

# A Comprehensive Review on Green Synthesized Silver Nanoparticles: Characterization, Applications, And Future Prospects

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**Abstract**—The green synthesis of silver nanoparticles (AgNPs) has emerged as a sustainable and ecofriendly alternative to traditional physical and chemical methods, offering advantages such as low toxicity, cost-effectiveness, and enhanced biocompatibility. Plant-mediated synthesis utilizes phytochemicals including flavonoids, phenolics, alkaloids, terpenoids, and proteins which act as natural reducing and stabilizing agents, enabling the controlled formation of stable, uniform nanoparticles. Characterization techniques such as UV–Vis spectroscopy, FTIR, XRD, SEM, and TEM confirm the successful synthesis, crystalline structure, and morphological stability of green-synthesized AgNPs. These nanoparticles exhibit remarkable antimicrobial, antifungal, antiviral, anti-inflammatory, antioxidant, and anticancer activities due to their unique physicochemical properties and high surface reactivity. Their broad potential applications span pharmaceuticals, wound healing, diagnostics, environmental remediation, biosensing, and industrial coatings. Despite their promise, challenges remain in achieving reproducibility, optimizing synthesis parameters, ensuring large-scale production, and evaluating long-term biosafety. Overall, green synthesis represents a promising pathway for developing safe, effective, and sustainable nanomaterials with significant biomedical and technological relevance.

**Index Terms**— Green synthesis, silver nanoparticles, plant extracts, phytochemicals, nanotechnology, characterization, antimicrobial activity, antioxidant activity, Biomedical applications, ecofriendly synthesis, and sustainable nanotechnology.

## I. INTRODUCTION

Rapid industrialization and urbanization have led to severe environmental degradation and the release of hazardous chemicals, prompting advancements in the

synthesis of nanoparticles through nature-inspired and eco-friendly approaches. Biological molecules possess unique characteristics that make them suitable for nanotechnology applications, as they can be precisely organized for metal nanoparticle synthesis in a reliable and environmentally sustainable manner. Metal and semiconductor nanoparticle production has emerged as a key area of research due to its potential in developing new technologies, while nanotechnology itself is rapidly expanding within material science because nanoparticles exhibit novel properties related to size, distribution, and shape. However, traditional chemical synthesis methods are often expensive and involve toxic substances that pose biological risks. Consequently, green synthesis and biological approaches—especially those utilizing plant extracts—are gaining importance for developing safer and more sustainable technologies. Compared to complex microbial methods involving fungi like *Fusarium oxysporum* and *Penicillium* species or bacteria such as *Bacillus subtilis*, plant extract-based nanoparticle synthesis offers a simpler, cost-effective, and eco-friendly alternative [1]. Plant-based synthesis of silver nanoparticles has gained significant attention due to its simplicity, safety, and sustainability. Plants are widely available, easy to handle, and rich in metabolites that aid in the reduction and stabilization of nanoparticles. Various medicinal plants, such as *Aloe vera*, *Azadirachta indica* (Neem), *Camellia sinensis* (green tea), and *Polyalthia longifolia*, have been successfully used to produce silver nanoparticles for pharmaceutical and biological applications [1]. Studies have also explored the green synthesis of

silver nanoparticles using methanolic extracts of *Eucalyptus hybrida* and other natural sources like green tea, neem, leguminous shrubs (*Sesbania drummondii*), natural rubber, starch, and lemongrass leaf extracts. These biologically synthesized nanoparticles exhibit strong antibacterial properties, primarily by binding to microbial cell walls and disrupting cell permeability and respiration. They can also interact with phosphorus- and sulfur-containing biomolecules such as DNA and proteins, leading to cell damage. The antibacterial efficacy of silver nanoparticles is largely size-dependent, with smaller nanoparticles demonstrating greater activity due to their larger surface area [2]. Moreover, microorganisms like diatoms, fungi, bacteria, and yeast can also synthesize biocompatible inorganic nanoparticles, making them valuable for various therapeutic applications [3].

