



# Microwave-Assisted Green Synthesis of *Zingiber officinale*-Derived Silver Nanoparticles and Their Environmental and Biological Applications

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## Abstract

This study reports a green and eco-friendly approach for the microwave-assisted synthesis of highly stable and uniformly dispersed silver nanoparticles (AgNPs) using *Zingiber officinale* extract as both a reducing and stabilizing agent. Conventional chemical stabilizers employed in silver nanoparticle synthesis pose environmental and biological hazards, necessitating the development of sustainable alternatives. The use of plant-based biomaterials effectively eliminates the need for toxic reagents while enhancing nanoparticle stability. The synthesized AgNPs were characterized using various spectroscopic and analytical techniques, which confirmed the formation of predominantly spherical nanoparticles with an average particle size of 11.5 nm. Functional group analysis revealed that phytoconstituents present in the *Zingiber officinale* extract played a crucial role in nanoparticle stabilization and monodispersity. The biosynthesized AgNPs exhibited significant antimicrobial activity against Gram-positive bacteria and demonstrated efficient photocatalytic dye degradation under irradiation. Additionally, the nanoparticles showed notable binding affinity toward DNA, indicating potential biological relevance. The therapeutic properties of *Zingiber officinale*, combined with microwave irradiation, make this green synthesis strategy promising for environmental and biological applications.

**Keywords:** Microwave-Assisted Green Synthesis, Silver Nano-particles, *Zingiber officinale* extract,  $\text{Fe}^{+3}$  metal Ions, Microbial activity.

## Introduction

Nanomaterials have attracted significant attention in recent years due to their remarkable potential in diverse scientific and technological fields, including ion sensing, semiconductor devices, and quantum information systems. The unique physical and chemical properties of nanoparticles primarily arise from their high surface-to-volume ratio, which imparts enhanced reactivity, superior electrocatalytic performance, and improved biocompatibility compared to their bulk counterparts. These features make nanoparticles promising candidates for advanced functional applications.

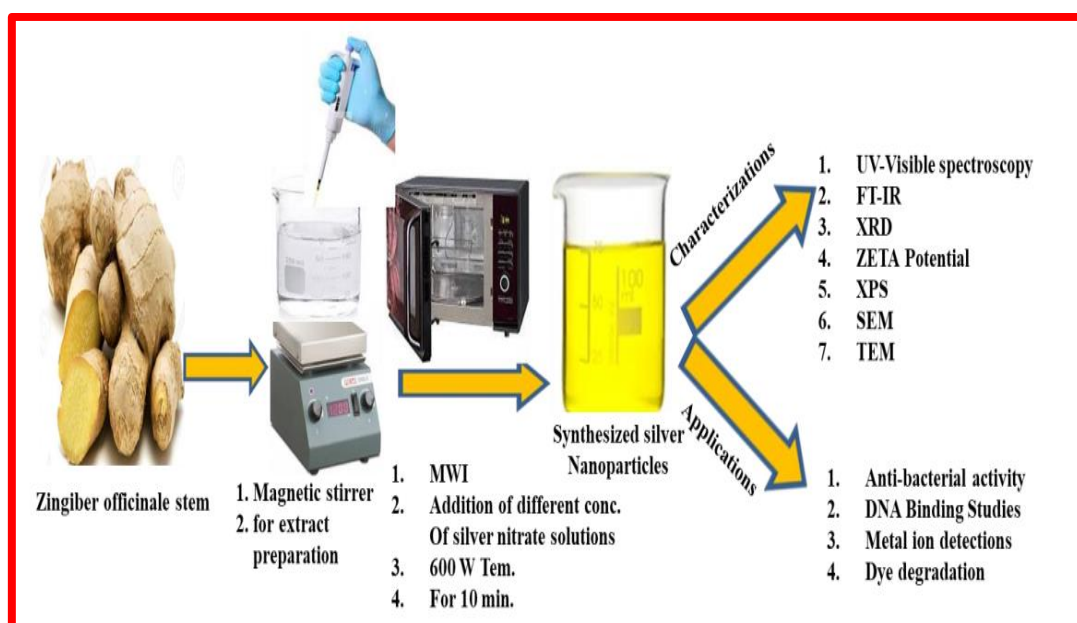
In industrial sectors such as chemical processing, energy production, and aerospace engineering, corrosion remains a critical challenge that compromises material durability and performance. Metal alloys are commonly employed to mitigate corrosion; however, the development of tailored nanomaterials capable of removing or preventing corrosion layers has become increasingly important. Owing to their low density, high mechanical strength, and excellent corrosion resistance, nanomaterials have found extensive applications in

petrochemical industries, automotive components, aviation structures, sports equipment, and biomedical devices.

Among various metal nanoparticles, silver nanoparticles (AgNPs) have gained considerable interest because of their outstanding physicochemical properties and broad-spectrum antimicrobial activity. Recently, green synthesis approaches using biological resources have emerged as sustainable alternatives to conventional chemical methods, which often involve toxic reagents and environmentally hazardous stabilizers. Plant-derived biomaterials serve as effective reducing and capping agents, offering improved nanoparticle stability while minimizing environmental impact.

In this context, *Zingiber officinale* extract was employed as a natural reducing and stabilizing agent for the microwave-assisted one-pot synthesis of highly stable and uniformly dispersed silver nanoparticles. Microwave irradiation offers rapid heating, enhanced reaction kinetics, and energy efficiency, making it a suitable technique for green nanoparticle synthesis. The prepared AgNPs were comprehensively characterized using UV-Visible spectroscopy, FT-IR, XRD, SEM, and TEM analyses, confirming the formation of predominantly spherical nanoparticles with an average size of  $11.5 \pm 2$  nm.

### Schematic representation:-



## MATERIALS AND METHOD

### Chemicals

All chemicals employed in this study were of analytical grade and used without further purification. Silver nitrate ( $\text{AgNO}_3$ , 99.99% purity), used as the precursor for silver nanoparticle synthesis, was procured from Sigma-Aldrich (Merck). Various metal salts, including  $\text{Fe}^{2+}$ ,  $\text{Ba}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Zn}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Sn}^{2+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{K}^+$ ,  $\text{Fe}^{3+}$ , and  $\text{Ca}^{2+}$ , were utilized for metal ion detection studies and were obtained from local suppliers (Avra Chemicals). Double-distilled water was used as the solvent throughout the entire synthesis and experimental procedures.

### Preparation of *Zingiber officinale* stems extract

To prepare the extract from *Zingiber officinale* stems, fresh stems were purchased from a local shop in Hyderabad, Telangana, India. After cleaning the stems under tap water and peeling off the skin, they were cut into small pieces. 25g of the *Zingiber officinale* stems were then boiled in 100ml of double-distilled water to obtain the extract. The resulting extract was used for the synthesis of silver nanoparticles after filtration through Whatman number 1 filter paper with a pore size of 11 micrometres.

