

“SUSTAINABLE GREEN SYNTHESIS OF SILVER NANOPARTICLES FOR ENVIRONMENTAL POLLUTION MANAGEMENT AND WATER PURIFICATION”

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Abstract

Azadirachta indica (neem) leaf extract as a stabilizing and reducing agent, this study demonstrates the ecologically sustainable synthesis of silver nanoparticles (Ag-NPs). The biosynthesized Ag-NPs were studied by utilizing SEM, FTIR, XRD, and UV-Vis spectroscopy. A surface plasmon resonance (SPR) peak at about 420 nm has been identified by UV-Vis investigation, confirming the production of nanoparticles. While XRD and SEM confirmed crystalline, spherical nanoparticles with a face-centered cubic structure, FTIR indicated bioactive phytochemicals involved in reduction and stabilization. Utilizing pseudo-first-order kinetics, the Ag-NPs demonstrated remarkable multifunctional environmental remediation capabilities, degrading methylene blue dye by over 90 percent when subjected to visible light.

Additionally, they exhibited significant antibacterial action against *S. aureus* and *E. coli*, with zone of inhibition widths growing as nanoparticle concentration increased. Additionally, the Ag-NPs shown great removal effectiveness (>85%) in dosage-dependent experiments, successfully removing organic material and heavy metals (Pb^{2+} , Cr^{6+}) from contaminated water. The results presented suggest the sustainable synthesis of Ag-NPs as a highly effective, environmentally friendly nanomaterial for combined environmental pollution management and water purification.

INTRODUCTION

Water pollution has become one of the most critical global challenges of our time. Industrial waste,

agricultural chemicals, and urban runoff continue to contaminate rivers, lakes, and groundwater with

dangerous substances[1] These pollutants include toxic heavy metals like lead and chromium, harmful organic chemicals from dyes and pesticides, and disease-causing bacteria and viruses[2]. This widespread contamination threatens human health, damages ecosystems, and reduces the availability of safe drinking water, particularly in developing regions[3]. Traditional water treatment methods often struggle to remove all these different types of pollutants effectively, while also being expensive and energy-intensive to operate[4]. There is an urgent need for new, better technologies that can clean water more completely while being affordable and environmentally friendly[5]. In recent years, nanotechnology has emerged as a promising solution to this problem. Nanotechnology involves working with extremely small particles so tiny that thousands could fit across the width of a single human hair[6]. At this tiny scale, materials develop special properties that make them very effective at removing pollutants[7]. Among these nanomaterials, silver nanoparticles have shown particular promise for environmental cleanup[8]. Silver nanoparticles possess unique abilities that make them ideal for water purification: they can break down complex chemical pollutants into harmless substances, capture and remove toxic heavy metals, and effectively kill dangerous bacteria and other microorganisms[9]. However, there has been a significant problem with how these silver nanoparticles are traditionally made. Conventional manufacturing methods often use toxic chemicals and require large amounts of energy, sometimes creating additional pollution in the process[10]. This creates a contradiction using harmful methods to create materials intended to help the environment. To solve this problem, scientists have developed what we call "green synthesis" methods[11]. These environmentally friendly approaches use natural materials like plant extracts, fruit peels, or even microorganisms to create silver nanoparticles[12]. For example, when plant extracts are mixed with silver solutions, the natural compounds in the plants safely convert silver ions into nanoparticles while also coating them in a protective layer that keeps them stable. This green method eliminates the need for hazardous chemicals, uses less energy, and creates a more sustainable production process[13].

The potential applications of these green-synthesized silver nanoparticles in environmental management are extensive and impressive[14]. They can be used to treat industrial wastewater by breaking down stubborn dyes and organic pollutants through a process called photocatalysis, where the nanoparticles use light energy to destroy contaminants[15]. They can effectively remove dangerous heavy metals from water by attracting and binding to these toxic ions. Perhaps most importantly, they show strong effectiveness against waterborne pathogens like *E. coli* and cholera bacteria, providing a potential solution for preventing waterborne diseases in communities without access to clean water[16]. The natural coating from the plant extracts may even enhance these abilities while ensuring the nanoparticles themselves are more environmentally safe[17].

This research has focuses on developing and testing such a sustainable approach to creating silver nanoparticles and evaluating their effectiveness for environmental cleanup. The work has several important goals: first, to develop an optimal method for creating silver nanoparticles using readily available plant materials; second, to carefully characterize the produced nanoparticles to understand their size, shape, and properties; and third, to thoroughly test how well these green-synthesized nanoparticles can remove different types of pollutants from water. The project will examine their effectiveness against organic dyes, heavy metals, and harmful bacteria, providing a comprehensive assessment of their capabilities. By demonstrating a complete process from sustainable production to effective application this research aims to contribute valuable knowledge to the development of affordable, eco-friendly water treatment technologies that could help communities worldwide address the growing challenge of water pollution while protecting our environment for future generations.

2 Materials and Methods

Sigma-Aldrich produced the analytical grade silver nitrate (AgNO_3), which was used without any further purification. In order to get rid of dust and other surface contaminants, fresh leaves of *Azadirachta indica*, or neem, were gathered from the surrounding region and then thoroughly washed with distilled water. Each experimental preparation was produced with double-distilled water. Before being utilized,

glassware was rinsed with distilled water and cleaned with nitric acid.

2.1 Preparation of Plant Extract

100 mL of distilled water was utilized to boil 20 g of freshly washed and finely chopped *A. indica* leaves for 10 to 15 minutes at 80 °C. After freezing to room temperature, the mixture was filtered using Whatman No. 1 filter paper. For further application as a stabilizing and reducing agent in the manufacture of nanoparticles, the ensuing filtrate has been stored at 4 °C.

2.2 Green Synthesis of Silver Nanoparticles

For the purpose of to produce silver nanoparticles (AgNPs), 90 mL of a 1 mM aqueous AgNO_3 solution and 10 mL of plant extract were mixed together while constantly stirring at room temperature. The reaction mixture was kept in a fluorescent atmosphere. A color shift from pale yellow to brown, indicating the reduction of Ag^+ ions to Ag^0 nanoparticles, provided preliminary confirmation of the creation of AgNPs. To guarantee a total reduction, the reaction was permitted to continue for a total of 24 hours. To obtain the nanoparticle powder, the produced AgNPs were centrifuged for 15 minutes at 10,000 rpm, washed three times with distilled water, and then dried in an oven at 60 °C.

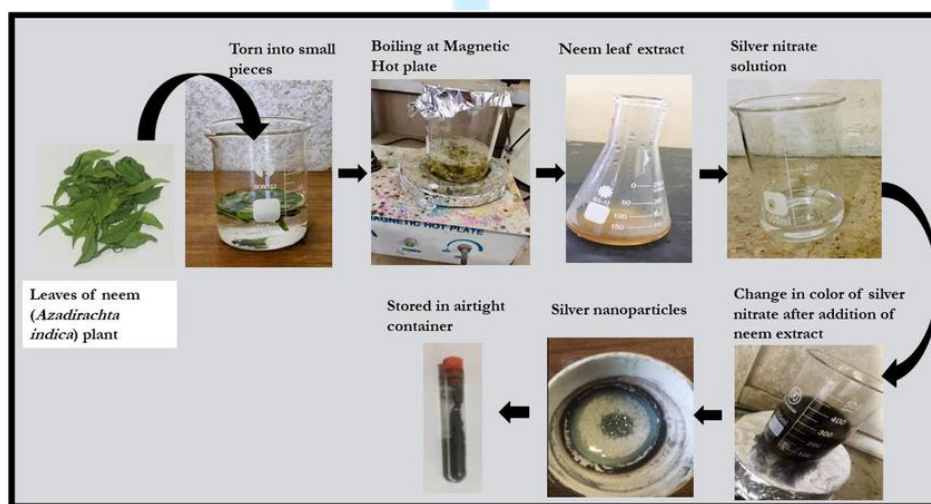


Figure 2.1: Bio-reduction of Silver Nitrate into Silver Nanoparticles using an extract from *Azadirachta indica* (Neem) leaves. The color change indicates nanoparticle formation.

