Comprehensive Characterisation and Potent Antibacterial Applications of Polymer-Capped Silver Nanoparticles: A Green Synthesis

Oza Kalrav*, Raj Praharsh, Makvana Chirag and Panchal Vikram
Department of Chemistry, Faculty of Science, Gokul Global University, Sidhpur 384151, Gujarat, INDIA
*kalravoza7865@gmail.com

Abstract

The distinctive antibacterial properties of silver nanoparticles (AgNPs) have attracted a significant inquisitiveness, particularly in their environmentally friendly synthesis. Using leaf extract of Swertia chirata plant as a reducing agent for the conversion of Ag^+ salt solution to AgNPs which was capped with polyvinylpyrrolidone (PVP), this work offers a unique and environmentally beneficial method. PVP-functionalized AgNPs were characterized by FTIR, UV-Vis spectroscopy, XRD and HR-TEM. The absorption spectra of PVP-capped AgNPs displayed distinctive peaks at 457 nm, indicating the stable formation of nanoparticles. FTIR analysis confirmed the successful synthesis of PVP-AgNPs, while the X-ray diffraction pattern verified their cubic structure.

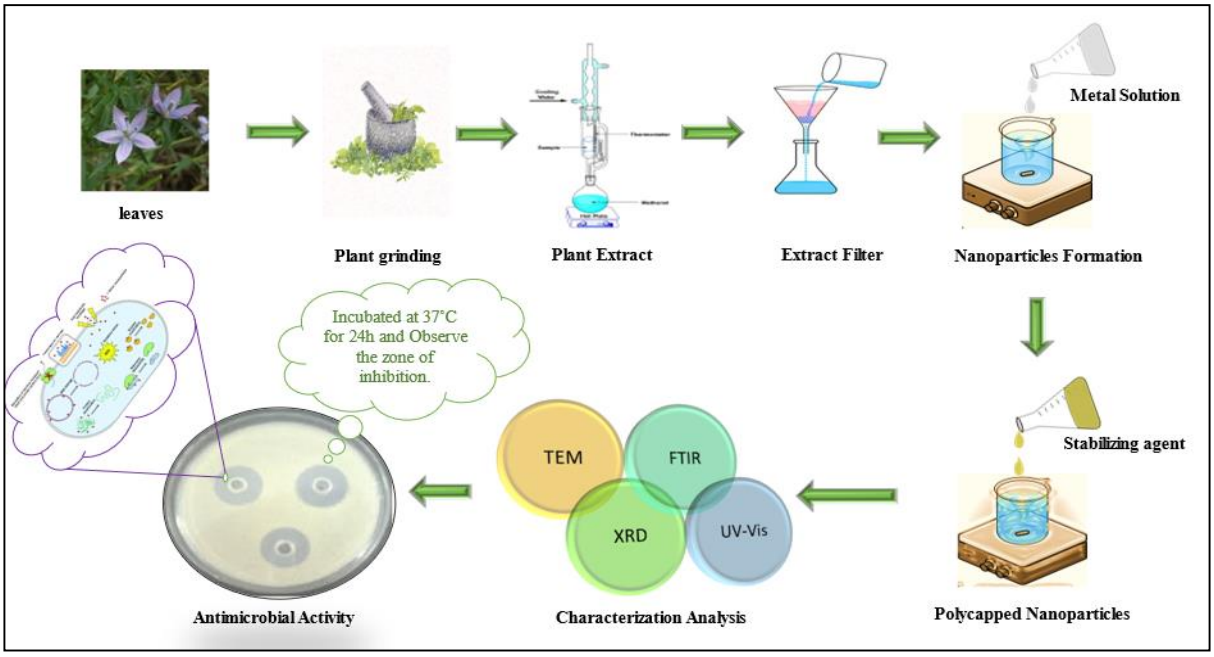
HR-TEM investigation showed spherical shape and homogeneous dispersion of PVP-AgNPs. The average particle size of synthesised AgNPs was 11.32 nm and they were functionalised with PVP to improve biological activity. The antibacterial activity of PVP-AgNPs was evaluated against miscellaneous bacteriological strains such as S. aureus, P. aeruginosa, GPB and E. coli showing efficacy against all of these bacterial strains.

Keywords: *Swertia chirata,* Silver nanoparticles, Polyvinyl Pyrrolidone, Antimicrobial activity.

Introduction

Nanotechnology is a key area of modern science focused on the synthesis of particles ranging from 1 to 100 nm, is growing interdisciplinary field driven by its diverse applications and innovative synthesis methods[16]. Nanoparticles play a significant therapeutic role in the energy sector, optics and other drug development applications due to their special characteristics[17,26.28]. It paves the way for rapidly evolving technologies focused on the development and enhancement of innovative materials with superior and unique properties. Also, metal nanoparticles have exceptional molecular properties, like high optoelectronic, thermal and catalytic effect, a large surface-to-volume ratio and the ability to be synthesized in precise shapes and crystallization[11,19,27].

Various metal nanoparticles have been synthesized using conventional methods; however, these physicochemical approaches are often environmentally damaging, toxic to humans due to the hazardous reducing and stabilizing agents involved and are economically expensive.