## Synthesis of Ag-NPs solutions

Fresh *Zingiber officinale* stems were procured from a local market in Hyderabad, Telangana, India. The stems were thoroughly washed under running tap water to remove surface impurities, peeled, and cut into small pieces. A total of 25 g of the prepared stem material was boiled in 100 mL of double-distilled water to obtain the plant extract. After cooling, the extract was filtered through Whatman No. 1 filter paper (11 µm pore size) and subsequently used for the synthesis of silver nanoparticles.

## CHARACTERIZATION

The optical properties of the *Zingiber officinale* stem extract-capped silver nanoparticles (AgNPs) were analyzed using a dual-beam UV-visible spectrophotometer (Shimadzu UV-3600, Japan). Fourier transform infrared (FTIR) spectra of both the *Zingiber officinale* stem extract and the extract-capped AgNPs were recorded separately to identify the functional groups involved in nanoparticle formation and stabilization, using a Bruker TENSOR 27 FTIR spectrometer (Bruker Optics, Germany). The spectra were acquired over a wavenumber range of 600–4000 cm<sup>-1</sup>.

Powder X-ray diffraction (XRD) analysis of the *Zingiber officinale* stem-capped AgNPs was performed using a Rigaku X-ray diffractometer (PANalytical BV, Netherlands) operated at 40 kV and 30 mA, with a scan rate of 0.366 min<sup>-1</sup>. For morphological and particle size analysis, the AgNPs were deposited onto carbon-coated copper grids and dried at 27 °C. Transmission electron microscopy (TEM) measurements were carried out using a FEI Tecnai G2 F30 S-TWIN transmission electron microscope (FEI Company, USA) at an accelerating voltage of 200 kV.

## Microbial studies

The antibacterial activity was evaluated using the pour plate technique. Briefly, 1 mL of actively growing bacterial culture was mixed with molten agar medium prior to solidification and poured into sterile Petri plates. Wells were then created using a sterile cork borer, and the test samples (100 µL) were introduced into the wells of both Gram-positive and Gram-negative bacterial plates. The inoculated plates were incubated at 37 °C for 48 h, after which antibacterial activity was assessed.

## Zeta Potential

The interaction between nanoparticles and bacterial cell membranes is primarily governed by electrostatic forces, with zeta potential playing a critical role in determining antibacterial efficacy. In the present study, the antimicrobial performance of silver nanoparticles possessing consistent zeta potential values was evaluated against both Gram-positive and Gram-negative bacteria. The results demonstrated a clear relationship between nanoparticle surface charge and their ability to inhibit bacterial growth. Among the tested strains, Gram-positive *Bacillus* species exhibited greater susceptibility to the synthesized silver nanoparticles. The zeta potential, which reflects electrostatic repulsion between negatively charged biomolecules on the bacterial cell surface and the negatively charged nanoparticle surface, contributes to variations in bacterial resistance.

## Result and discursion

### UV-Visible spectroscopy

In this study, *Zingiber officinale* stem extract was employed as a reducing agent for the synthesis of silver nanoparticles (AgNPs). The reaction mixture containing the stem extract and AgNO<sub>3</sub> was monitored using UV-visible spectroscopy over a wavelength range of 200–800 nm. The formation of AgNPs was confirmed by the appearance of a characteristic surface plasmon resonance (SPR) band centered at approximately 430 nm.

Different concentrations of  $\text{AgNO}_3$  were investigated to evaluate their influence on nanoparticle formation. The UV-visible absorption spectra of AgNPs synthesized using a fixed extract concentration (0.5%) and varying  $\text{AgNO}_3$  concentrations (0.1–0.4 mM), under microwave irradiation for 10 min at 600 W, are presented in Fig. 1. The intensity of the SPR band increased progressively with increasing  $\text{AgNO}_3$  concentration and reached a maximum at 0.4 mM. This enhancement in SPR intensity indicates increased AgNP formation, as the SPR peak intensity is directly related to the availability and concentration of silver precursor in the reaction system.

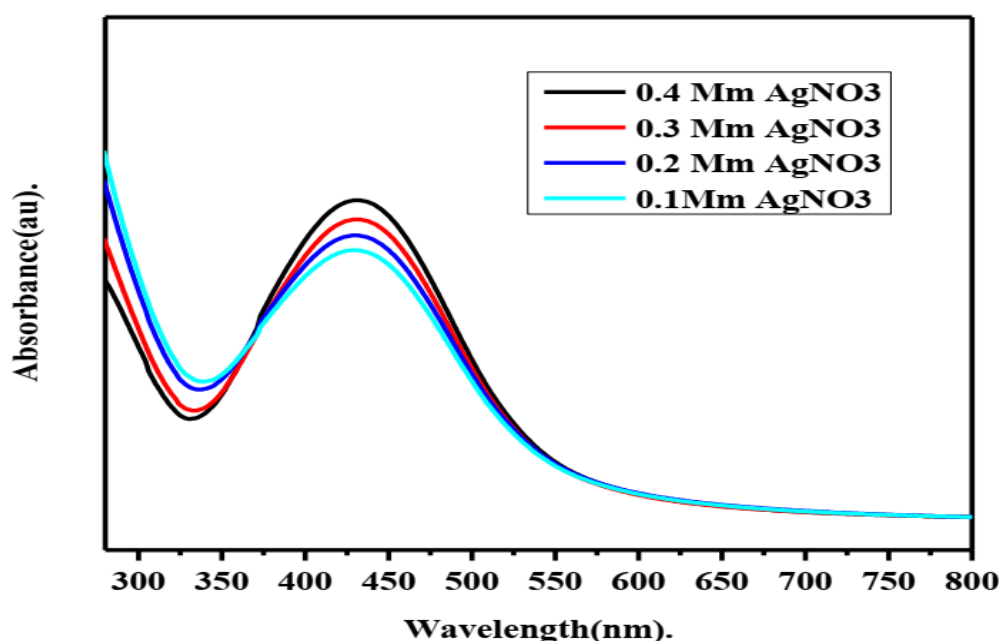


**Fig.1** UV-Visible spectroscopy of synthesized silver nanoparticles with different concentration of  $\text{AgNO}_3$  solution.

#### Fourier transfer infrared spectroscopy (FT-IR)

FTIR spectra were recorded for both the synthesized silver nanoparticles and the *Zingiber officinale* stem extract to identify the functional groups involved in the reduction of  $\text{Ag}^+$  ions and the stabilization of the AgNPs. The FTIR analysis revealed characteristic absorption bands corresponding to various functional moieties present in the plant extract.