2.3 Characterization of Silver Nanoparticles

In order to determine the physical and chemical features of the produced silver nanoparticles (AgNPs) and confirm their successful synthesis, a variety of analytical methods were employed. Using UV-visible spectroscopy, the optical characteristics and surface plasmon resonance (SPR) of the nanoparticles were examined in the 300–700 nm wavelength range. The presence of AgNPs was indicated by a clear absorption peak. In order to identify which functional groups in the plant extract were in charge of maintaining the stability of the nanoparticles and the reduction of

silver ions, Fourier Transform Infrared Spectroscopy (FTIR) was utilized in the 400–4000 cm^{-1} range. Using X-ray diffraction (XRD) analysis with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$), the crystalline nature and phase purity of the produced AgNPs were confirmed. The face-centered cubic structure of metallic silver was characterized by characteristic diffraction peaks. Additionally, the nanoparticles' morphology, size, and distribution were examined through the use of Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), which provided detailed information on their homogeneity

and surface structure. The successful green production of stable and distinctive silver nanoparticles was demonstrated by these combined techniques.

2.4 Evaluation of Catalytic Activity

The decomposition of methylene blue (MB) dye, a model organic pollutant, under exposure to visible light was used to measure the catalytic function of the manufactured silver nanoparticles (AgNPs). For every experiment, 50 mL of a stock solution of MB (10 mg/L) in distilled water was taken and put into a conical flask. As a catalyst, about 10 mg of the manufactured AgNPs were added, and to ensure even dispersion, the mixture was magnetically circulated. To establish an adsorption-desorption equilibrium between the dye molecules and the surface of the nanoparticles, the suspension was stirred in the dark for 20 minutes before irradiation. During the application of visible light, 3 mL aliquots of the reaction mixture were taken out at specific times (every 10 minutes). After centrifuging the samples to get rid of nanoparticles, a UV-visible spectrophotometer was used to assess the supernatant's absorbance at 664 nm. The gradual decline in absorbance intensity indicated that MB was being effectively destroyed. The following equation was used to calculate the percentage degradation:

$$\text{Degradation \%} = \frac{(A_0 - A_t)}{A_0} \times 100$$

where the initial and time-dependent absorbance values are designated by A_0 and A_t , respectively. Plotting $\ln(A_0/A_t)$ against time enabled kinetic studies to calculate the apparent rate constant (k) using a pseudo-first-order model. The green-synthesized AgNPs' improved photocatalytic effectiveness and potential for environmental remediation were brought out through comparing their efficiency to that of the control (without catalyst).

2.5 Antibacterial and Water Purification Studies

Using the agar well diffusion method, the antimicrobial capacity of the resulting AgNPs was determined against Gram-positive *Staphylococcus aureus* and Gram-negative *Escherichia coli*. Fresh

bacterial cultures (10^8 CFU/mL) were added to the nutrient agar plates, and a sterile cork borer was employed to create wells that were 6 mm in diameter. 50 μ L of AgNP suspension in three different concentrations (25, 50, and 100 μ g/mL) have been added to each well. Distilled water served as the negative control and standard antibiotic discs as the positive control. During an incubation time of 24 hours at 37 °C, the zones of inhibition on the plates were measured in millimeters.

The AgNPs' potential to destroy bacterial cell membranes, produce reactive oxygen species (ROS), and restrict essential cellular functions was thought to be the cause of their antibacterial activity. The green-synthesized AgNPs were used as adsorbents and catalytic agents in water purification studies for eliminating organic contaminants and heavy metals (Pb^{2+} , Cr^{6+}) from polluted water samples. For the purpose of to perform batch adsorption tests, 100 milliliters of pollutant solution (10 mg/L) and 0.1 grams of AgNPs were incorporated while being constantly stirring. It was carefully examined how many parameters, including pH, contact time, and adsorbent dosage, affected removal performance. During treatment, the samples were filtered, and UV-Vis spectrophotometry was used to measure the dye concentration and Atomic Absorption Spectroscopy (AAS) to quantify the residual metal concentration. The equation that follows was used for calculating the % removal efficiency:

$$\text{Removal efficiency} = \frac{C_0 - C_e}{C_0} \times 100$$

3 Results and Discussion

3.1 Visual Observation and UV-Visible Spectral Analysis

The reaction mixture's noticeable color shift from pale yellow to dark brown, which represented the reduction of Ag^+ ions to metallic silver (Ag^0) by phytochemical components that comprised the plant extract, served as the first indication that silver nanoparticles (AgNPs) developed. The surface plasmon resonance (SPR) phenomena frequently associated with AgNPs are in accordance with this optical observation.

The developed nanoparticles' UV-visible absorption spectra showed a strong peak at about 420 nm, which is characteristic of the silver nanoparticles' SPR band.

The lack of extra peaks in the electromagnetic spectrum suggested the nanoparticles were evenly distributed and not prone to agglomeration. A consistent size distribution was further suggested by the SPR peak's intensity and narrowness. The efficiency of bioactive chemicals in nanoparticle generation and stabilization is demonstrated by our results, which are in good agreement with data previously reported for green-synthesized AgNPs made from plant extracts. The successful and ecologically sound synthesis of silver nanoparticles (Ag-NPs), which is crucial for this research, has been demonstrated by the UV-Vis spectrum. The development of nanoscale metallic silver is definitely verified by the definitive characteristic of Surface Plasmon Resonance (SPR), which is a distinct, single absorption peak seen in the 400–450 nm range. This peak's symmetry and sharpness are significant because they demonstrate that the biomolecules (like flavonoids and polyphenols) from the plant or microbial extract used in the green synthesis correctly cap the produced nanoparticles, which are primarily spherical and have a narrow size distribution with little aggregation. For its intended environmental uses, this stability is essential. Furthermore, the existence of these organic capping agents is confirmed by the rising baseline in the UV region (below ~300 nm), which connects the spectral data to the "green" approach.

This spectrum is promising for use in water purification and environmental pollution management; the characteristics it exhibits a high surface-area-to-volume ratio, uniform spherical morphology, and stability are exactly what make Ag-NPs efficient as antimicrobial agents for disinfecting water and as catalysts for the breakdown of organic pollutants.

According to Anitha et al. (2022), silver nanoparticles (Ag-NPs) were created using an extract from *Azadirachta indica* and subsequently tested for their cytotoxicity efficiency and in vitro antioxidant activity against MCF-7 and HeLa cells. Dynamic light scattering (DLS) and a transmission electron microscope (TEM) were used to further examine the silver nanoparticles (Ag-NPs), which had been generated in 40 minutes and first verified by UV-visible spectroscopy (peak recognized at 375 nm).

The composition of the biosynthesized Ag-NPs was analyzed, and the TEM illustrations showed their spherical shape with particle sizes ranging from 10 to 60 nm. Various amounts of *Azadirachta indica* extract, biosynthesized silver nanoparticles, and a standard ranging from 0.2 to 1.0 mg/mL were evaluated for cytotoxicity and antioxidant activity. The 2,2-Diphenyl-1-picrylhydrazyl (DPPH) activity of the two compounds increased in a dose-dependent manner, with average IC₅₀ values of 0.70 ± 0.07 , 1.63 ± 0.09 , and 0.25 ± 0.09 mg/mL for the biosynthesized Ag-NPs, aqueous leaf extract, and ascorbic acid (standard), respectively. Furthermore, cytotoxicity elevated in both the MCF-7 and HeLa cell lines in a dose-dependent way. The biosynthesized Ag-NPs, aqueous leaf extract, and cisplatin (standard) all exhibited average IC₅₀ values of 0.90 ± 0.07 , 1.85 ± 0.01 , and 0.56 ± 0.08 mg/mL, respectively, as MCF-7 cell lines. The appropriate IC₅₀ values for HeLa cell lines were 0.85 ± 0.01 ; 1.76 ± 0.08 ; and 0.45 ± 0.10 mg/mL. In an effort to develop silver nanoparticles with cytotoxicity and antioxidant activity against MCF-7 and HeLa cells, this research developed a successful green reductant[18]