Graphical Abstract

This has driven the search for greener synthesis approaches that are safer, more sustainable and cost-effective[4,29]. Noble metal nanoparticles including Magnesium (Mg)[9], Silver (Ag)[7], Gold (Au), Platinum (Pt)[14], Zinc (Zn)[18], Copper (Cu)[8] and Titanium (Ti)[3], have attracted significant interest in biomedical applications for their versatile therapeutic capabilities.

Among the studied metal nanoparticles, silver nanoparticles are particularly prominent in nanotechnology and nanomedicine, with extensive research focused on their antimicrobial properties. However, the rising demand for more sustainable approaches has elevated the role of biosynthesis, capturing the attention of industries such as pharmaceuticals, agriculture, water purification, air filtration, textiles and catalysis due to the unique properties of AgNPs[21,24,30]. Biosynthesis of AgNPs harnesses a diverse array of biological materials including vitamins, fungi, enzymes, biodegradable polymers, bacteria and plants, which serve as natural reducing and stabilizing agents[1,10]. This green synthesis not only promotes nanoparticle formation but also enhances biocompatibility while minimizing toxicity.

Moreover, the use of plant extracts, microbial cultures and enzyme-mediated pathways optimizes the efficiency of AgNPs production and introduces novel functionalities, making them highly effective in applications such as antimicrobial coatings, drug delivery systems, wound healing therapies, anticancer, anti-inflammatory and anti-diabetic[5,20,25]. The plant world has gained renewed interest due to the recognition of nature's ability to function as a nano factory. Plants provide an excellent platform for the synthesis of nanoparticles due to their absence of harmful substances and the presence of natural capping agents that stabilize and control its formation.

A survey of earlier literature suggests that crude extracts from various plant such as, *Hagenia abyssinica (Brace) JF. Gmel, Carduus crispus, Uvaria narum, Bacopa monnieri (Linn.) Wettst, Buddleja globosa* and many other medicinal plants have been examined for the synthesis of AgNPs[6,12,23,31]. *Swertia chirata*, is native to the temperate Himalayas and is found at altitudes ranging from 1,200 to 3,000 meters, from Kashmir to Bhutan. It belongs to the Gentianaceae family. The plant has been reported to possess hypoglycaemic, anti-inflammatory, hepatoprotective, wound healing and antibacterial activities[15]. It also holds great potential for the green synthesis of AgNPs, further expanding their therapeutic uses. Given these diverse properties, the plant is further evaluated for its antimicrobial activity.

In this analysis, a green synthesis of AgNPs has been conducted using leaf extracts from *Swertia chirata*, a plant commonly found in markets and is native to Kashmir and Bhutan. Synthesized nanoparticles were systematically analysed to determine using UV-Vis spectroscopy, FTIR, HR-TEM and X-ray scattering techniques. Additionally, their antimicrobial activity was tested against various pathogenic microorganisms commonly associated with human infections. This investigation aims to explore the nanoparticles' ability to inhibit the growth of these pathogens, highlighting their potential applications in enhancing medical treatments.

Material and Methods

Materials: Silver Nitrate ($AgNO_3$) AR grade (99.9%) was purchased from SD Fine Chemicals. Fresh Chirata leaves of *Swertia Chirata* were purchased from Namo Organic Store (Amazon), India. All the solution and chemicals were prepared in double distilled water. The plant leaves were washed with distilled water, dried at room temperature for 12 days and ground into a fine powder using mixture grinder. The power was then stored in airtight box for further use. Bacterial cultures, which include Gram positive and Gram negative bacteria such as *Staphylococcus Aureus*, GPB, *E. coli*, *Pseudomonas aeruginosa*.

Extraction procedure for plant extract: *Swertia Chirata* leaf extract was made using the Soxhlet extraction technique, with 400 ml of double distilled water and 10g of leaf powder packed in thimbles. The extraction procedure was maintained until the solvent in the siphon tube of the extract dropped from the thimble became colourless[13]. Dark green colour crude extract was cooled and processed through no.1 Whatmann filter paper and extract was stored in an airtight container at -4°C for further studies.

Synthesis of silver nanoparticles: A saturated solution of $AgNO_3$ (90 ml, 0.03 M) and *Swertia Chirata* (30 ml) leaf extract were added to an Erlenmeyer flask at room temperature for 30 minutes while stirring continuously. After 30 min, the transformation of Ag^+ to Ag^0 was visually evident as the solution shifted from light brown to dark brown, as seen in figure 1. UV-visible spectroscopy further verified the formation of SC-AgNPs.

Synthesis of PVP Encapsulated AgNPs: After dissolving 0.5g of polyvinyl pyrrolidone in 250 mL of (ddw), mixture was agitated at room temperature for one hour. The AgNPs solution made from the leaf extract was subsequently progressively mixed with solution of PVP. The colour changed from dark brown to light brown after one hour, as shown in figure 1. The resulting mixture was centrifuged for 30 minutes at 5000 rpm at room temperature. The precipitate was cleaned with double distilled water and dried in an oven at 70 °C for four hours.