The stretching vibrations of  $\text{C-H}$  and  $\text{N-H}$  bonds were observed in the  $1000\text{--}650\text{ cm}^{-1}$  region, indicating their potential involvement in nanoparticle formation. Absorption bands in the  $1300\text{--}1000\text{ cm}^{-1}$  range corresponded to functional groups such as  $\text{C-O-C}$ ,  $\text{C-OH}$ , and  $\text{C=O}$ . The presence of  $\text{NO}_2$  or aliphatic  $\text{CH}_3$  and  $\text{CH}_2$  stretching vibrations was evident in the  $1550\text{--}1300\text{ cm}^{-1}$  region, while bands appearing between  $1650$  and  $1550\text{ cm}^{-1}$  were attributed to the stretching of  $\text{C=C}$ ,  $\text{C=N}$ , and  $\text{N-H}$  bonds.

Additionally, peaks in the  $2250\text{--}2100\text{ cm}^{-1}$  and  $2800\text{--}2200\text{ cm}^{-1}$  regions were assigned to  $\text{C}\equiv\text{C}$  stretching of alkynes and  $\text{C-N}$  stretching of nitriles, respectively. The absorption bands observed in the  $1780\text{--}1650\text{ cm}^{-1}$  region were associated with  $\text{C=O}$  stretching vibrations of esters, ketones, and aldehydes. The broad absorption band in the  $3650\text{--}3200\text{ cm}^{-1}$  region corresponded to  $\text{O-H}$  stretching of alcohols, whereas the band in the  $3300\text{--}2500\text{ cm}^{-1}$  range indicated  $\text{O-H}$  stretching of carboxylic acids.

Notably, several peaks exhibited shifts between the stem extract and AgNP spectra, while others were common to both, suggesting the involvement of phytochemicals in the reduction and capping processes. The observed spectral features are attributed to secondary metabolites present in the *Zingiber officinale* stem extract, which plays a crucial role in the stabilization of the synthesized silver nanoparticles.

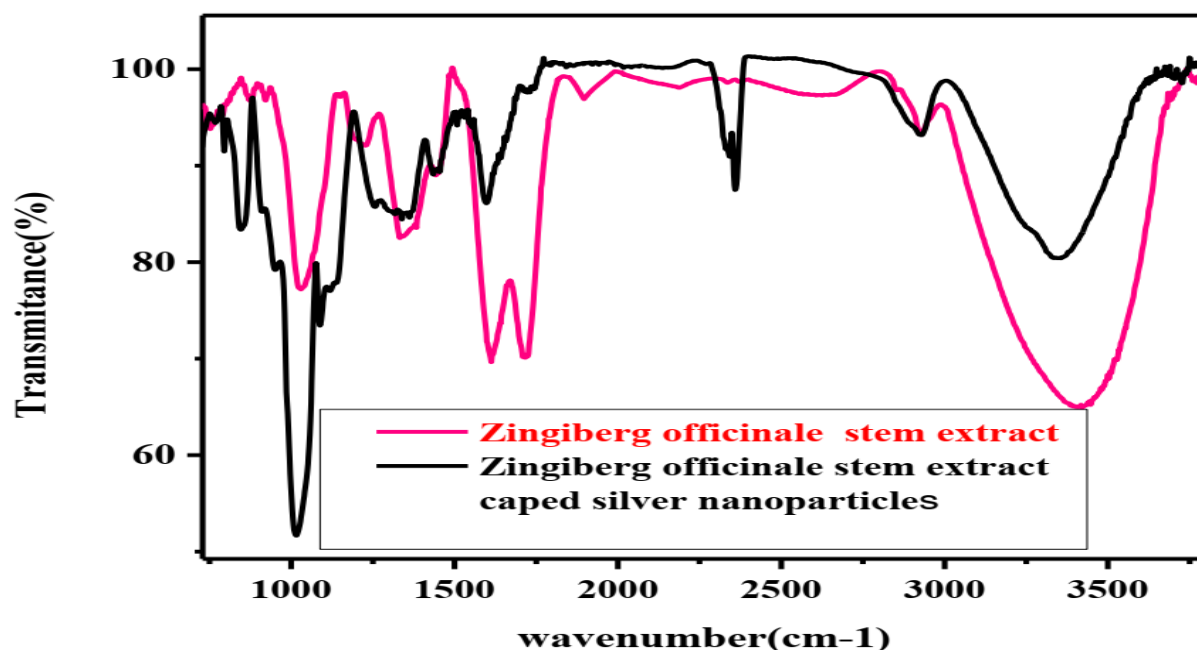


**Fig.2** FT-IR studies of synthesized silver nanoparticles with 0.4 Mm concentration of AgNO<sub>3</sub> solution.

### X-RAY Diffraction studies of synthesized silver nanoparticles (XRD)

X-ray diffraction (XRD) analysis was performed to investigate the crystalline structure of *Zingiber officinale* extract-capped silver nanoparticles (AgNPs). As shown in Fig. 3, the diffraction pattern exhibited distinct peaks at  $2\theta$  values of 28.35°, 33.32°, 38.50°, 46.25°, 54.44°, 56.22°, and 76.54°. These reflections were indexed to the lattice planes (111), (200), (111), (220), (311), (222), and (311), respectively, in agreement with previously reported studies.

The presence of these characteristic diffraction peaks confirms the face-centered cubic (FCC) crystalline structure of the synthesized AgNPs. The pronounced intensity of the diffraction peak corresponding to the (200) plane indicates the high crystallinity of the nanoparticles. Furthermore, the observed peak broadening supports the nanoscale crystalline nature of the AgNPs, consistent with earlier reports [24].

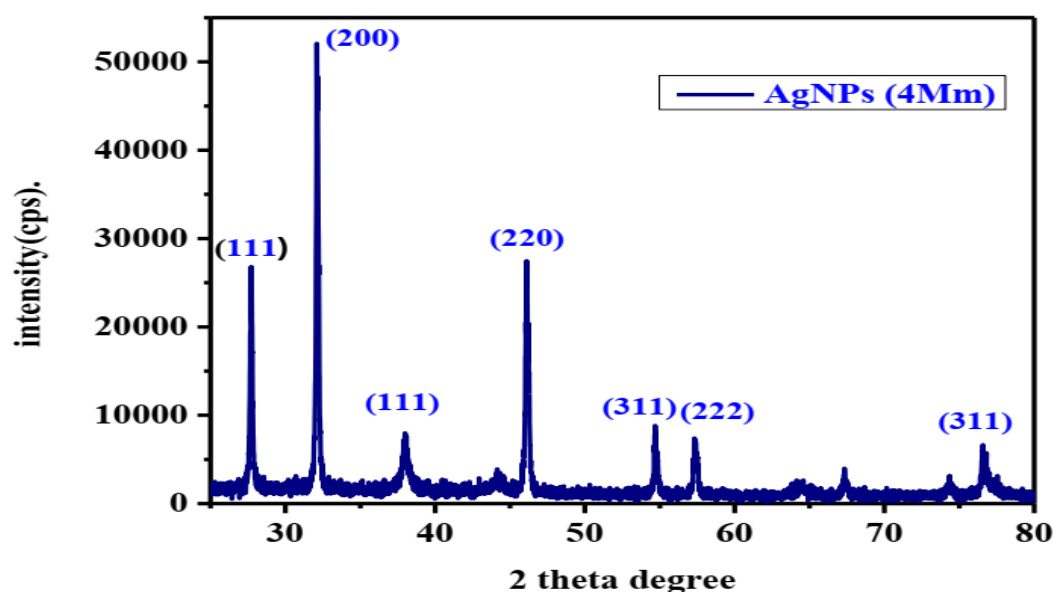


**Fig.3** XRD studies of synthesized silver nanoparticles with 0.4 Mm concentration of AgNO<sub>3</sub>. Solution.

The average crystallite size of the synthesized silver nanoparticles was estimated using the Debye–Scherrer equation. Based on this analysis, the average particle size was determined to be approximately 30.02 nm.

