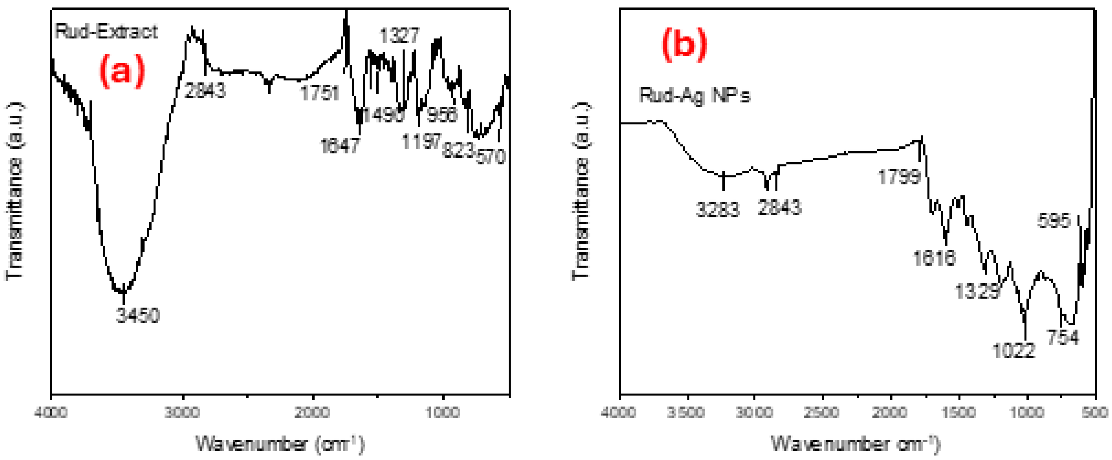

Fig. 4. (a) FTIR **s**pectra of Rudrakshya leaf extract and **(b)** Rud-AgNPs.

SEM Analysis

SEM was utilised to describe the AgNPs' surface morphology. SEM images (**Figure 5**) revealed spherical to fibrous particles with non-uniform sizes, though some agglomeration was observed. Indirect heating causes particles to group together, which makes metal nanoparticles connect with each other electronically. This causes the SPR band to shift to the red and the UV-Vis spectrum to absorb more light (Bhuyar et al., 2020; Xu et al., 2020).

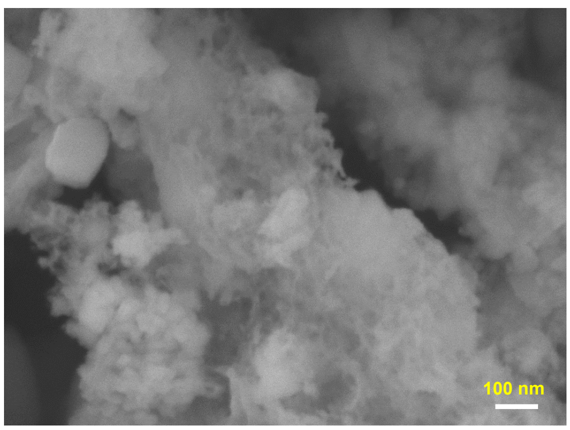

Fig. 5. SEM image of synthesized Rud-AgNPs

Antimicrobial Properties of AgNPs, Rudraksha Extract

Antimicrobial test displayed that both Rudraksha extract and AgNPs had moderate effects on the pathogens that were tested (**Figure 6**). Their combined formulation (Rudh:AgNP, 1:1), on the other hand, indicated greater activity, particularly to bacterial strains.

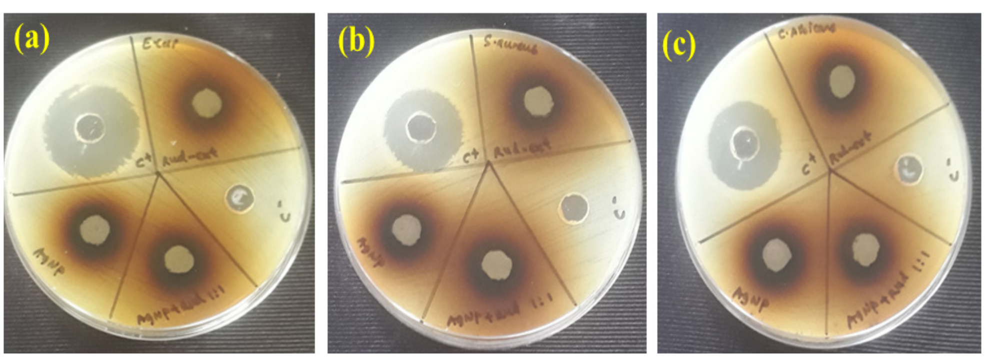

Fig. 6. Antimicrobial activity of Rud-Ag NPs against representative pathogens: (a) *E. coli*, (b) *S. aureus* and (c) *C. albicans*

The ZOI for *E. coli* and *S. aureus* were 15.0 mm and 16.0 mm, respectively. These zones were larger than those produced by either Rudraksha extract or AgNPs alone. This causes a redshift in the SPR band and higher absorbance in the UV-Vis spectrum when matched to isolated particles. These results signify that Rudraksha phytochemicals possess intrinsic antimicrobial properties and AgNPs exhibit moderate activity; however, their combination intensifies antibacterial activity, highlighting their potential as synergistic antimicrobial agents. The results that were seen are shown in **Table 1**: The ZOI was reported as the mean ± SD (n = 3).

Table 1. Antimicrobial activity of Ag NPs against representative pathogens.

Strain	Reference culture	Type	Positive control (+c) mm	Ag- NPs	Rudrakshya extract	Rud:Ag NPS
E. coli	ATCC8739	G−	27.0 ± **0.4**	11.0 ± 0.2	13.0 ± **0.4**	15.0 ± **0.3**
S. aureus	ATCC 6538P	G+	22.0 ± **0.3**	11.0 ± **0.3**	13.0 ± **0.3**	16.0 ± **0.2**
C. albicans	ATCC2091	Fungi	23.0 ± **0.3**	11.0 ± **0.2**	14.0 ± **0.2**	14.0 ± **0.2**

The phytochemicals present in Rudraksha extract inhibit bacterial growth by damaging cell membranes and disrupting enzymatic functions. AgNPs release Ag^+ ions, which damage cell membrane, produce reactive oxygen species (ROS), inhibit respiratory enzymes, and interact with DNA and ribosomes, thus hindering reproduction and protein synthesis. The synergistic action improves antibacterial effectiveness with phytochemicals stimulating the uptake and stability of nanoparticles, while silver nanoparticles increase intracellular damage, leading to better bacterial inhibition (More et al., 2023; Thapa et al., 2025).

Conclusions

An eco-friendly and sustainable approach to the creation of nanoparticles is the synthesis of AgNPs using Rudraksha extract. The characterization of synthesized NPs confirm the spherical, crystalline nanoparticles with a diameter of roughly 11.93 nm. The AgNPs made from Rudraksha demonstrated greater antibacterial efficacy than the extract alone, as shown by larger inhibition zones against both Gram-positive and Gram-negative bacteria. The results highlight the benefits of green synthesis for the advancement of sustainable nanotechnology and the possible uses of AgNPs mediated by Rudraksha in biomedical domains. Future studies must concentrate on improving synthesis parameters and investigating wider industrial and medicinal applications in order to fully realize the potential of these NPs.

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