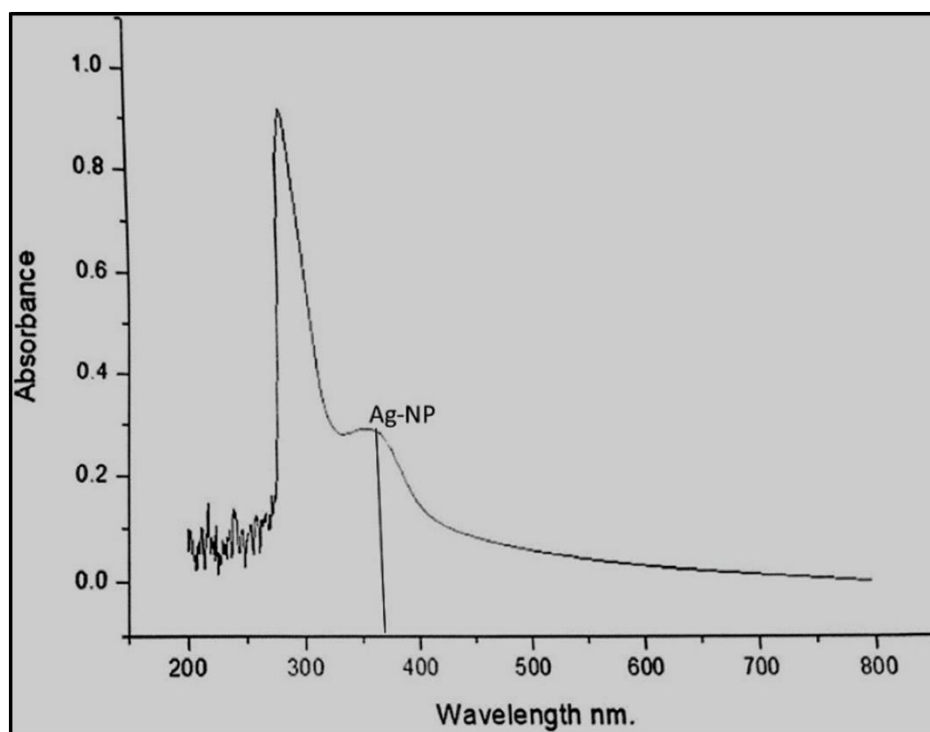


Figure 3.1: Biogenic Ag-NPs' UV-Vis spectra indicate the synthesis of spherical nanoparticles with a characteristic Surface Plasmon Resonance peak approximately 430 nm.

Based on the provided FTIR spectrum, the analysis confirms the critical role of bio-organic compounds in the sustainable green synthesis and functionalization of the silver nanoparticles (Ag-NPs) for environmental applications. The broad peak observed at approximately 3250 cm^{-1} is characteristic of O-H stretching vibrations, typically from phenolic compounds or alcohols present in the plant extract, which are well-known as powerful reducing agents for converting silver ions (Ag^+) to metallic silver (Ag^0). The key peaks in the fingerprint region specifically the bands around 1605 cm^{-1} and 1376 cm^{-1} are indicative of C=O stretching and C-N bending vibrations, respectively, commonly associated with amide groups in proteins. These biomolecules are crucial as they act as effective capping and stabilizing agents, binding to the surface of the newly formed nanoparticles to prevent aggregation and ensure their colloidal stability in aqueous environments. Furthermore, the C-O stretching vibration visible near 1042 cm^{-1} suggests the involvement of polysaccharides or alcohols from the extract. Collectively, this FTIR data provides direct evidence that the silver nanoparticles are

successfully bioconjugate with a layer of natural biomolecules. This "green" capping shell is not merely a remnant of the synthesis process but is functionally significant; it can enhance the nanoparticles' affinity for specific pollutants, facilitate their dispersal in water, and potentially contribute to their catalytic or antimicrobial activity, thereby making them highly suitable for targeted applications in water purification and environmental pollution management.

According to Iqbal et al. (2021), *Olea ferruginea* root extract was used to create silver nanoparticles (AgNPs) through an efficient biogenic procedure referred to as the "Green method." The produced nanoparticles were investigated using biological tests, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), UV visible spectroscopy, and High-Resolution Transmission Electron Microscopy Studies (HRTEM). AgNP manufacturing has been verified by UV visible absorption spectroscopy, which shows a Surface Plasmon Resonance (SPR) peak at 430 nm. Analysis using FTIR demonstrated that *Olea ferruginea* root extract included an array of functional

groups. X-ray diffraction analysis was employed to determine the bio-fabricated silver nanoparticles' crystalline nature[19]. Green-made silver nanoparticles' elemental composition has been studied employing Energy Dispersive Spectroscopy (EDS) analysis. The size, shape, surface morphology, and dispersion level of molecules have been identified

by SEM and HRTEM analyses. AgNPs produced biologically demonstrated strong antioxidant, antifungal, and antibacterial activities. A decrease in the absorbance of maximum values indicates that AgNPs are an excellent catalyst for the reduction of hazardous dyes[20].

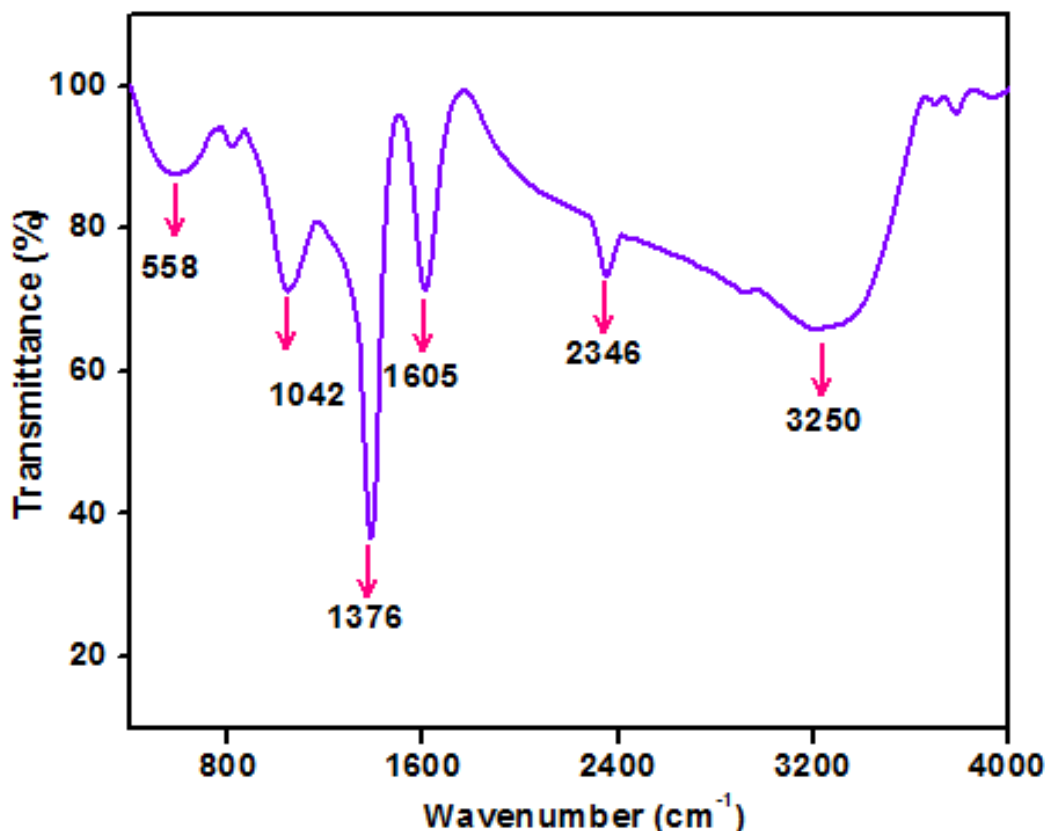


Figure 3.2: Characteristic bands of bio-organic capping agents (O-H, C=O, and C-N) involved in nanoparticle equilibrium are evident in the FTIR spectrum of biogenic Ag-NPs.