$$\text{Particle Size} = (0.9 \times \lambda) / (d \cos \theta)$$

| S.NO | Peak positions(2theta) | FWHM       | Crystalline size | Average size |
|------|------------------------|------------|------------------|--------------|
| 1    | 27.68173               | 0.26814    | 30.51338194      | 30.01596789  |
| 2    | 3.21E+01               | 1958.46012 | 0.004221053      |              |
| 3    | 38.04396               | 32.11216   | 0.261681399      |              |
| 4    | 44.18307               | 0.20072    | 42.71490987      |              |
| 5    | 64.40644               | 1129.01119 | 0.008315773      |              |
| 6    | 64.40644               | 0.10036    | 93.54923493      |              |
| 7    | 77.35188               | 0.23632    | 43.06003028      |              |

**Table. 1.** Average size of the synthesized Silver nanoparticles.

### Size and morphological studies of synthesized silver nanoparticles by Transmitted Electronic Microscopic Techniques. (TEM)

Silver nanoparticles synthesized at an  $\text{AgNO}_3$  concentration of 0.4 mM, which exhibited the highest SPR intensity, were selected for transmission electron microscopy (TEM) analysis. The nanoparticles were deposited onto carbon-coated copper grids and allowed to dry at 27 °C prior to examination. TEM analysis was performed to evaluate the size and morphology of the synthesized AgNPs. The results indicated that the nanoparticles possessed an average size of  $11.5 \pm 2$  nm, with particle sizes ranging from approximately 5 to 20 nm.

X-ray crystallographic analysis further confirmed that the AgNPs exhibited a highly crystalline nature with a face-centered cubic (FCC) structure. Compared to previously reported studies, the synthesized AgNPs were smaller in size, demonstrating the effectiveness of microwave irradiation as a heat source in the synthesis process. In addition, the selected area electron diffraction (SAED) pattern displayed distinct concentric rings with bright spots, indicating that the nanoparticles were well dispersed, non-agglomerated, and retained their individual crystalline structure.

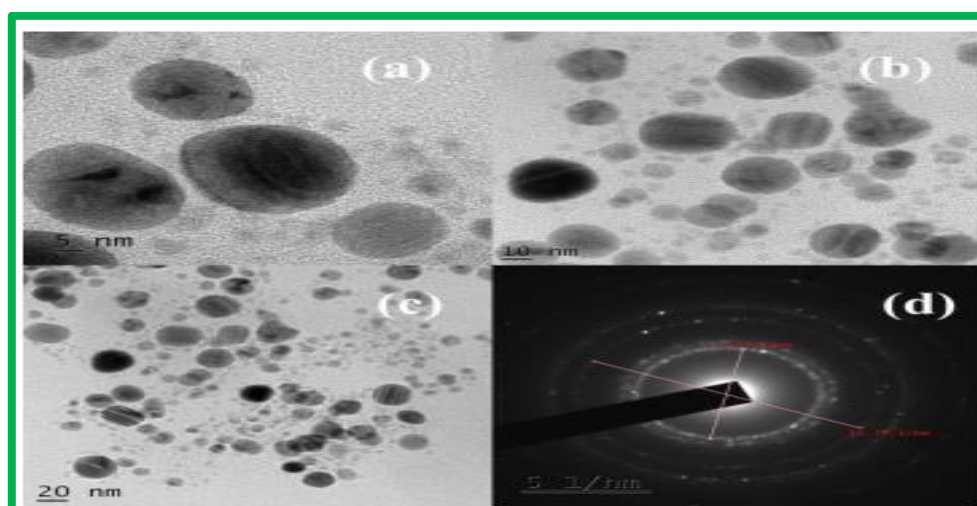
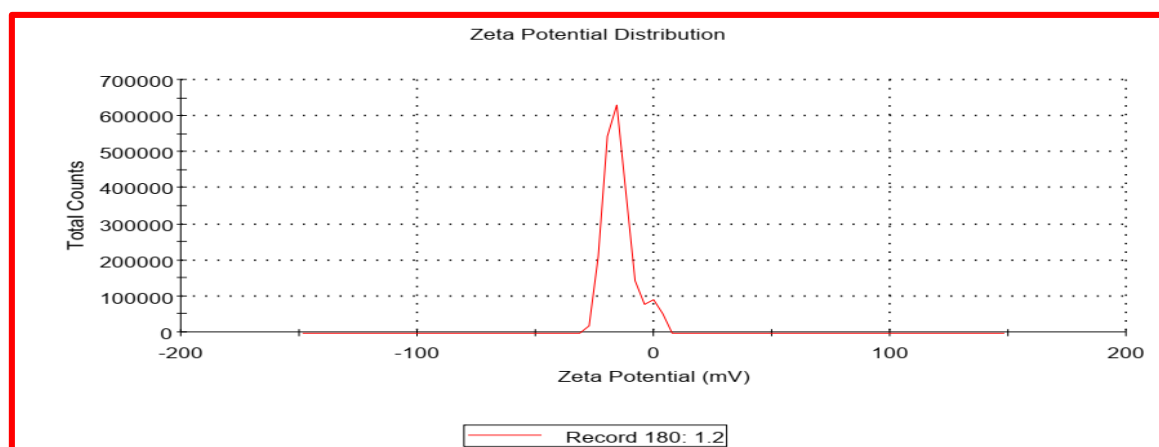