Characterization: The spectral properties of the synthesized and PVP-functionalized AgNPs were analyzed using a UV-Vis spectrophotometer (Shimadzu UV-1800) within the wavelength range of 200–800 nm. FTIR analysis was conducted using a Shimadzu spectrometer in the 4000–400 cm^{-1} range with a resolution of 5 cm^{-1} to determine the functional biomolecules associated with the synthesis of

AgNPs and PVP-functionalized AgNPs. To verify purity, an X-ray diffraction spectrometer (Rigaku D/max 40 kV) was used for the XRD investigation. AgNPs that were produced and AgNPs that had been functionalized with PVP were examined for structural morphology using HR-TEM.

Antimicrobial Activity: The antibacterial activity of biosynthesized AgNPs and PVP-functionalized AgNPs was assessed against Gram-positive and Gram-negative bacterial strains to determine their broad-spectrum effectiveness. The antimicrobial efficacy was evaluated using agar well diffusion methods. The nourishing agar medium was equally distributed in a Petri dish plate and 100 µL of AgNPs and PVP-functionalized AgNPs were carefully placed at the center of each dish to evaluate their antimicrobial activity. The plates were incubated at 37°C for 24 hours under aerobic conditions. AgNPs and PVP-AgNPs antibacterial properties are related to the formation of zones on Petri dish plates.

Results and Discussion

UV-Vis spectroscopy: UV-Vis spectroscopy is an important method for assessing metal nanoparticle production and stability in aqueous solutions. The stabilizing agent technique was employed to facilitate the reduction of Ag^+ ions, ensuring the controlled formation of AgNPs. The successful synthesis and stability of silver nanoparticles (AgNPs) are indicated by the presence of a distinct absorption peak at 446 nm in the UV-visible spectrum of biosynthesized AgNPs (Figure 2). The surface plasmon peak of silver nanoparticles measured between 400 and 500 nm[2]. The leaf extract of *Swertia chirata* serves as both a reducing and surface capping agent in the biosynthesis of AgNPs. AgNPs enclosed in PVP showed absorbance maxima ranging from 457 nm.

FTIR studies: The biosynthesized PVP-encapsulated AgNPs displayed IR peaks at 3485, 3450, 1639, 1394, 1367, 1184, 1095, 952 and 792 cm^{-1} (Figure 3)[22]. The absorption peaks at 3485 and 3450 cm^{-1} interacted with primary amines of N-H stretching. Absorption peaks at 1639 cm^{-1} can be associated with C=C stretching of monosubstituted alkene. The absorption peaks at 1394 and 1367 cm^{-1} are assigned to the phenol group of O-H bending. The strong peak of tertiary alcohol of C-O stretching is observed at 1184 cm^{-1}.

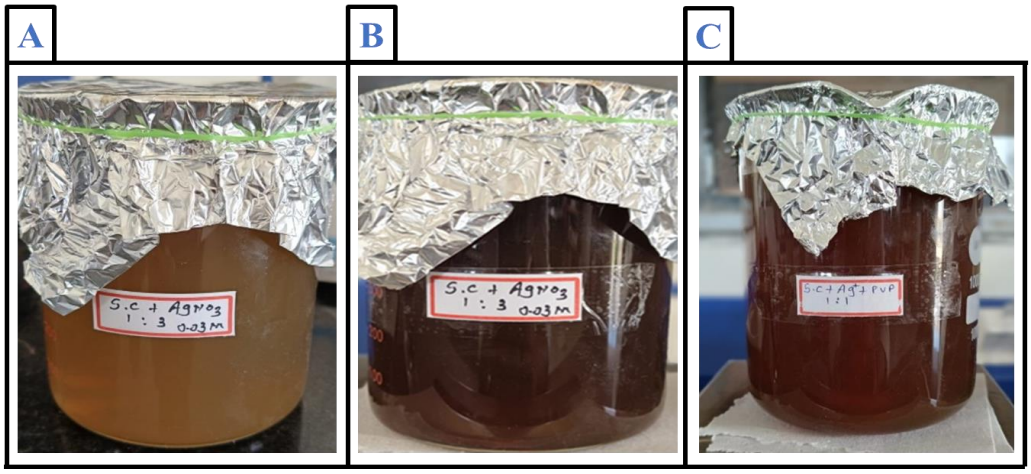


Figure 1: A) SC-Ag NPs (light brown colour) B) SC-Ag NPs Colour change (Dark brown) C) SC-Ag NPs + PVP (Colour change)