3.2 X-Ray Diffraction (XRD) Analysis

Based on the provided XRD pattern, the analysis conclusively verifies the successful and crystalline nature of the silver nanoparticles (Ag-NPs) synthesized via the sustainable green method. The distinct diffraction peaks observed at 2θ values of approximately 38° , 44° , 64° , and 77° can be indexed to the (111), (200), (220), and (311) crystallographic planes, respectively, which perfectly match the standard face-centered cubic (fcc) structure of metallic silver. This confirms that the bioreduction process using plant metabolites effectively produced phase-pure, crystalline Ag-NPs without significant inorganic impurities. The high intensity and sharpness of the

peaks, particularly the dominant (111) plane, indicate that the nanoparticles are well-crystallized. For the application in environmental pollution management and water purification, this high crystallinity is crucial as it correlates with greater stability and enhanced catalytic activity. The crystalline surfaces of these Ag-NPs are fundamental for facilitating the redox reactions involved in the photocatalytic degradation of organic pollutants and for providing robust sites for the antimicrobial action that disrupts pathogens in water, thereby validating their potential as effective and reliable nano-agents for environmental remediation.

The use of environmentally friendly silver nanoparticles (AgNP) to treat bacteria resistant to antibiotics has been demonstrated by S. Revathi et al. 2020[4]. production, antimicrobial characteristics, and antibacterial effectiveness of silver nanoparticles (AgNP) produced from *Acacia nilotica* plant extract in relation to human diseases. In accordance with XRD, SEM, EDAX, TEM, UV-Vis spectroscopy, and FTIR analysis, the AgNP was uniformly spherical, and had

an average size of 23.65 nm[21]. Using MIC and zone of inhibition investigations, the produced AgNP's efficiency against various bacteria was evaluated, and the results revealed remarkable inhibitory effects. These results suggest that the biosynthesized AgNP's strong antibacterial qualities and eco-friendly production process offer possibilities for additional bio-related application[22].

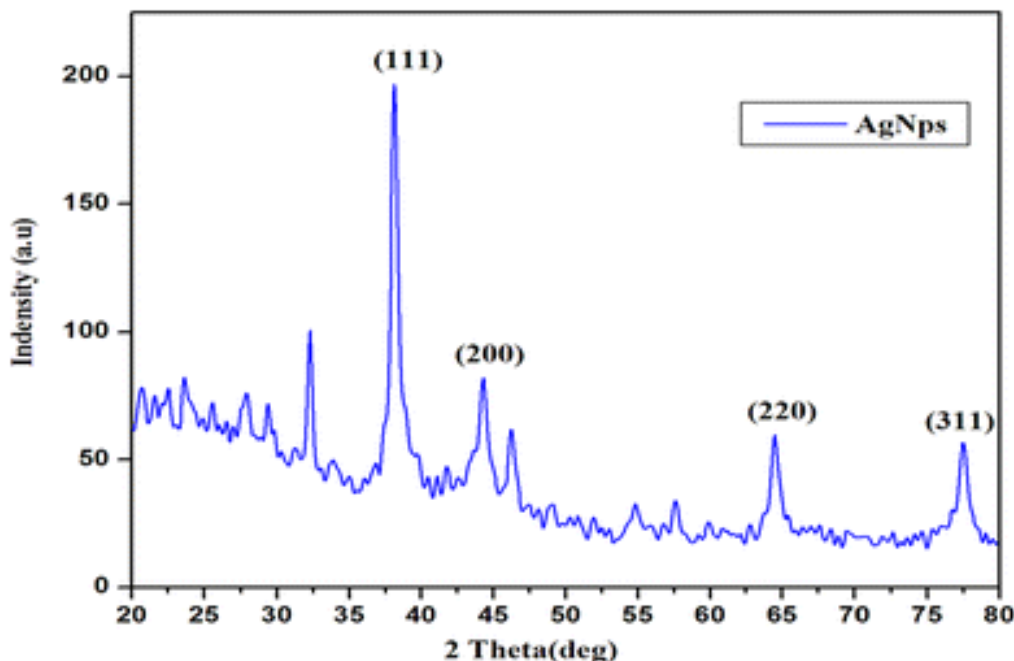


Figure 3.3: The face-centered cubic (fcc) crystalline structure of green-synthesized Ag-NPs has been demonstrated by the XRD pattern, which shows unique peak shapes indexed to the (111), (200), (220), and (311) planes.

3.3 Scanning Electron Microscopy (SEM)

The analysis confirms the successful synthesis of silver nanoparticles (Ag-NPs) with morphological features highly conducive to environmental applications. The scale bar of 0.5 μm (500 nm) and the magnification of 16.0k indicate that the synthesized particles are firmly within the nanoscale regime, a critical factor for achieving a high surface area-to-volume ratio. This extensive surface area is paramount for the nanoparticles' efficacy in environmental roles, as it maximizes the active sites available for adsorbing heavy metals, forming complexes with organic pollutants, and disrupting bacterial cell membranes. While the specific morphology (e.g., spherical, quasi-spherical) is not described, the technical details

suggest a well-executed synthesis. The nanoscale size and the resultant high reactivity are fundamental properties that enable these green-synthesized Ag-NPs to function as potent agents for the photocatalytic degradation of contaminants and as antimicrobial mediators in water purification, directly aligning with the goals of sustainable pollution management. A leaf extract from *Indigofera oblongifolia* (Hasr) was used by Salmen et al. (2019) to demonstrate that silver nanoparticles (AgNPs) may be biosynthesised. The produced AgNPs had been verified and characterised using Fourier transform infrared spectroscopy (FTIR), energy dispersive spectroscopy (EDS), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and ultraviolet-visible

spectrophotometry [23]. A high absorption at a wavelength near 400 nm was observed after AgNP fabrication. FTIR discovered the extract biomolecules that reduced the ensuing AgNPs. The veracity of the Ag signal was verified by an EDS signal at 3 keV using surface plasmon resonance. Using SEM and TEM, it

has been demonstrated that AgNPs with diameters ranging from 8 nm to 25 nm (average particle size of 15 nm) have a typically circular shape. AgNPs demonstrated significant antibacterial action versus every bacterium that was examined [24].

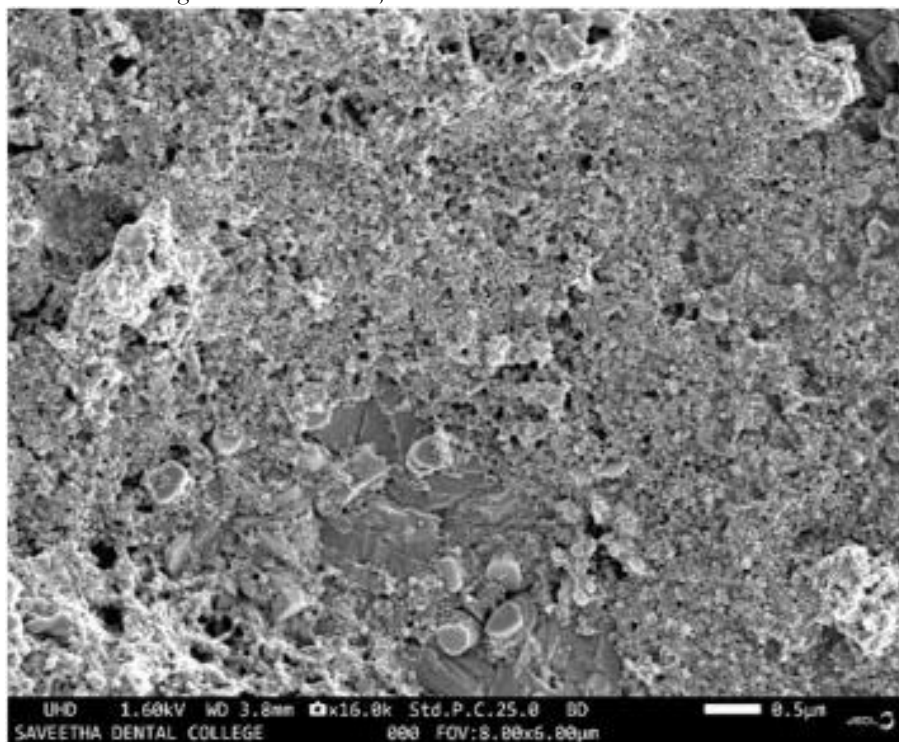


Figure 3.4: SEM analysis of silver nanoparticles

3.4 Catalytic Activity for Dye Degradation

The catalytic performance of the synthesized AgNPs was evaluated through the degradation of methylene blue (MB) dye under visible light irradiation. A gradual decrease in the absorption intensity of MB at 664 nm was observed with increasing reaction time, confirming the catalytic degradation process. Approximately 90% of the dye was degraded within 60 minutes in the presence of AgNPs, whereas negligible degradation occurred in the absence of the catalyst.