## II. CATEGORIES OF NANOPARTICLES

Nanoparticles are broadly categorized into two main types: organic nanoparticles, which include carbon-based structures such as fullerenes, and inorganic nanoparticles, which comprise magnetic, noble metal (gold and silver), and semiconductor types like titanium oxide and zinc oxide. Inorganic nanoparticles, particularly noble metal nanoparticles, have attracted increasing scientific interest owing to their distinctive material characteristics, exceptional stability, and multifunctional capabilities. Their nanoscale dimensions and superior characteristics compared to conventional chemical imaging agents and drugs make them promising candidates for medical imaging, diagnostics, and therapeutic applications. Inorganic nanomaterials are particularly valuable in cellular delivery systems owing to their wide availability, tunable surface chemistry, excellent biocompatibility, and ability to facilitate targeted drug delivery and controlled release, thereby enhancing treatment efficacy while minimizing side effects [4].

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## III. METHODS FOR NANOPARTICLE SYNTHESIS

Traditionally, nanoparticles have been synthesized through physical and chemical methods such as ion

sputtering, solvothermal synthesis, reduction, and the sol-gel technique. These techniques are generally classified into two main approaches: top-down and bottom-up. The top-down method breaks down bigger materials into nanoscale particles, while the bottom-up method builds nanoparticles one atom or molecule at a time using chemical or biological processes [5]. Among these, green synthesis—a type of bottom-up method—has gained prominence for its environmentally friendly nature, as it utilizes plant biomolecules or microbial enzymes to reduce metal ions and control nanoparticle nucleation and growth. This eco-friendly strategy provides superior control over particle size, shape, and uniformity while eliminating the use of toxic chemicals, making it a sustainable and biocompatible alternative to conventional synthesis methods [5].

## IV. PRINCIPLE OF GREEN SYNTHESIS

Over the past 15 years, the concept of green chemistry within the framework of sustainable development has gained global significance, emphasizing progress that meets present needs without jeopardizing the ability of future generations to meet theirs [6]. This approach is especially vital for chemistry-dependent industries, as it addresses major concerns related to environmental pollution and the excessive consumption of natural resources. Traditionally, chemistry has been perceived as a hazardous discipline due to the risks and toxicity associated with chemical processes. Although safety equipment can help mitigate some dangers, inadequate safety measures can lead to serious consequences, including injuries or fatalities. Therefore, minimizing inherent hazards and designing safer chemical processes are fundamental goals of sustainable chemical practices [7]. In this context, green synthesis has emerged as a promising strategy aimed at developing eco-friendly, non-toxic, and sustainable methods for nanoparticle production, promoting both environmental protection and industrial safety.

### ➤ Reduction of Metal Ions

The formation of silver nanoparticles (AgNPs) begins with the reduction of silver ions ( $\text{Ag}^+$ ) into elemental silver ( $\text{Ag}^0$ ), a key step in nanoparticle synthesis. In green synthesis, this transformation is facilitated by naturally occurring biomolecules such as phenols, flavonoids, alkaloids, terpenoids, and sugars derived

from plants, as well as by microbial enzymes and proteins. These biological compounds serve as natural reducing and stabilizing agents, initiating and controlling nanoparticle formation without the need for hazardous chemicals like sodium borohydride or hydrazine, which are commonly used in traditional chemical synthesis [7]. This eco-friendly approach not only minimizes toxicity and environmental impact but also enhances the biocompatibility of the resulting silver nanoparticles, making green synthesis a safer and more sustainable alternative.

#### ➤ Stabilization and Capping

After nanoparticles are synthesized, they naturally tend to aggregate because of their high surface energy and strong intermolecular attractions. To prevent this, various biomolecules such as proteins, polysaccharides, and secondary metabolites bind to the nanoparticle surface, forming a protective layer. This process, known as capping, plays a crucial role in stabilizing the nanoparticles, preventing agglomeration, and maintaining their colloidal stability [7-8]. Additionally, these biomolecular capping agents help regulate the nanoparticles' morphology, size distribution, and surface properties, thereby enhancing their functionality and suitability for various biological and industrial applications.

#### ➤ Use of Eco-Friendly Solvents

Green synthesis generally utilizes water or other non-toxic solvents as the reaction medium, thereby avoiding the use of hazardous organic solvents commonly employed in conventional chemical synthesis. This approach not only minimizes environmental pollution but also ensures a safer and more sustainable process. By relying on ecofriendly solvents, green synthesis reduces chemical waste, lowers energy consumption, and enhances the biocompatibility of the resulting nanoparticles [9]. Overall, this method aligns with the principles of green chemistry by promoting environmental safety, economic efficiency, and sustainable technological advancement.