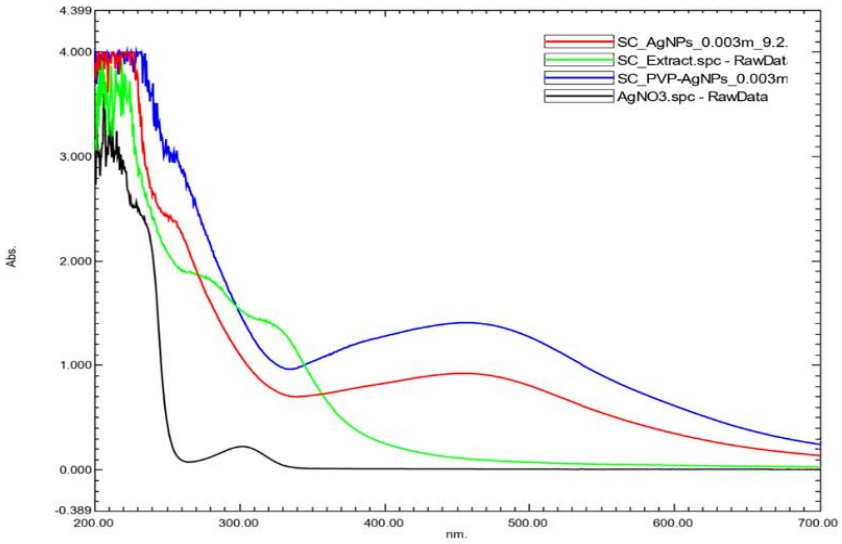


Figure 2: UV-Vis spectra of (a) Silver salt $AgNO_3$ (b) Plant extract (c) Ag-NPs (d) PVP – AgNPs

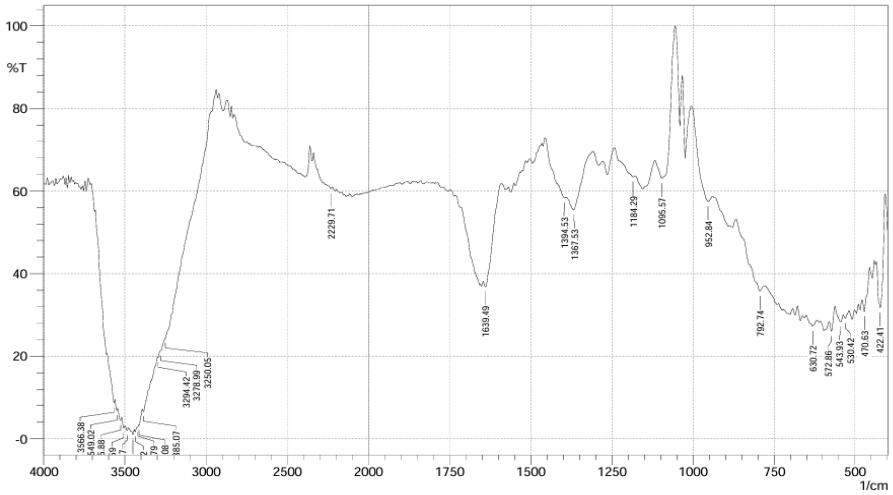


Figure 3: FTIR spectrum of PVP-AgNPs

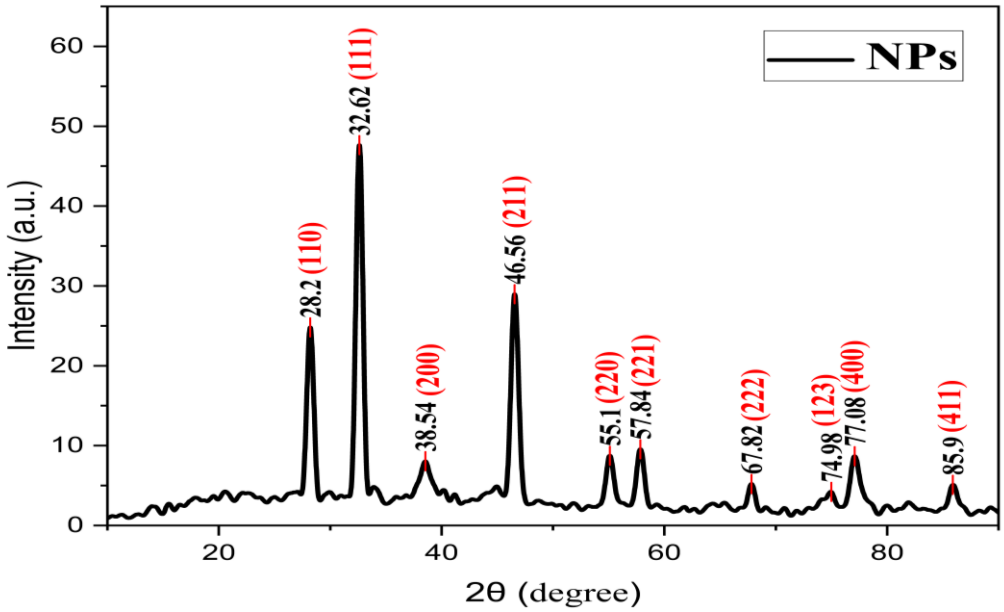


Figure 4: XRD Analysis of biosynthesized PVP-AgNPs

Furthermore, characteristic peaks at 1095, 952 and 792 cm^{-1} correspond to aliphatic ether and secondary alcohol of C-O stretching, as well as monosubstituted and trisubstituted alkenes of C=C bending, highlighting the diverse functional groups present.