**Fig.4** TEM Images of synthesized silver nanoparticles with 0.4 Mm concentration of  $\text{AgNO}_3$ . Solution.

**Table. 2.** Different morphological studies of synthesized Metal Nanoparticles.

| S. No | Synthetic method      | Reducing Agent                                           | Operating conditions                                                                    | Size of the nanoparticle s (TEM) | References                 | Shape of Ag NPs      |
|-------|-----------------------|----------------------------------------------------------|-----------------------------------------------------------------------------------------|----------------------------------|----------------------------|----------------------|
| 1.    | Simple heating        | Ethyl acetate extract of <i>Ulva fasciata</i>            | 1 Mm, 2 min, room tem<br>3mi/100 ml, static                                             | Size—28 - 41 nm                  | Rajesh et al. (2012)       | Spherical (FCC)      |
| 2.    | At 60 <sup>o</sup> C  | Aqueous filtrate of <i>Nephrolepis sexaltata</i> L. fern | 1mM, 4h, 10 ml/90 ml                                                                    | Size—avg 24.76 nm                | Bhor et al. (2014)         | Spherical (FCC)      |
| 3.    | Simple heating method | <i>Jatropha curcas</i> (Euphorbiaceae)                   | 10 ml AgNO <sub>3</sub> and 100 ml of extract                                           | 30–50 nm                         | Bar H et al.               | Spherical (FCC)      |
| 4.    | Heating               | <i>Galega officinalis</i>                                | boiled at 100 °C for 5 min                                                              | 21.1 ± 6.4 nm                    | M. et al. 2019             | Spherical (FCC)      |
| 5.    | 30 min heating        | <i>Brassica nigra</i> seeds                              | 100 µL of plant extract was added to 0.9 mL methanol and 2 mL of DPPH solution (0.1 mM) | 13 ± 2 nm                        | Aneta sanayova et. al 2021 | Spherical FCC) (FCC) |
| 6.    | MWI                   | <i>Zingiber officinale</i>                               | 600W                                                                                    | 11.5±2 nm                        | Present study              | Spherical (FCC)      |

#### Surface charge phenomenon study of synthesized silver nanoparticles with Zeta potential

**Fig.5** Zeta potential studies of synthesized silver nanoparticles.

The stability of silver nanoparticles synthesized in an aqueous medium is strongly influenced by their zeta potential. In the present study, the zeta potential of silver nanoparticles synthesized at an AgNO<sub>3</sub> concentration of 0.4 mM was determined to be −15.0 mV. As shown in Fig. 2, the electrostatic interactions among the nanoparticles in solution exhibit a zeta potential value of −15.0 mV, indicating good colloidal stability.

Furthermore, the negative surface charge of the nanoparticles suggests favorable interactions with negatively charged species, supporting their potential applicability in antibacterial activity, DNA binding, and catalytic dye degradation studies.

## XPS Studies of synthesized N Doped carbon dots

X-ray photoelectron spectroscopy (XPS) analysis was carried out to examine the surface composition and chemical states of the silver nanoparticles synthesized using *Zingiber officinale* extract. The survey spectrum shown in Fig. 5 displays distinct peaks at binding energies of 877.5 and 882.5 eV corresponding to Ag–Ag, along with peaks at 715.50 eV (O 1s), 710.10 eV (C 1s), and 837.50 and 837.60 eV (N 1s), confirming the presence of silver, oxygen, carbon, and nitrogen elements in the synthesized nanoparticles [28].

The high-resolution C 1s spectrum (Fig. 5a) was deconvoluted into three components, indicating carbon atoms present in different chemical environments. The peaks observed at binding energies of 710.10 eV, 952.60 eV, and 952.70 eV were attributed to C–C/C=C, C–N/C–O, and C–O/C–N bonding environments, respectively [29].

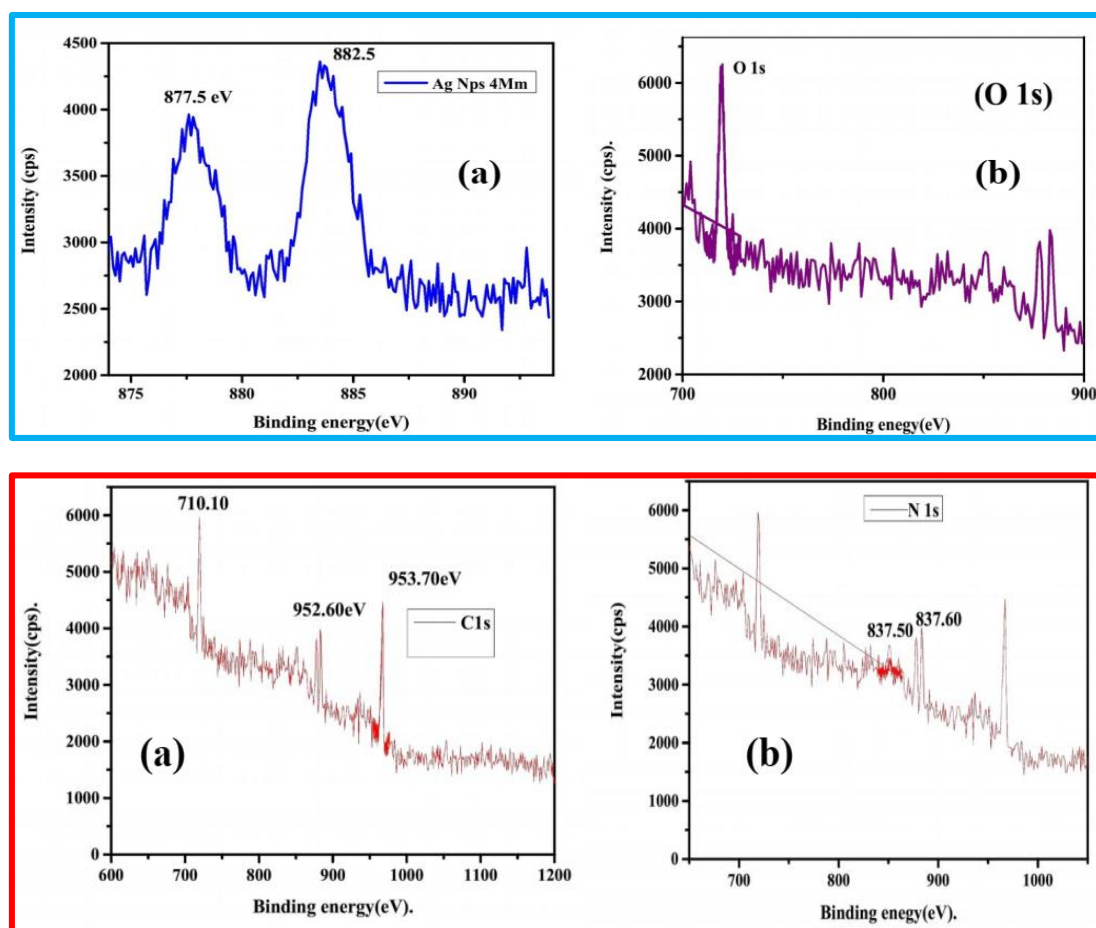


**Fig.6** XPS Spectrum of synthesized Ag Nanoparticles of (a) Ag, (b) O<sub>2</sub> (a) C and (b) N<sub>2</sub> spectrum.