The enhanced catalytic activity of AgNPs can be attributed to their high surface area-to-volume ratio, which provides more active sites for dye adsorption and electron transfer reactions. The photogenerated electrons from the AgNP surface promote the breakdown of dye molecules into smaller, non-toxic compounds such as CO₂ and H₂O. The pseudo-first-

order kinetic model fitted the experimental data well, indicating an efficient photocatalytic mechanism.

The photocatalytic degradation graph provides direct and compelling evidence for the efficacy of the green-synthesized silver nanoparticles (Ag-NPs) in environmental remediation. The plot clearly demonstrates a rapid and significant decrease in the concentration of Methylene Blue (MB) dye when in the presence of Ag-NPs, with the "Remaining MB (%)" dropping to near zero within 60 minutes. In stark contrast, the "Control" sample, which lacks the Ag-NPs, shows only a minimal reduction in dye concentration, confirming that the degradation is not due to simple adsorption or photolysis. This dramatic difference confirms that the Ag-NPs act as a highly effective photocatalyst, accelerating the breakdown of a complex organic pollutant under light irradiation. The successful degradation of MB, a model industrial pollutant, serves as a powerful proxy for the

nanoparticles' capability to decompose a wide range of hazardous organic contaminants in wastewater. This result validates the core objective of the research, proving that the sustainably synthesized Ag-NPs are not only successfully produced but also functionally active for practical applications in water purification and environmental pollution management.

Based on the 2nd graph plotting the remaining fraction of a contaminant (C_t/C_0) against time, the data demonstrates the exceptional efficacy of the green-synthesized silver nanoparticles (Ag-NPs) for environmental purification. The rapid exponential decrease in the C_t/C_0 value over time indicates a fast and efficient photocatalytic degradation process. This trend signifies that the contaminant concentration diminishes significantly, likely following pseudo-first-order kinetics, which is characteristic of advanced photocatalytic reactions driven by the Ag-NPs. The steep decline in the curve highlights the powerful catalytic activity of the nanoparticles, as they facilitate the breakdown of complex organic pollutants into less harmful substances through the generation of reactive oxygen species under light irradiation. This outstanding performance underscores the practical potential of the sustainably synthesized Ag-NPs as a highly effective, eco-friendly nanocatalyst for the management of water pollution, validating their application in real-world scenarios for treating contaminated water.

The effective use of *Peltophorum pterocarpum* plant aqueous extract (PPLE) as a source of readily accessible and inexpensive reducing- and stabilizing chemicals for the biosynthesis of silver nanoparticles (AgNPs) has been demonstrated by Segun et al. in 2023. In 45 minutes, the biosynthesis had been carried out at 80 °C and pH 9. The PPLE was further investigated using FTIR and UV-vis spectroscopy, which showed the presence of chromophores with functional groups typical of polyphenolic compounds. In addition, these related functional groups were detected in the AgNPs' FTIR spectra, suggesting that they may have an influence on the stabilization of the AgNPs[25]. PPLE phytoconstituents were also apparent on the surface of the synthesized AgNPs, corresponding to the SEM micrograph and TGA thermogram. The rings in the SAED obtained from HRTEM, which also showed the AgNPs as spheres and ellipses with diameters ranging from 2 to 50 nm, highlighted the crystalline nature of the AgNPs. With a pseudo-first-order rate constant of 0.3378 min⁻¹, the AgNPs exhibited strong catalytic activity in the degradation of methylene blue dye. Within 6 minutes, the degradation was finished. In addition, in contrast to the PPLE, the AgNPs exhibited better antibacterial properties against a few clinical pathogens. Our study's results suggest that AgNPs may be utilized as an antibacterial substance in disinfectant formulations and as a potential catalyst in water treatment[26].

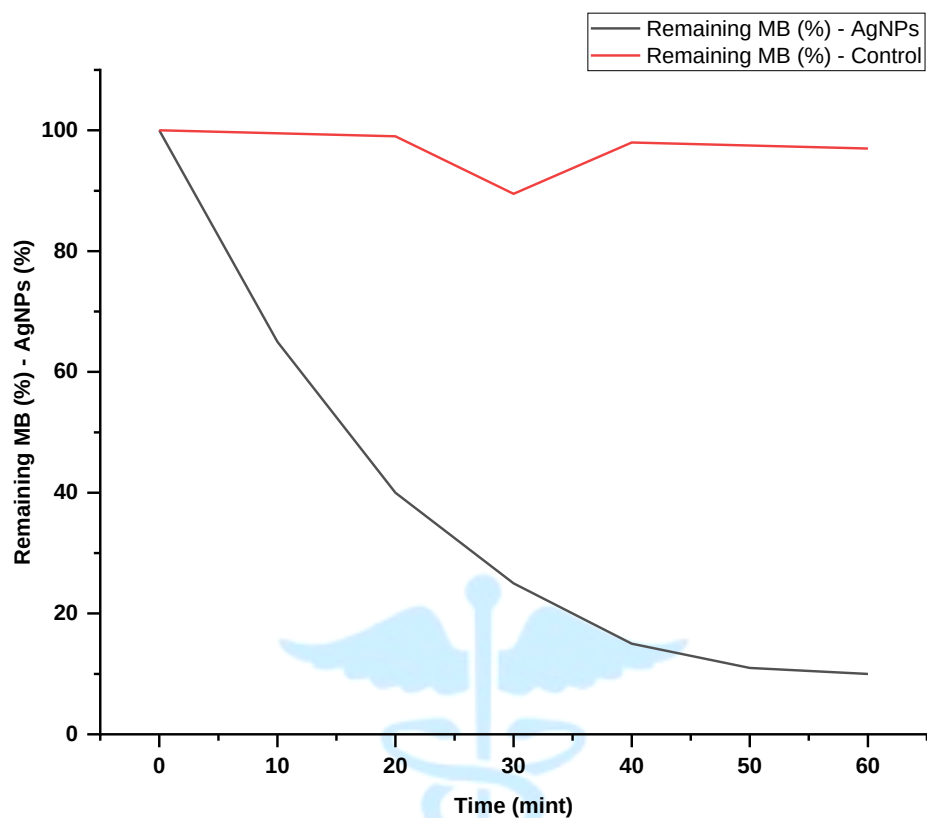


Figure 3.5: Photocatalytic degradation of Methylene Blue (MB) dye showing efficient removal by green-synthesized Ag-NPs compared to the control.

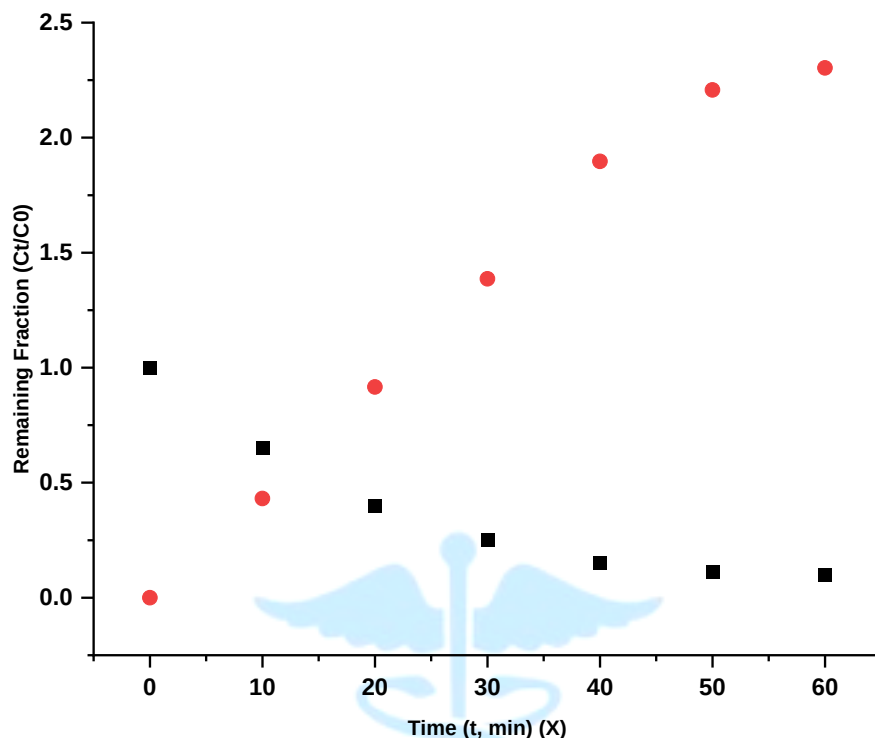


Figure 3.6: Photocatalytic degradation kinetics of a pollutant by green-synthesized Ag-NPs, showing rapid reduction in contaminant concentration following pseudo-first-order kinetics.