XRD studies: The crystalline structure of the synthesised nanomaterials was confirmed using XRD analysis of PVP-AgNPs. The XRD spectra of PVP-AgNPs are displayed in figure 4. All diffraction peaks are well-indexed, indicating that the silver phase possesses a face centred cubic (FCC) crystal structure. The synthesised samples were verified as PVP-AgNPs using X-ray diffraction (XRD) with a diffraction angle (2θ) ranging from 0˚ to 90˚. The XRD reflection lines for bare PVP-AgNPs were detected at 28.2°, 32.62°, 38.54°, 46.56°, 55.1°, 57.84°, 67.82°, 74.98°, 77.08°, 85.9° which correspond to (110), (111), (200), (211), (220), (221), (222), (123), (400), (411) respectively to the planes' HKL according to the miller indexes. These closely correspond to JCPDS card No. 01-076-1393, which indicates the cubic structure of AgNPs.

HR-TEM studies: The shape and size distribution of colloidal particles were assessed using high resolution transmission electron microscopy. The synthesised PVP-encased AgNPs particles were homogenous, spherical and uniformly dispersed, with average particle size estimated as 11.32 nm, as seen by the HR-TEM analysis (Figure 5A-5C). Figure 5D illustrated the SAED pattern which reveals the ring patterns. Figure 6 illustrates the size distribution curve derived from TEM.

Antimicrobial activity: Agar well diffusion approach was used to evaluate the antibacterial activity of AgNPs produced from *Swertia chirata* leaf extract and polymeric encapsulated AgNPs was examined (Figure 7). PVP-AgNPs

showed significant antibacterial activity against all tested pathogenic bacteria at a dose of 100 µL. As shown in figure 5, the maximum zone of inhibition for *E. coli* is around 28 mm. The zone of Inhibition for *S. aureus, P, aeruginosa* and GPB measured around 22, 24 and 26 mm respectively (Table 1). This study concludes that *Swertia chirata* plant extracts and AgNPs have promise as antibacterial agents against pathogenic microorganisms. It has been demonstrated that AgNPs in polymer PVP are more potent antibacterial agents as compare to additional drug.