#### ➤ Energy Efficiency

Unlike traditional physical and chemical synthesis methods that often demand high temperatures, elevated pressures, or radiation, green synthesis of nanoparticles is typically conducted under mild and

environmentally friendly conditions such as ambient temperature, atmospheric pressure, and near-neutral pH. These gentle reaction conditions significantly reduce energy consumption and minimize the formation of hazardous by-products [10]. As a result, green synthesis not only offers a cost-effective and sustainable alternative but also enhances safety and scalability for large-scale production, aligning with the broader goals of sustainable and eco-conscious nanotechnology.

#### ➤ Bottom-Up Approach

The mechanism of green synthesis operates through a bottom-up approach, in which nanoparticles are gradually formed starting from individual atoms that combine into molecules, then clusters, and ultimately develop into well-defined nanoscale structures. This controlled nucleation and growth process allows for precise regulation of particle formation, resulting in nanoparticles with uniform size, shape, and morphology. The use of biological reducing and stabilizing agents in this method further enhances control over structural characteristics while ensuring an eco-friendly and sustainable synthesis route [10].

### V.NEED FOR GREEN SYNTHESIS

The biosynthesis of nanoparticles is a bottom-up approach that primarily relies on reduction and oxidation reactions to form nanoscale structures. This method has gained increasing attention as a cost-effective and sustainable alternative to traditional physical and chemical synthesis, which often involves high operational costs and the use of toxic reagents that may remain adsorbed on nanoparticle surfaces, limiting their biomedical applications. In green synthesis, microbial enzymes and plant-derived phytochemicals with natural antioxidant or reducing properties facilitate the conversion of metal ions into stable nanoparticles without the use of harmful chemicals [10]. This eco-friendly method offers multiple advantages, including low cost, environmental safety, scalability for industrial production, and the elimination of the need for extreme conditions such as high pressure, temperature, or energy input, making it a highly promising approach for sustainable nanotechnology development.

### VI.ADVANTAGES OF GREEN SYNTHESIS OF NANOPARTICLES

Biological synthesis has led to the advancement of “green” nanoparticle synthesis methods, which are highly valued for their simplicity, cost-effectiveness, and environmental friendliness. Unlike conventional chemical approaches that rely on hazardous reducing and stabilizing agents, green synthesis provides better control over nanoparticle shape and size while utilizing biological materials such as plant extracts, fungi, bacteria, and enzymes that serve dual roles as reducing and capping agents [10]. This natural stabilization enhances nanoparticle biocompatibility, making them ideal for pharmaceutical and biomedical applications [11]. Among these biological routes, plant-based synthesis is particularly advantageous due to the abundance and diversity of phytochemicals like flavonoids, terpenoids, alkaloids, phenolic acids, and proteins, which influence particle size, surface charge, and stability while imparting antimicrobial, antifungal, and antioxidant properties. Additionally, reaction parameters such as pH, temperature, concentration, duration, and light exposure can be optimized to yield uniform, monodisperse nanoparticles with tailored characteristics. Green-synthesized nanoparticles are inherently biocompatible and find applications in the medicine, cosmetics, and food industries, with silver nanoparticles being especially notable for their exceptional antimicrobial, electrical, and thermal properties useful in wound healing, biosensing, and drug delivery [11]. Overall, green synthesis represents a scalable, energy-efficient, and eco-friendly alternative to traditional methods, aligning seamlessly with the principles of green chemistry and sustainable development.

### VII.FACTORS THAT AFFECT GREEN SYNTHESIS PROCESS

Table 1: Factors that affect green synthesis processes.

Factor	Description	Impact on NPs Synthesis
pH	How alkaline or acidic the reaction medium is	pH affects the nucleation and growth processes of NPs by altering the charge on their surfaces. Higher pH frequently produces smaller particles, yet lower pH

		might lead to aggregation.
Temperature	Temperature throughout the synthesis process.	Greater heat can produce aggregation; lower temperatures increase nucleation and reduction rates, resulting in fewer and more homogeneous NPs.
Concentration	The amount of reducing agent and metal precursor	Reducing agent amount influences stability and reduction rate; higher precursor levels boost nucleation sites, yielding reduced atoms, but can also encourage accumulation.
Time	Time intervals of the reaction process	Impacts the formation and maturity of NPs. Longer periods may result in larger, more defined shapes, but they can also lead to aggregation and polydispersity.
Light intensity	A critical component that greatly influences the synthesis of SNPs	UV radiation emits energy that increases the reduction of silver ions, hence its role is very significant.