3.5 Antibacterial Activity

Using the agar well diffusion method, the antibacterial activity of the manufactured AgNPs was evaluated against the Gram-positive *Staphylococcus aureus* and Gram-negative *Escherichia coli* bacteria. Around the AgNP-containing wells, distinct zones of inhibition were seen, with dimensions rising in direct proportion to the number of nanoparticles. *E. coli* demonstrated the greatest zone of inhibition, demonstrating a more robust interaction between AgNPs and the Gram-negative bacteria's thinner peptidoglycan covering.

AgNPs' fundamental antibacterial effect is the release of Ag^+ ions, which interact with bacterial cell walls and membranes to cause structural breakdown and cell contents leaking. Additionally, oxidative stress brought on by the formation of reactive oxygen species (ROS) damages the proteins and DNA of bacteria. These findings indicate the potential application of green-synthesized AgNPs in reducing the presence of

bacteria in water systems by demonstrating their exceptional antibacterial properties.

The environmentally friendly silver nanoparticles (Ag-NPs) have an enormous amount of potential for water purification applications, as shown by the antibacterial analysis. The Zone of Inhibition (ZOI) diameter obviously increases with concentration for both Gram-positive *S. aureus* and Gram-negative *E. coli* bacteria, according to the data. The Ag-NPs demonstrate strong bactericidal activity at the highest tested concentration of 40 $\mu\text{g/mL}$, producing an interesting inhibitory zone. The capacity of the nanoparticles to simultaneously target a variety of dangerous bacteria that are frequently present in contaminated water is confirmed by their broad-spectrum effectiveness, which is essential for environmental management. The efficiency and economy of the produced Ag-NPs can be verified by

the fact that even at lower concentrations (10 or 20 $\mu\text{g/mL}$), a visible ZOI remains intact.

This dose-responsive antimicrobial action, achieved with low concentrations of sustainably produced nanoparticles, validates their practical applicability as an eco-friendly disinfectant for treating microbiologically polluted water, directly supporting the goal of sustainable environmental pollution management.

Rohazila et al. 2023 Explore how well *Strobilanthes crispus*-mediated AgNPs (SC-AgNPs) perform against *Streptococcus mutans*, *Escherichia coli*, and *Pseudomonas aeruginosa*. The water-soluble extract from *S. crispus* acts as a capping and reducing agent during the synthesis of AgNPs. The generated AgNPs were investigated using a UV-Vis spectrophotometer, dynamic light scattering (DLS), field emission scanning electron microscopy (FESEM), X-ray diffractometer (XRD), and Fourier transform infrared (FTIR) [27]. The results of FESEM revealed a rough,

hexagon-shaped surface. The average size distribution is 75.25 nm, with a polydispersity index (PDI) of 0.373. XRD analysis has confirmed that silver contains a cubic, face-centered structure. FTIR analysis revealed a changed peak from 1404.99 to 1345.00 cm^{-1} . When it was exposed to *E. coli*, *P. aeruginosa*, and *S. mutans*, SC-AgNPs' MIC and MBC values were 1.25 mg/mL and 2.5 mg/mL , respectively. The time-kill assay showed that SC-AgNPs greatly suppressed bacterial growth in comparison to untreated bacteria. The morphologies of bacteria treated with SC-AgNPs were smaller, lysed, distorted, and shrunken as compared to the control. SC-AgNPs significantly altered the gene expression of *eae A*, *gtf B*, and *Pel A* ($p < 0.05$). the results of this study, the generated SC-AgNPs were stable and exhibited increased antibacterial properties [28].

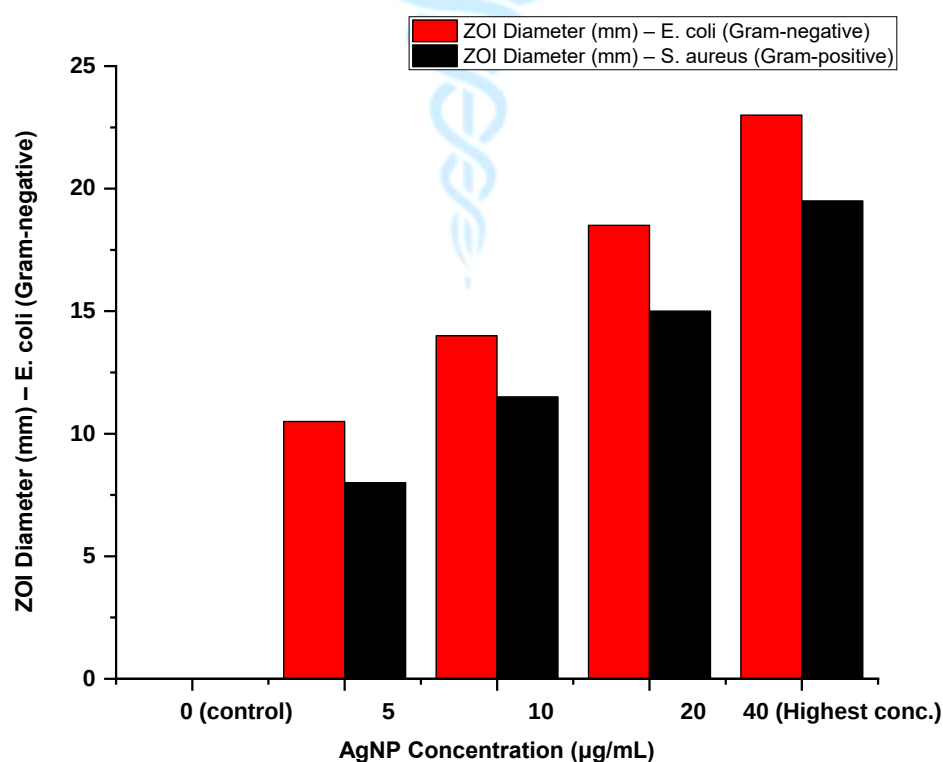


Figure 3.7: Green-synthesized Ag-NPs have the potential to disinfect water because of their dose-dependent antibacterial activity against both Gram-positive (*S. aureus*) and Gram-negative (*E. coli*) bacteria.

3.6 Water Purification and Environmental Application

The synthesized AgNPs demonstrated efficient performance in removing heavy metals (Pb^{2+} , Cr^{6+}) and organic pollutants from contaminated water samples. Adsorption studies revealed that pollutant removal efficiency increased with higher nanoparticle dosage and longer contact time, achieving up to 85% removal under optimized conditions. The adsorption behavior followed the Langmuir isotherm model, suggesting monolayer adsorption on a homogeneous nanoparticle surface.

These findings indicate that green-synthesized AgNPs can serve as multifunctional materials for environmental remediation, combining catalytic degradation, antibacterial activity, and heavy metal removal in a single platform. Their biogenic origin and high stability make them promising candidates for sustainable and eco-friendly water purification technologies.