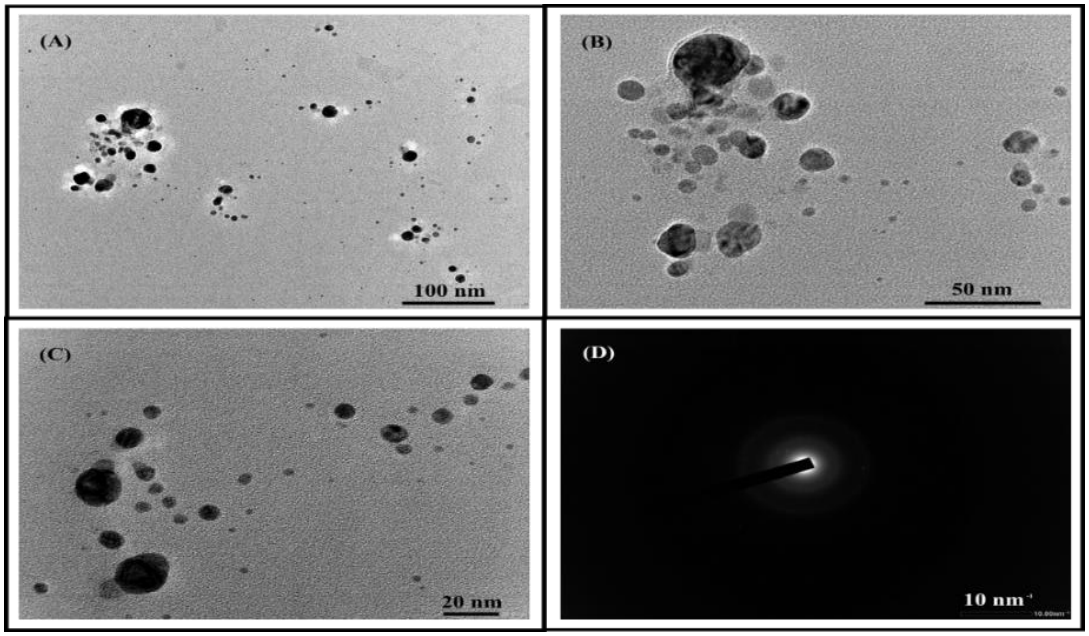


Figure 5: HR-TEM Analysis of Biosynthesis PVP-AgNPs

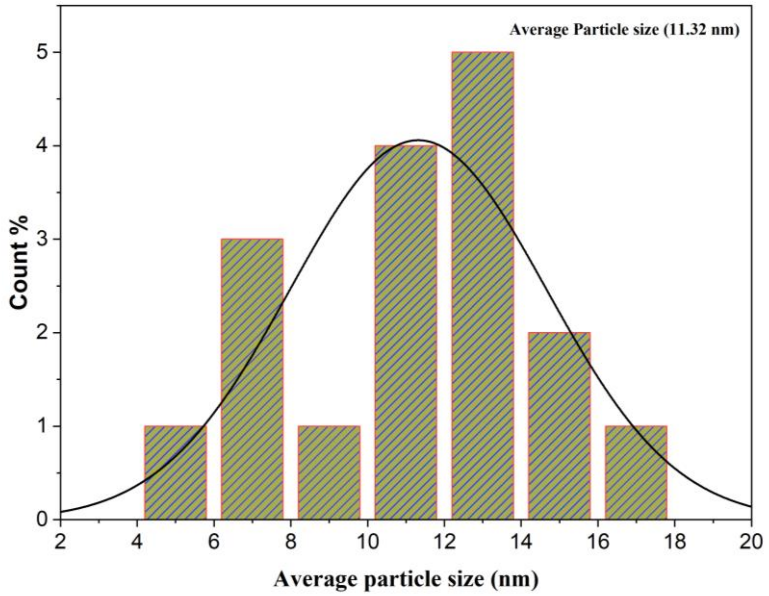


Figure 6: Size distribution curves from the TEM analysis and SAED pattern of PVP functionalized AgNPs

Table 1
Comparative study of Antibacterial activity of plant extract, silver nanoparticles and PVP capped silver nanoparticles

Test Sample	Concentration (µL)	Zone of Inhibition (mm)			
		E. coli	*S. aureus*	*P. aeruginosa*	GPB
Plant Extract	100	15	12	15	13
Silver Metal Salt	100	18	15	17	16
AgNPs	100	23	17	20	21
Streptomycin	100	27	21	22	23
PVP-AgNPs	100	28	22	24	26

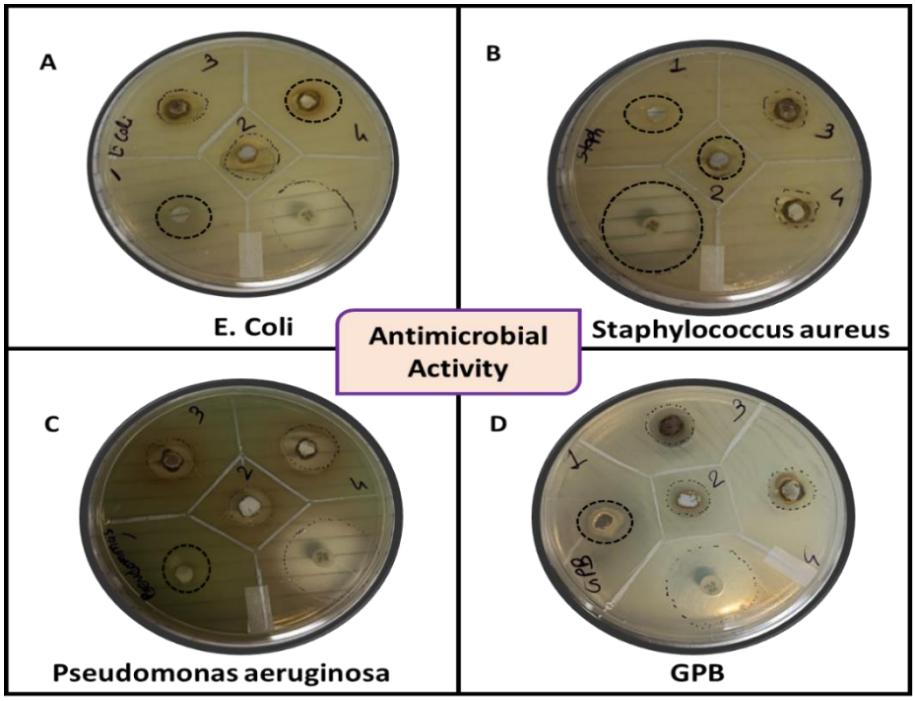


Figure 7: Antimicrobial activity of biosynthesize against (A) *E. coli* (B) *Staphylococcus aureus* (C) *Pseudomonas aeruginosa* (D) GPB