### VIII.PROPERTIES OF SILVER

Silver (Ag) is a rare but naturally occurring element renowned for its outstanding electrical, thermal, and optical properties. Slightly harder than gold yet highly ductile and malleable, silver exhibits the highest electrical and thermal conductivity among all metals. It commonly exists in the oxidation states  $Ag^0$  and  $Ag^+$ , which are the most stable and predominant in aqueous systems. Although metallic silver is insoluble in water, its salts such as silver nitrate ( $AgNO_3$ ) and silver chloride ( $AgCl$ ) are water-soluble and extensively used in medical and industrial applications. Due to their potent antimicrobial activity, silver compounds have long been employed in wound dressings, dental materials, surgical implants, and various antimicrobial formulations [11]. Historically, silver and its derivatives were used to treat infections such as syphilis, gonorrhoea, and skin ailments. In recent years, silver nanoparticles (AgNPs) have

emerged as a focus of biomedical research because of their enhanced antimicrobial, anti-inflammatory, and antiviral properties, largely attributed to their high surface area and controlled ion release [11]. These exceptional physicochemical and biological characteristics position silver as an ideal material for the development of advanced biomedical products, including coatings, sensors, drug delivery systems, and Nano therapeutics [12].

### IX. GREEN SYNTHESIS OF SILVER NANOPARTICLES (SNPs)

The green synthesis of silver nanoparticles (AgNPs) relies on three essential components: a non-toxic stabilizing agent, an effective reducing agent, and an environmentally friendly solvent. Unlike conventional physical and chemical methods that often use expensive reagents and toxic reducing agents, leading to hazardous by-products, green synthesis offers a safer and more sustainable approach. Biological synthesis, in particular, utilizes microorganisms such as bacteria, fungi, algae, and plants to produce AgNPs in an eco-friendly manner [13]. Among these, plant-mediated synthesis has gained the most attention due to the abundance of phytochemicals—such as flavonoids, terpenoids, alkaloids, phenolic compounds, and proteins—that serve both as reducing and capping agents, facilitating nanoparticle formation and stabilization. Moreover, various plant parts, including leaves, stems, roots, fruits, and seeds, have been effectively employed to synthesize AgNPs with controlled size, shape, and morphology, highlighting the versatility and sustainability of this green approach [14].

The synthesis of nanoparticles typically follows two main strategies:

#### Top-down approach

The top-down approach involves breaking down bulk materials into nanosized particles through the application of physical forces such as milling, grinding, or laser ablation. This method starts with larger structures and progressively reduces them to the nanoscale, typically using mechanical, thermal, or lithographic techniques. While it allows for the production of nanoparticles with controlled dimensions, the process can be energy-intensive and

may introduce surface defects or contamination due to the mechanical stress involved [15]. Despite these limitations, the top-down approach remains widely used for fabricating nanoparticles, particularly when high-purity and well-defined materials are required for applications in electronics, optics, and materials science [15].

#### Bottom-up approach

The bottom-up approach involves the assembly of atoms or ions into nanoparticles through processes such as reduction and stabilization, allowing precise control over particle composition and structure. In this method, nanoparticles are built from the molecular or atomic level rather than broken down from bulk materials. Green synthesis commonly follows the bottom-up pathway, wherein silver ions ( $Ag^+$ ) are biologically reduced to metallic silver ( $Ag^0$ ) by plant-derived biomolecules. These biomolecules not only act as reducing agents but also serve as natural capping agents, providing stability to the nanoparticles and preventing their aggregation [16]. This environmentally friendly strategy offers a sustainable and efficient means of producing uniform, stable, and biocompatible silver nanoparticles.