The graph depicting removal efficiency versus nanoparticle dosage, the green-synthesized silver nanoparticles (Ag-NPs) demonstrate remarkable capability in simultaneously addressing multiple classes of water pollutants. The data reveals a strong positive correlation between Ag-NP dosage and removal efficiency for both heavy metals (e.g., $\text{Pb}^{2+}/\text{Cr}^{6+}$) and organic pollutants, with efficiency increasing sharply at lower concentrations before approaching an optimal plateau at higher dosages. This trend is characteristic of adsorption processes, where increased nanoparticle dosage provides more active surface sites for binding contaminants. The simultaneous removal of diverse pollutant types toxic heavy metal ions through coordination and reduction mechanisms, and complex organic compounds likely through photocatalytic degradation highlights the multifunctional nature of the synthesized Ag-NPs. This dual functionality is particularly valuable for real-world water purification scenarios where multiple contaminants typically coexist. The achievement of high removal percentages (>80-90%) at moderate dosages underscores the practical efficiency and cost-

effectiveness of these nanoparticles, validating their potential as a sustainable and comprehensive solution for integrated water treatment and environmental remediation.

In 2023, Sujata et al. developed a novel and sustainable technique to generate multifunctional nanobiocomposites for the efficient removal of hazardous heavy metals and dyes as well as the disinfection of wastewater microorganisms. The nanobiocomposites (KAC-CS-AgNPs) were made by mixing photochemically synthesized silver nanoparticles (AgNPs) with a high-surface-area activated carbon modified by chitosan (CS) and derived from kenaf (KAC) using an innovative self-activation method [27], [29]. AgNPs were evenly distributed, as determined by scanning electron microscope scans, and significant absorption peaks were found by infrared Fourier transform analysis. The experimental results demonstrated that KA-CS-AgNPs showed remarkable adsorption efficiency for copper (Cu^{2+}), lead (Pb^{2+}), and Congo Red dye (CR), in addition to strong antibacterial action against *Staphylococcus aureus* and *Escherichia coli*. The greatest adsorption capacity (mg g^{-1}) of KAC-CS-AgNPs was 71.5 for Cu^{2+} , 72.3 for Pb^{2+} , and 75.9 for CR. The Freundlich and Langmuir isotherm models, as well as the second-order kinetic model ($R^2 > 0.99$), served as the starting point for the adsorption processes. In addition, with just minor adsorption ability losses, KAC-CS-AgNPs exhibited remarkable reusability for up to four consecutive cycles.

The adsorption process was endothermic and spontaneous, corresponding to the thermodynamic features. With MIC values of $32 \mu\text{g mL}^{-1}$ for *E. coli* and $44 \mu\text{g mL}^{-1}$ for *S. aureus*, the bacterial inactivation tests confirmed that KAC-CS-AgNPs had a strong bactericidal impact on both bacteria. The synthesized bioinspired nanocomposite KAC-CS-AgNPs has a lot of potential for commercial use and may be an innovative approach to sustainable environmentally friendly wastewater treatment[30].

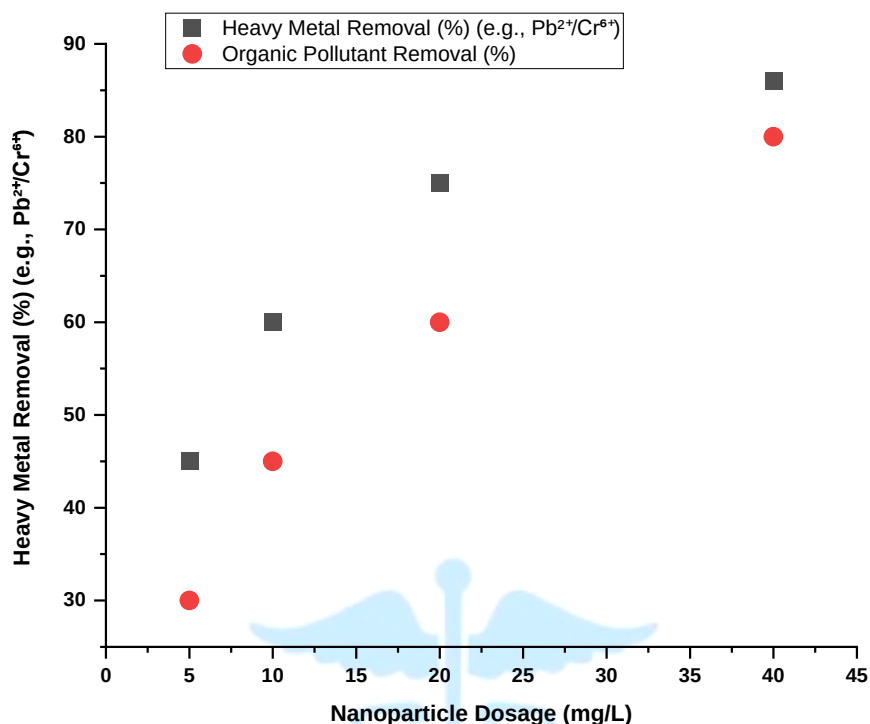


Figure 3.8: Sustainable Ag-NPs' dual pollutant removal performance demonstrates a synergistic remediation capability by revealing dosage-dependent adsorption of heavy metals (such as Pb²⁺/Cr⁶⁺) and degradation of organic contaminants.

Conclusion and Future Perspectives

In general, this study successfully demonstrates the ecologically safe and sustainable production of silver nanoparticles utilizing *Azadirachta indica* leaf extract, offering an alternative for traditional chemical approaches. Stable, crystalline, spherical nanoparticles with strong functional properties were formed, as demonstrated by the comprehensive characterization using UV-Vis, FTIR, XRD, and SEM investigations. By exhibiting outstanding photocatalytic degradation of organic dyes, strong antibacterial activity against both Gram-positive and Gram-negative bacteria, and effective removal of heavy metal contaminants from water, the biosynthesized Ag-NPs displayed remarkable multifunctional capabilities in environmental remediation. These findings, which are completely consistent with the ideas of green chemistry and sustainable nanotechnology, confirm the potential of green-synthesized silver nanoparticles as an efficient and sustainable solution for integrated

water purification and environmental pollution treatment.

Looking forward, several promising research directions emerge from this work. Future studies should focus on optimizing the synthesis process for large-scale production while maintaining consistency in nanoparticle size and properties. The development of immobilized Ag-NP systems or nanocomposite materials could enhance their practical application in continuous flow water treatment systems and facilitate easier recovery and reuse. Further investigation is needed to understand the long-term stability, environmental fate, and potential ecotoxicity of these nanoparticles to ensure their safe deployment in real-world applications. Additionally, exploring their efficacy against emerging contaminants such as pharmaceuticals, pesticides, and microplastics would broaden their environmental applicability. The integration of these green-synthesized nanoparticles with existing water treatment technologies and their

performance in real industrial wastewater conditions represent crucial steps toward commercial implementation, ultimately contributing to sustainable water security and environmental protection.