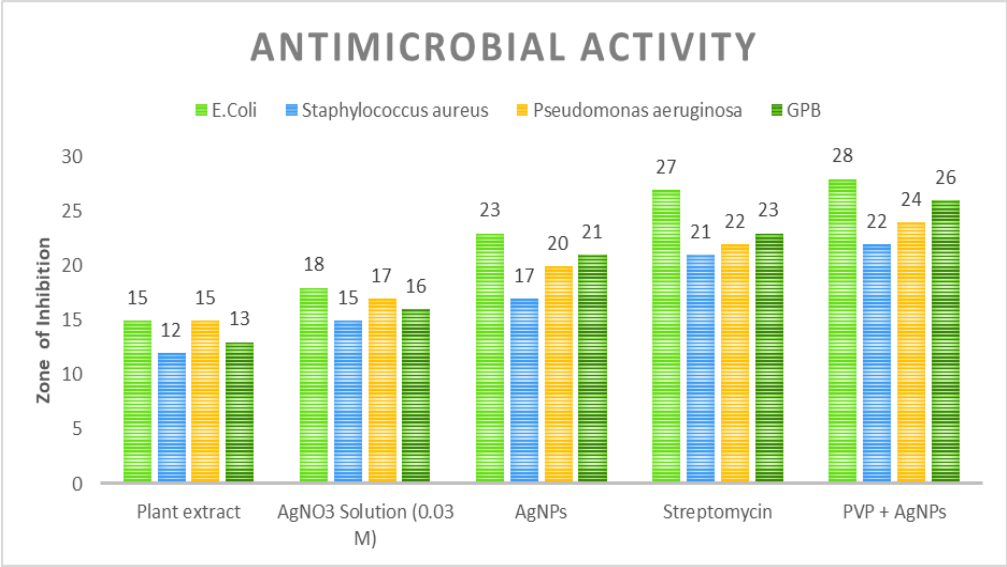


Figure 8: Antimicrobial Activity of *Swertia chirata* leaves extract

Conclusion

Using *Swertia chirata*, which are environmentally safe, reasonably priced and are more effective, than both physical and chemical techniques, colloidal silver nanoparticles have been successfully produced. For the nanoparticles, the plant extract provides both protective layer and reducing agent, therefore guaranteeing their stability. Stable colloidal silver nanoparticles are produced from *Swertia chirata* using it as an efficient reducing agent.

PVP was encapsulating substance used to increase the biocompatibility of AgNPs. Using many analytical methods including UV-Visible spectroscopy, FTIR, XRD and TEM, these PVP-AgNPs were further defined. Against Gram positive (GPB, *Staphylococcus aureus*) and Gram negative (*E. coli*, *Pseudomonas aeruginosa*), these PVP-AgNPs show amazing efficacy.

Acknowledgement

Authors gratefully acknowledge Gokul Global University, Sidhpur, Gujarat for infrastructure facility. The authors extend their gratitude to Pratham Laboratory, Mehsana, Gujarat for providing the bacterial cultures for antibacterial analysis. One of the authors Kalrav Oza would like to thank Dr. Manoj Vora for continuous support and guidance. The authors also acknowledge HNG University, Gujarat; SKPCPER, Ganpat University (Gujarat), Central Instrument Lab (Panjab University) and Vaibhav Analytical service,

Ahmedabad for providing instrumental facilities and UGC Infonet and Information and Library Network (INFLIBNET) (Ahmedabad) for e-journals.

References

1. Abalkhil T.A., Alharbi S.A., Salmen S.H. and Wainwright M., Bactericidal activity of biosynthesized silver nanoparticles against human pathogenic bacteria, *Biotechnology and Biotechnological Equipment*, **31**, 411–417 **(2017)**

2. Adnan M., Heliyon Plant extract preparation and green synthesis of silver nanoparticles using Swertia chirata: Characterization and antimicrobial activity against selected human pathogens, *Heliyon*, **10**, e28038 **(2024)**

3. Ahmad W., Jaiswal K.K. and Soni S., Green synthesis of titanium dioxide (TiO2) nanoparticles by using Mentha arvensis leaves extract and its antimicrobial properties, *Inorganic and Nano-Metal Chemistry*, **50**, 1032–1038 **(2020)**

4. Ahmed R.H. and Mustafa D.E., Green synthesis of silver nanoparticles mediated by traditionally used medicinal plants in Sudan, *Int Nano Lett*, **10**, 1-14 **(2020)**

5. Ahn E.Y., Jin H. and Park Y., Assessing the antioxidant, cytotoxic, apoptotic and wound healing properties of silver nanoparticles green-synthesized by plant extracts, *Materials Science and Engineering C*, **101**, 204–216 **(2019)**

6. Ajaykumar A.P., Green Synthesis of Silver Nanoparticles Using the Leaf Extract of the Medicinal Plant, Uvaria narum and Its Antibacterial, Antiangiogenic, Anticancer and Catalytic Properties, *Antibiotics*, **12**, 564 **(2023)**

7. Allafchian A.R., Jalali S.A.H., Hashemi S.S. and Vahabi M.R., Green synthesis of silver nanoparticles using phlomis leaf extract and investigation of their antibacterial activity, *J Nanostructure Chem*, **6**, 129–135 **(2016)**

8. Alshammari S.O., Mahmoud S.Y. and Farrag E.S., Synthesis of Green Copper Nanoparticles Using Medicinal Plant Krameria sp. Root Extract and Its Applications, *Molecules*, **28**, 4629 **(2023)**

9. Ammulu M.A., Phytoassisted synthesis of magnesium oxide nanoparticles from Pterocarpus marsupium rox.b heartwood extract and its biomedical applications, *Journal of Genetic Engineering and Biotechnology*, **19**, 21 **(2021)**

10. Balciunaitiene A., Antimicrobial Activities against Opportunistic Pathogenic, *Plants*, **11**, 1833 **(2022)**

11. Bharathi D., Diviya Josebin M., Vasantharaj S. and Bhuvaneshwari V., Biosynthesis of silver nanoparticles using stem bark extracts of Diospyros montana and their antioxidant and antibacterial activities, *J Nanostructure Chem*, **8**, 83–92 **(2018)**

12. Carmona E.R., Green Chemistry Letters and Reviews Green synthesis of silver nanoparticles by using leaf extracts from the endemic Buddleja globosa hope, *Green Chemistry Letters and Reviews*, **10(4)**, 250-256 **(2017)**