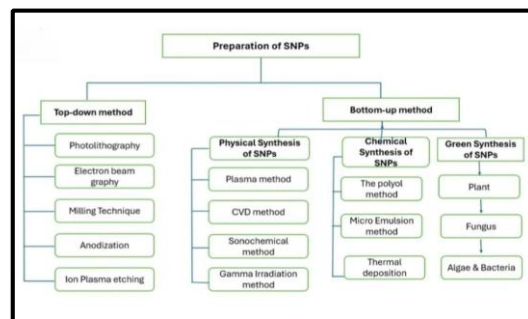


Fig 1 (a) :- Preparation of SNPs

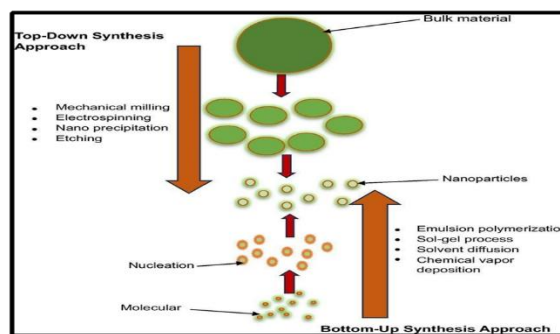


Fig 1 (b) :- Mechanisms for Producing NPs

## X. EXPERIMENTAL APPROACHES FOR SYNTHESIZING SILVER NANOPARTICLES WITH PLANT EXTRACTS.

Several studies have demonstrated the successful green synthesis of silver nanoparticles

(AgNPs) using various plant extracts such as *Nelumbo nucifera*, *Eucalyptus hybrida*, *Aloe vera*, *Mentha piperita*, and *Polyalthia longifolia* [17-18]. Typically, aqueous leaf extracts are mixed with silver nitrate ( $\text{AgNO}_3$ ) solutions, leading to the reduction of silver ions ( $\text{Ag}^+$ ) to metallic silver ( $\text{Ag}^0$ ), which is visually indicated by a colour change from colourless to brown [18-19]. For instance, *Polyalthia longifolia* leaf extract combined with D-sorbitol has produced stable AgNPs exhibiting strong antibacterial activity, while extracts of *Acalypha indica* and *Azadirachta indica* have efficiently reduced  $\text{Ag}^+$  ions under ambient conditions, yielding nanoparticles with characteristic surface plasmon resonance (SPR) peaks near 430–440 nm. Other plants such as *Eucalyptus hybrida*, *Boswellia ovalifoliolata*, and *Cleome viscosa* have also been employed to synthesise AgNPs ranging from 20 to 100 nm, as confirmed by UV–Vis and microscopic analyses. Factors such as pH, temperature, and extract concentration significantly influence nanoparticle size, morphology, and stability. Overall, plant-mediated synthesis offers distinct advantages, including operational simplicity, scalability, and the avoidance of microbial contamination or complex culture conditions, while phytochemicals in the extracts act as natural reducing and stabilising agents, yielding biocompatible nanoparticles ideal for pharmaceutical, cosmetic, and biomedical applications [20].

## XI. CHARACTERIZATION

Characterisation of silver nanoparticles (AgNPs) is essential to evaluate their physicochemical properties, including size, shape, morphology, crystallinity, surface chemistry, and stability, which directly influence their functional performance and biological activity [21]. Various analytical techniques are employed to confirm successful synthesis and assess structural and optical characteristics. UV–Visible spectroscopy is commonly used to detect the surface plasmon resonance (SPR) band, indicating nanoparticle formation [21-22], while X-ray diffraction (XRD) provides information on crystalline

structure. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) reveal detailed morphology, particle size, and distribution. Fourier-transform infrared spectroscopy (FTIR) helps identify functional groups responsible for reduction and stabilisation, and dynamic light scattering (DLS) determines particle size distribution and colloidal stability. Together, these methods offer comprehensive insight into the composition and behaviour of AgNPs, ensuring their suitability for targeted applications in biomedical, environmental, and industrial fields [23].

### ❖ UV Spectrometry Analysis

UV–Visible (UV–Vis) spectroscopy is a rapid and reliable method for confirming the formation of silver nanoparticles (AgNPs) and assessing their optical properties. This technique detects the surface plasmon resonance (SPR) phenomenon, which results from the collective oscillation of conduction electrons in response to light. The SPR absorption peak for AgNPs typically appears between 410 and 440 nm, depending on factors such as particle size, shape, and distribution [24]. An increase in absorbance intensity indicates the progressive reduction of silver ions ( $\text{Ag}^+$ ) to metallic silver ( $\text{Ag}^0$ ), while shifts in peak position reflect changes in particle size or aggregation state. For example, AgNPs synthesised using *Euphorbia hirta* and *Acalypha indica* leaf extracts exhibited distinct SPR bands near 425 nm, confirming the successful reduction of silver ions and the formation of stable nanoparticles [25].