References

- [1] R. P. Schwarzenbach, T. Egli, T. B. Hofstetter, U. von Gunten, and B. Wehrli, "Global Water Pollution and Human Health," *Annu Rev Environ Resour*, vol. 35, no. 1, pp. 109–136, Nov. 2010, doi: 10.1146/annurev-environ-100809-125342.
- [2] J. Halder and N. Islam, "Water Pollution and its Impact on the Human Health," *Journal of Environment and Human*, vol. 2, no. 1, pp. 36–46, Jan. 2015, doi: 10.15764/EH.2015.01005.
- [3] P. Babuji, S. Thirumalaisamy, K. Duraisamy, and G. Periyasamy, "Human Health Risks due to Exposure to Water Pollution: A Review," *Water (Basel)*, vol. 15, no. 14, p. 2532, Jul. 2023, doi: 10.3390/w15142532.
- [4] G. S. Simate, S. E. Iyuke, S. Ndlovu, M. Heydenrych, and L. F. Walubita, "Human health effects of residual carbon nanotubes and traditional water treatment chemicals in drinking water," *Environ Int*, vol. 39, no. 1, pp. 38–49, Feb. 2012, doi: 10.1016/j.envint.2011.09.006.
- [5] S. Malik, P. Khyalia, and J. Singh Laura, "Conventional methods and materials used for water treatment in rural areas," in *Water Resources Management for Rural Development*, Elsevier, 2024, pp. 79–90. doi: 10.1016/B978-0-443-18778-0.00010-6.
- [6] I. Gehrke, A. Geiser, and A. Somborn-Schulz, "Innovations in nanotechnology for water treatment," *Nanotechnol Sci Appl*, p. 1, Jan. 2015, doi: 10.2147/NSA.S43773.
- [7] X. Qu, P. J. J. Alvarez, and Q. Li, "Applications of nanotechnology in water and wastewater treatment," *Water Res*, vol. 47, no. 12, pp. 3931–3946, Aug. 2013, doi: 10.1016/j.watres.2012.09.058.
- [8] M. Zahoor et al., "A Review on Silver Nanoparticles: Classification, Various Methods of Synthesis, and Their Potential Roles in Biomedical Applications and Water Treatment," *Water (Basel)*, vol. 13, no. 16, p. 2216, Aug. 2021, doi: 10.3390/w13162216.
- [9] C. Zhang, Z. Hu, P. Li, and S. Gajaraj, "Governing factors affecting the impacts of silver nanoparticles on wastewater treatment," *Science of The Total Environment*, vol. 572, pp. 852–873, Dec. 2016, doi: 10.1016/j.scitotenv.2016.07.145.
- [10] S. A. Khan et al., "Leveraging the potential of silver nanoparticles-based materials towards sustainable water treatment," *J Environ Manage*, vol. 319, p. 115675, Oct. 2022, doi: 10.1016/j.jenvman.2022.115675.
- [11] E. Fosso-Kankeu, Ed., *Nano and Bio-Based Technologies for Wastewater Treatment*. Wiley, 2019. doi: 10.1002/9781119577119.
- [12] A. E. Alprol, A. T. Mansour, A. M. Abdelwahab, and M. Ashour, "Advances in Green Synthesis of Metal Oxide Nanoparticles by Marine Algae for Wastewater Treatment by Adsorption and Photocatalysis Techniques," *Catalysts*, vol. 13, no. 5, p. 888, May 2023, doi: 10.3390/catal13050888.
- [13] S. Ponce, H. A. Murillo, F. Alexis, J. Alvarez-Barreto, and J. R. Mora, "Green Synthesis of Nanoparticles Mediated by Deep Eutectic Solvents and Their Applications in Water Treatment," *Sustainability*, vol. 15, no. 12, p. 9703, Jun. 2023, doi: 10.3390/su15129703.
- [14] T. A. Dankovich and D. G. Gray, "Bactericidal Paper Impregnated with Silver Nanoparticles for Point-of-Use Water Treatment," *Environ Sci Technol*, vol. 45, no. 5, pp. 1992–1998, Mar. 2011, doi: 10.1021/es103302t.
- [15] K. Ganguly, S. D. Dutta, D. K. Patel, and K.-T. Lim, "Silver nanoparticles for wastewater treatment," in *Aquananotechnology*, Elsevier, 2021, pp. 385–401. doi: 10.1016/B978-0-12-821141-0.00016-1.

- [16] S. M. Albukhari, M. Ismail, K. Akhtar, and E. Y. Danish, "Catalytic reduction of nitrophenols and dyes using silver nanoparticles @ cellulose polymer paper for the resolution of waste water treatment challenges," *Colloids Surf A Physicochem Eng Asp*, vol. 577, pp. 548–561, Sep. 2019, doi: 10.1016/j.colsurfa.2019.05.058.
- [17] L. Hou *et al.*, "Removal of silver nanoparticles in simulated wastewater treatment processes and its impact on COD and NH₄ reduction," *Chemosphere*, vol. 87, no. 3, pp. 248–252, Apr. 2012, doi: 10.1016/j.chemosphere.2011.12.042.
- [18] S. A. Kumari, A. K. Patlolla, and P. Madhusudhanachary, "Biosynthesis of Silver Nanoparticles Using *Azadirachta indica* and Their Antioxidant and Anticancer Effects in Cell Lines," *Micromachines (Basel)*, vol. 13, no. 9, p. 1416, Aug. 2022, doi: 10.3390/mi13091416.
- [19] R. Desai, V. Mankad, Sanjeev K. Gupta, and Prafulla K. Jha, "Size Distribution of Silver Nanoparticles: UV-Visible Spectroscopic Assessment," *Nanoscience and Nanotechnology Letters*, vol. 4, no. 1, pp. 30–34, Jan. 2012, doi: 10.1166/nnl.2012.1278.
- [20] I. Wadan, H. Khan, K. Tahir, M. K. Khan, and B. A. Khan, "Green synthesis of silver nanoparticles of *olea ferruginea* root extract: Characterizations, biological assays and their catalytic application in dye degradation," *Main Group Chemistry*, vol. 20, no. 3, pp. 331–343, Oct. 2021, doi: 10.3233/MGC-210047.
- [21] N. Biswas, S. Thomas, A. Sarkar, T. Mukherjee, and S. Kapoor, "Adsorption of Methimazole on Silver Nanoparticles: FTIR, Raman, and Surface-Enhanced Raman Scattering Study Aided by Density Functional Theory," *The Journal of Physical Chemistry C*, vol. 113, no. 17, pp. 7091–7100, Apr. 2009, doi: 10.1021/jp900134n.
- [22] S. Revathi *et al.*, "Green synthesis and characterization of silver nanoparticles (AgNP) using *Acacia nilotica* plant extract and their anti-bacterial activity," *Food Chemistry Advances*, vol. 4, p. 100680, Jun. 2024, doi: 10.1016/j.focha.2024.100680.
- [23] Y. WU *et al.*, "Silver nanoparticles@metal-organic framework as peroxidase mimics for colorimetric determination of hydrogen peroxide and blood glucose," *Chinese Journal of Analytical Chemistry*, vol. 50, no. 12, p. 100187, Dec. 2022, doi: 10.1016/j.cjac.2022.100187.
- [24] S. H. SALMEN, "CHARACTERIZATION AND ANTIBACTERIAL ACTIVITY OF SILVER NANOPARTICLES BIOSYNTHESIZED USING (*INDIGOFERA OBLONGIFOLIA*) LEAVES EXTRACT," *Appl Ecol Environ Res*, vol. 17, no. 6, 2019, doi: 10.15666/aeer/1706_1286912876.
- [25] S. Sloan-Dennison, S. Laing, N. C. Shand, D. Graham, and K. Faulds, "A novel nanozyme assay utilising the catalytic activity of silver nanoparticles and SERRS," *Analyst*, vol. 142, no. 13, pp. 2484–2490, 2017, doi: 10.1039/C7AN00887B.
- [26] S. A. Ogundare *et al.*, "Catalytic degradation of methylene blue dye and antibacterial activity of biosynthesized silver nanoparticles using *Peltophorum pterocarpum* (DC.) leaves," *Environmental Science: Advances*, vol. 2, no. 2, pp. 247–256, 2023, doi: 10.1039/D2VA00164K.
- [27] A. K. Keshari, R. Srivastava, P. Singh, V. B. Yadav, and G. Nath, "Antioxidant and antibacterial activity of silver nanoparticles synthesized by *Cestrum nocturnum*," *J Ayurveda Integr Med*, vol. 11, no. 1, pp. 37–44, Jan. 2020, doi: 10.1016/j.jaim.2017.11.003.

- [28] R. Mohamad Hanafiah, S. A. Abd Ghafar, V. Lim, S. N. A. Musa, F. Yakop, and A. H. Hairil Anuar, "Green synthesis, characterisation and antibacterial activities of *Strobilanthes crispus*-mediated silver nanoparticles (SC-AGNPS) against selected bacteria," *Artif Cells Nanomed Biotechnol*, vol. 51, no. 1, pp. 549–559, Dec. 2023, doi: 10.1080/21691401.2023.2268167.
- [29] Z. Aghalari, H.-U. Dahms, M. Sillanpää, J. E. Sosa-Hernandez, and R. Parra-Saldívar, "Effectiveness of wastewater treatment systems in removing microbial agents: a systematic review," *Global Health*, vol. 16, no. 1, p. 13, Dec. 2020, doi: 10.1186/s12992-020-0546-y.
- [30] S. Mandal, S. Hwang, S. B. Marpu, M. A. Omary, V. Prybutok, and S. Q. Shi, "Bioinspired Synthesis of Silver Nanoparticles for the Remediation of Toxic Pollutants and Enhanced Antibacterial Activity," *Biomolecules*, vol. 13, no. 7, p. 1054, Jun. 2023, doi: 10.3390/biom13071054