## Application

### Detection of Fe<sup>3+</sup> metal ion

A mixture containing 2  $\mu$ L of various metal ion solutions, including Fe<sup>3+</sup>, Ca<sup>2+</sup>, Ba<sup>2+</sup>, Na<sup>+</sup>, Zn<sup>2+</sup>, Mg<sup>2+</sup>, Cu<sup>2+</sup>, Cd<sup>2+</sup>, Sn<sup>2+</sup>, Ni<sup>2+</sup>, Pb<sup>2+</sup>, Sr<sup>2+</sup>, and Mn<sup>2+</sup>, was prepared for metal ion sensing studies. To detect metal ions present in hard water, 2 mL of each ion solution was separately mixed with the silver nanoparticle (AgNP) solution, and the resulting mixtures were analyzed using UV–visible spectroscopy.

A distinct color change was observed specifically in the presence of ferric (Fe<sup>3+</sup>) ions, where the characteristic yellow color of the AgNP solution gradually disappeared, indicating a chemical interaction between the AgNPs and Fe<sup>3+</sup> ions [30]. This phenomenon can be attributed to the oxidation of silver nanoparticles to Ag<sup>+</sup> ions by ferric ions, accompanied by the reduction of Fe<sup>3+</sup> to Fe<sup>2+</sup>. Consequently, the AgNP solution serves as an effective probe for the selective detection of Fe<sup>3+</sup> ions in contaminated water samples.

The oxidation of AgNPs leads to a decrease in UV–visible absorption intensity, resulting in a transition from a hyperchromic to a hypochromic shift in the absorption spectra [31], further confirming the interaction between AgNPs and  $\text{Fe}^{3+}$  ions.

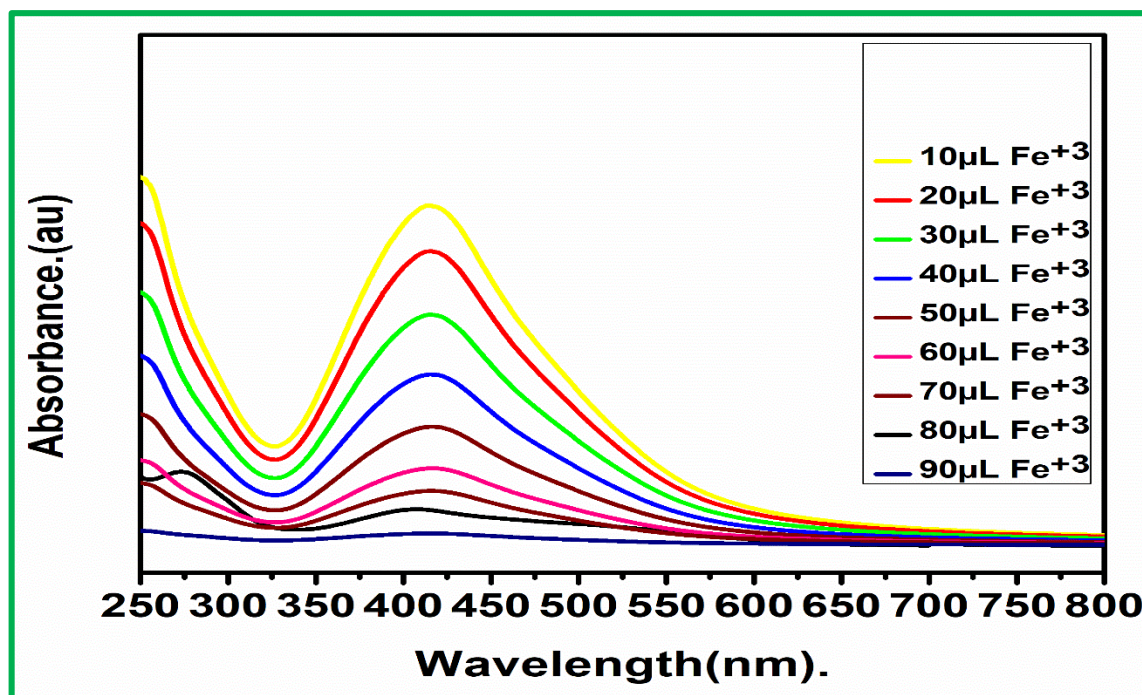


Fig.7  $\text{Fe}^{+3}$  Detection with synthesized silver nanoparticles.

### Anti-bacterial activity

The antimicrobial activity of silver nanoparticles synthesized at concentrations ranging from 0.1 to 0.4 mM was evaluated against Gram-positive bacteria (*Staphylococcus aureus* and *Streptococcus pyogenes*) and Gram-negative bacteria (*Pseudomonas aeruginosa* and *Escherichia coli*). The results showed that higher nanoparticle concentrations produced larger zones of inhibition compared to lower concentrations. A clear concentration-dependent increase in antibacterial activity was observed, with the zone of inhibition expanding as the concentration of silver nanoparticles increased.

Notably, silver nanoparticles synthesized at 0.3 and 0.4 mM exhibited significantly enhanced antibacterial activity compared to those prepared at 0.1 and 0.2 mM. Ampicillin was used as a standard antibiotic for comparison and displayed smaller zones of inhibition than the silver nanoparticles synthesized at 0.4 mM. These findings suggest that higher concentrations of the synthesized silver nanoparticles effectively disrupt the bacterial cell structure, ultimately leading to bacterial cell death.

Table.3 Anti-bacterial activity of synthesized silver nanoparticles

| Sample        | <i>S- aureus</i> |        | <i>S-pyogens</i> |        | <i>P-aeruginosa</i> |        | <i>E- coli.</i> |        |
|---------------|------------------|--------|------------------|--------|---------------------|--------|-----------------|--------|
| Concentration | 50 µL            | 100 µL | 50 µL            | 100 µL | 50 µL               | 100 µL | 50 µL           | 100 µL |
| 0.1           | 0.6cm            | 0.8 cm | 0.4 cm           | 0.8 cm | 0.4 cm              | 0.6 cm | 0.2 cm          | 0.4 cm |
| 0.2           | 0.6              | 0.5    | 0.4              | 0.6    | 0.6                 | 0.8    | 0.4             | 0.6    |
| 0.3           | 1.0              | 1.2    | 0.8              | 1.0    | 0.4                 | 0.8    | 0.6             | 0.6    |
| 0.4           | 1.2              | 1.6    | 1.4              | 1.8*   | 0.8                 | 1.0    | 1.1             | 1.2    |
| Ampicillin    | 0.4              | 0.6    | 0.2              | 0.4    | 0.6                 | 0.8    | 0.4             | 0.2    |

## Dye degradation

### Schematic representation of degradation studies

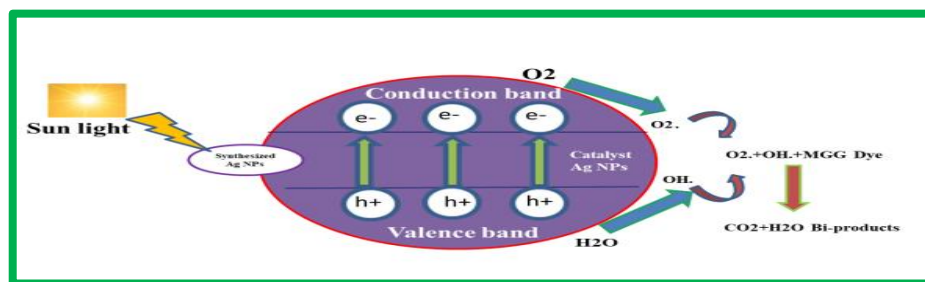


Fig.8 dye degradation Schematic representation.