13. Das P. and Sarma M.P., Green synthesis of silver nanoparticles using Swertia chirayita leaves and its effect against selected human pathogens against selected human pathogens, *International Journal of Botany Studies*, **7(2)**, 227-232 **(2022)**

14. Eltaweil A.S., Green synthesis of platinum nanoparticles using Atriplex halimus leaves for potential antimicrobial, antioxidant and catalytic applications, *Arabian Journal of Chemistry*, **15**, 103517 **(2022)**

15. Hu T.Y., Anti-inflammation action of xanthones from Swertia chirayita by regulating COX-2/NF-κB/MAPKs/Akt signaling pathways in RAW 264.7 macrophage cells, *Phytomedicine*, **55**, 214–221 **(2019)**

16. Ijaz I., Gilani E., Nazir A. and Bukhari A., Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles, *Green Chem Lett Rev*, **13**, 59–81 **(2020)**

17. Jalab J., Abdelwahed W., Kitaz A. and Al-Kayali R., Green synthesis of silver nanoparticles using aqueous extract of Acacia cyanophylla and its antibacterial activity, *Heliyon*, **7**, 2405-8440 **(2021)**

18. Kiani B.H., Comparative evaluation of biomedical applications of zinc nanoparticles synthesized by using Withania somnifera Plant Extracts, *Plants*, **11**, 1525 **(2022)**

19. Kongor A., Calix [4] pyrrole Stabilized PdNPs as an Efficient Heterogeneous Catalyst for Enhanced Degradation of Water - Soluble Carcinogenic Azo, *Catal Letters*, **151**, 548-558 **(2020)**

20. Lava M.B., Muddapur U.M., Basavegowda N., More S.S. and More V.S., Characterization, anticancer, antibacterial, anti-diabetic and anti-inflammatory activities of green synthesized silver nanoparticles using Justica wynaadensis leaves extract, *Mater Today Proc*, **46**, 5942–5947 **(2020)**

21. Lv D., Ecofriendly Electrospun Membranes Loaded with Visible-Light-Responding Nanoparticles for Multifunctional Usages: Highly Efficient Air Filtration, Dye Scavenging and Bactericidal Activity, *ACS Appl Mater Interfaces*, **11**, 12880–12889 **(2019)**

22. Mengie T., Mequanente S., Nigussie D., Legesse B. and Makonnen E., Investigation of wound healing and antiinflammatory activities of solvent fractions of 80% methanol leaf extract of achyranthes aspera l. (amaranthaceae) in rats, *Journal of Inflammation Research*, **14**, 1775–1787 **(2021)**

23. Murthy H.C.A., Zeleke T.D., Ravikumar C.R., Kumar M.R.A. and Nagaswarupa H.P., Electrochemical properties of biogenic silver nanoparticles synthesized using Hagenia abyssinica (Brace) JF. Gmel. medicinal plant leaf extract, *Mater Res Express*, **7**, 55016 **(2020)**

24. Nahari M.H., Green Synthesis and Characterization of Iron Nanoparticles Synthesized from Aqueous Leaf Extract of Vitex leucoxylon and Its Biomedical Applications, *Nanomaterials*, **12**, 2404 **(2022)**

25. Paul S., Biochemical estimation of Moringa oleifera leaf extract for synthesis of silver nanoparticle mediated drug delivery system, *J Plant Biochem Biotechnol*, **29**, 86–93 **(2020)**

26. Pugazhendhi S., Usha R. and Mary Anjalin F., Comparative study of different plant extract mediated silver nanoparticles for nonlinear optics, *Mater Today Proc*, **33**, 3984–3988 **(2020)**

27. Rajput S., Kumar D. and Agrawal V., Green synthesis of silver nanoparticles using Indian Belladonna extract and their potential antioxidant, anti-inflammatory, anticancer and larvicidal activities, *Plant Cell Rep*, **39**, 921–939 **(2020)**

28. Rasheed T., Bilal M., Iqbal H.M.N. and Li C., Green biosynthesis of silver nanoparticles using leaves extract of Artemisia vulgaris and their potential biomedical applications, *Colloids Surf B Biointerfaces*, **158**, 408–415 **(2017)**

29. Sharma V., Green synthesis of silver nanoparticles from medicinal plants and evaluation of their antiviral potential against chikungunya virus, *Appl Microbiol Biotechnol*, **103**, 881–891 **(2019)**

30. Sharon A., Obed G.M. and Priya S., Green Synthesis of Silver Nanoparticles using Plant Extracts and Their Applications for Water Purification and Anti-Diabetic Properties, *Res. J. Chem. Environ.*, **26(4)**, 27-35 **(2022)**

31. Urnukhsaikhan E., Bold B.E., Gunbileg A., Sukhbaatar N. and Mishig-Ochir T., Antibacterial activity and characteristics of silver nanoparticles biosynthesized from Carduus crispus, *Sci Rep*, **11**, 1–12 **(2021)**.

(Received 07th May 2025, accepted 11th July 2025)