### UV-Visible studies of Malachite green dye degradation

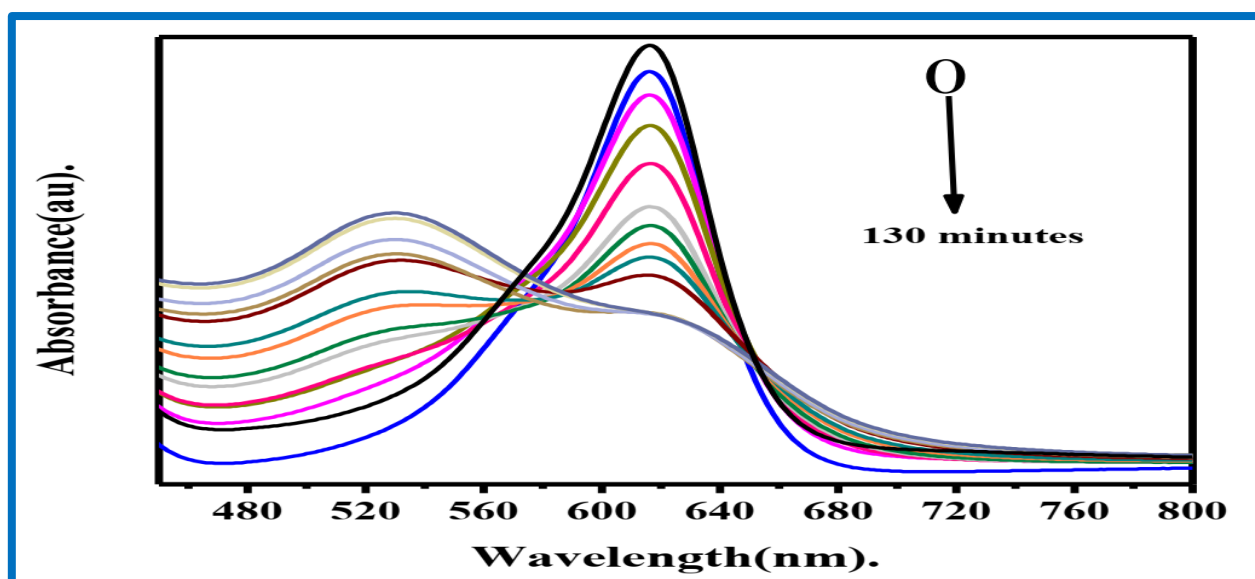


Fig.9 UV-Visible studies of Malachite green dye degradation with 0.4 mM concentrated synthesized silver nanoparticles.

The photocatalytic degradation of malachite green (MG), a hazardous organic pollutant commonly originating from various anthropogenic sources, was investigated using the synthesized silver nanoparticles (AgNPs) to elucidate the degradation mechanism. In this study, MG at a concentration of 50 ppm was examined. Under sunlight irradiation, approximately 78.13% degradation of MG was achieved within 130 min. This result demonstrates that the synthesized AgNPs exhibit high photocatalytic efficiency at lower dye concentrations.

The study indicates that MG concentration plays a crucial role in determining the rate of photocatalytic degradation, as it influences surface charge, adsorption behavior, and electron transfer efficiency of the photocatalyst. At higher dye concentrations, a reduction in degradation efficiency was observed, suggesting that dye concentration is the dominant factor governing MG removal, although temperature and pH also significantly affect the degradation process.

The synthesized AgNPs were found to be effective photocatalysts for MG degradation at pH 6, where higher degradation efficiency was observed with increasing pH values up to this level. The effect of temperature on MG degradation was evaluated at 50 ppm concentration for 130 min at pH 6 and 27 °C. The results revealed that elevated temperatures enhance photocatalytic activity due to increased generation of hydroxyl radicals, which accelerate the degradation process.

Overall, the findings demonstrate that the synthesized AgNPs are promising photocatalysts for the treatment of wastewater contaminated with toxic organic dyes. During photocatalytic degradation, MG molecules are adsorbed onto the AgNP surface and become photoexcited, leading to electron transfer to the conduction band of the nanoparticles. These electrons are subsequently captured by dissolved oxygen to form reactive

superoxide radicals ( $O_2^{\bullet-}$ ), which interact with  $H_2O_2$  to generate hydroxyl radicals ( $\bullet OH$ ). The combined action of  $O_2^{\bullet-}$  and  $\bullet OH$  radicals ultimately decomposes MG into simple, non-toxic inorganic products such as  $CO_2$  and  $H_2O$ .

### Mechanism of malachite green dye degradation

- 1).  $MG^* + Ag-NPs \rightarrow MG^{(+)*} + Ag-NPs^{(e-)}$
- 2).  $Ag-NPs^{(e-)} + O_2 \rightarrow O^{2*-}$
- 3).  $O^{2*-} + H_2O \rightarrow H_2O_2 \rightarrow OH^*$
- 4).  $OH^*$  (or)  $O^{2*-} + MG \rightarrow CO_2 + H_2O + \text{bi-products}$ .

### DNA Binding studies.

The present study demonstrates the enhanced compatibility of polyanionic DNA backbones with silver nanoparticles synthesized using *Zingiber officinale* stem extract. These biosynthesized AgNPs facilitate the binding of native DNA oligonucleotides to their negatively charged surfaces. Among the nucleobases, adenine exhibited a strong affinity toward AgNPs, forming interactions with the nanoparticle surface through its exocyclic amine group and the N7 atom. Guanine, cytosine, and adenine were found to interact with AgNPs via their keto functional groups and coordinating nitrogen atoms. In contrast, thymine showed the weakest adsorption behavior toward the synthesized AgNPs, likely due to its limited interaction through the keto oxygen atom.

DNA molecules were able to covalently attach to the silver nanoparticles through the formation of Ag–S bonds. In this study, buffer-dissolved DNA was gradually added to *Zingiber officinale* stem extract–capped AgNPs in increasing volumes (25, 50, 75, and 100  $\mu L$ ) while maintaining an optimized  $AgNO_3$  concentration of 0.4 mM. Upon the incremental addition of DNA, a gradual decrease in the UV–visible absorption intensity was observed, indicating the occurrence of intercalative binding interactions. These results confirm the stabilization of DNA and associated biomolecules on the surface of AgNPs and highlight the functional role of the biosynthesized silver nanoparticles in DNA binding applications.

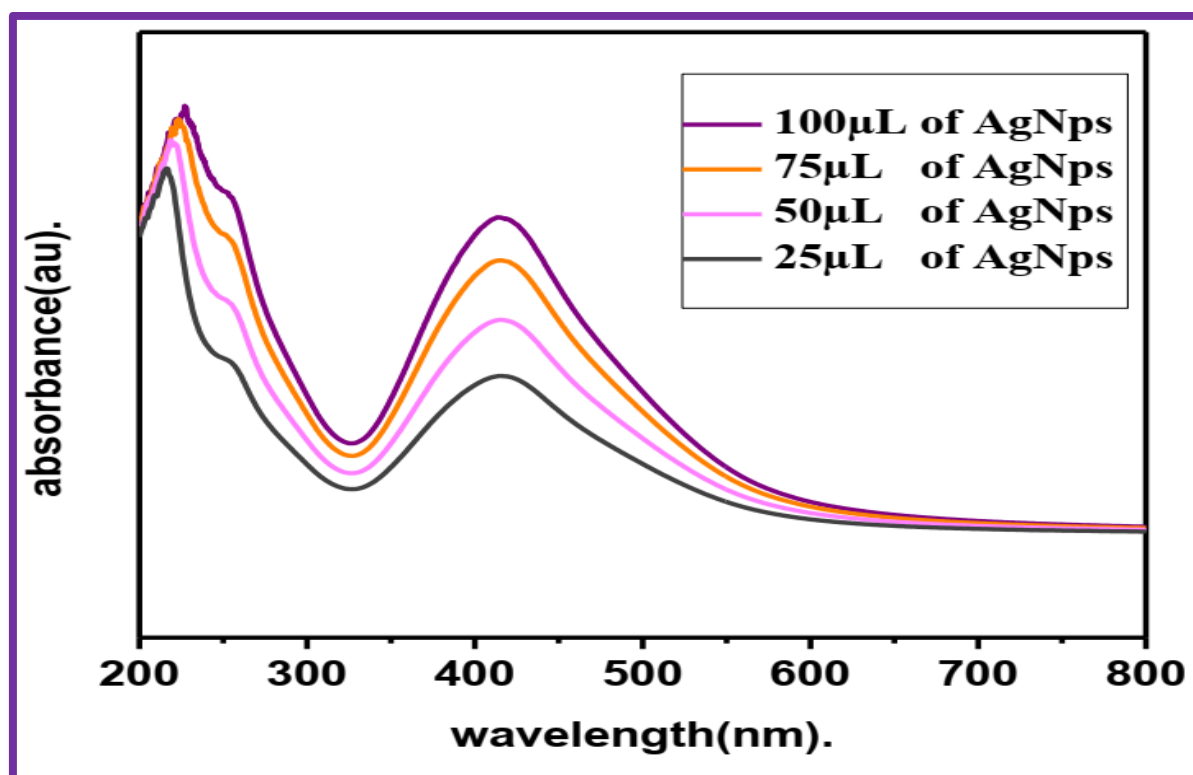


**Fig.10** DNA binding studies of synthesized silver nanoparticles

## Conclusion

In the present study, silver nanoparticles were synthesized via a biological route using *Zingiber officinale* stem extract. The results demonstrated that the synthesized AgNPs exhibited superior morphological characteristics compared to those reported for silver nanoparticles prepared using ethyl acetate extract of *Ulva fasciata*, aqueous filtrate of *Nephrolepis sexaltata* L. fern, *Jatropha curcas* (Euphorbiaceae), *Galega officinalis*, and *Brassica nigra* seeds, among other biological sources. FTIR analysis confirmed the presence of key functional groups in the *Zingiber officinale* stem extract that are suitable for the reduction and stabilization of AgNPs, highlighting the extract's crucial role in nanoparticle formation and stabilization.

TEM analysis revealed that the synthesized silver nanoparticles possessed an average particle size of  $11.5 \pm 2$  nm, with predominantly spherical morphology. These findings were consistent with XRD results, which confirmed a face-centered cubic (FCC) crystalline structure. The biosynthesized AgNPs exhibited significant antibacterial activity, effective DNA binding capability, and selective metal ion detection performance. In antibacterial studies, Gram-positive bacteria were found to be more susceptible to the synthesized nanoparticles than Gram-negative bacteria. Among the tested metal ions, selective detection of  $\text{Fe}^{3+}$  was observed, where  $\text{Fe}^{3+}$  ions were reduced to  $\text{Fe}^{2+}$ , accompanied by the oxidation of silver nanoparticles to silver ions.

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## Conflict of interest

The author declares that there are no known financial or personal relationships that could have appeared to influence the work reported in this paper.

## References

1. Rafique, M., Sadaf, I., Rafique, M. S., & Tahir, M. B. (2017). A review on green synthesis of silver nanoparticles and their applications. *Artificial cells, nanomedicine, and biotechnology*, 45(7), 1272-1291.
2. Srikar, S. K., Giri, D. D., Pal, D. B., Mishra, P. K., & Upadhyay, S. N. (2016). Green synthesis of silver nanoparticles: a review. *Green and Sustainable Chemistry*, 6(1), 34-56.
3. Roy, A., Bulut, O., Some, S., Mandal, A. K., & Yilmaz, M. D. (2019). Green synthesis of silver nanoparticles: biomolecule-nanoparticle organizations targeting antimicrobial activity. *RSC advances*, 9(5), 2673-2702.
4. Okafor, F., Janen, A., Kukhtareva, T., Edwards, V., & Curley, M. (2013). Green synthesis of silver nanoparticles, their characterization, application and antibacterial activity. *International journal of environmental research and public health*, 10(10), 5221-5238.
5. Geoprincy, G., Srri, B. V., Poonguzhali, U., Gandhi, N. N., & Renganathan, S. (2013). A review on green synthesis of silver nanoparticles. *Asian J. Pharm. Clin. Res*, 6(1), 8-12.
6. Ahmed, S., Saifullah, Ahmad, M., Swami, B. L., & Ikram, S. (2016). Green synthesis of silver nanoparticles using *Azadirachta indica* aqueous leaf extract. *Journal of radiation research and applied sciences*, 9(1), 1-7.
7. Mallikarjuna, K., Narasimha, G., Dillip, G. R., Praveen, B., Shreedhar, B., Lakshmi, C. S., ... & Raju, B. D. P. (2011). Green synthesis of silver nanoparticles using *Ocimum* leaf extract and their characterization. *Digest Journal of Nanomaterials and Biostructures*, 6(1), 181-186.
8. Garibo, D., Borbón-Nuñez, H. A., de León, J. N. D., García Mendoza, E., Estrada, I., Toledano-Magaña, Y., ... & Susarrey-Arce, A. (2020). Green synthesis of silver