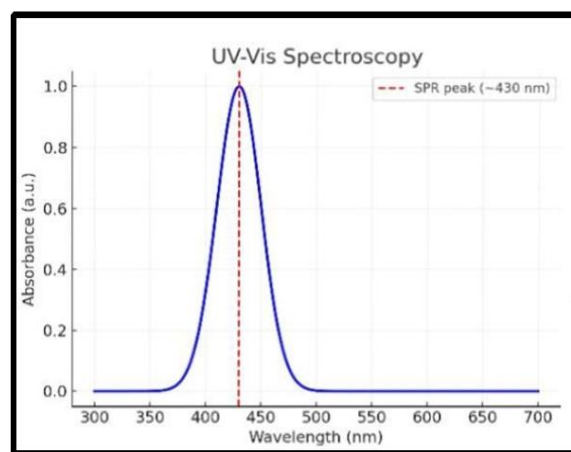


Figure 2:- UV – Vis Spectroscopy (wavelength vs Absorbance).

- ✓ Purpose: This technique is used to confirm the formation of silver nanoparticles (AgNPs) through the detection of surface plasmon resonance (SPR).
- ✓ Observation: The characteristic SPR absorption band for AgNPs typically appears within the range of 410–440 nm, confirming successful nanoparticle synthesis.
- ✓ Significance: The position of the SPR peak provides valuable information about particle size and shape, while variations in peak intensity and wavelength shifts indicate changes in nanoparticle stability and degree of aggregation.
- ✓ Example: Silver nanoparticles synthesised using *Euphorbia hirta* and *Acalypha indica* extracts exhibited strong SPR peaks at around 425 nm, confirming nanoparticle formation.

❖ Fourier Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy is employed to identify the specific functional groups involved in the reduction, stabilisation, and capping of silver nanoparticles (AgNPs). The presence of characteristic absorption bands corresponding to O–H (alcohols and phenols), C=O (carbonyl groups), N–H (proteins), and C–O (esters and ethers) confirms the participation of biomolecules in the synthesis process. Typical FTIR spectra display peaks near  $3300\text{ cm}^{-1}$  (O–H stretching),  $1650\text{ cm}^{-1}$  (amide I), and  $1550\text{ cm}^{-1}$  (amide II), indicating the involvement of proteins and polyphenolic compounds as reducing and capping agents. These biomolecules serve a dual function by reducing  $\text{Ag}^+$  ions to  $\text{Ag}^0$  and stabilising the resulting nanoparticles to prevent agglomeration [26].

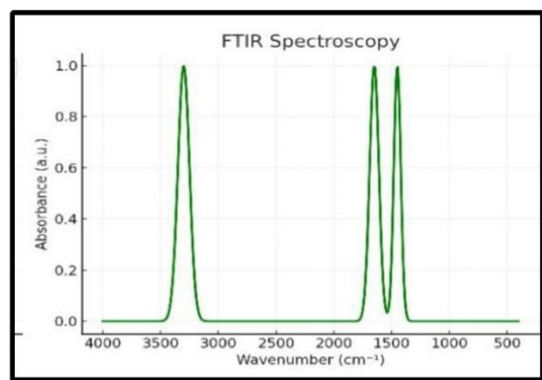


Figure 3:- FTIR Spectroscopy (Wavelength vs Absorbance)

- ✓ Purpose: FTIR spectroscopy is used to identify the functional groups involved in the reduction, stabilization, and capping of AgNPs[26].

✓ Characteristic Bands:

$3300\text{ cm}^{-1}$  → O–H stretching vibrations (alcohols, phenols)

$1650\text{ cm}^{-1}$  → Amide I band (proteins)

$1550\text{ cm}^{-1}$  → Amide II band (peptide linkages)

- ✓ Interpretation: The presence of these absorption peaks confirms that proteins, flavonoids, and Polyphenols play significant roles as reducing and capping agents, preventing nanoparticle Aggregation and enhancing stability.

❖ X-Ray Diffraction Analysis

XRD analysis confirms the crystalline nature and phase purity of green-synthesized

AgNPs, with characteristic diffraction peaks typically appearing at  $2\theta$  angles of around  $38^\circ$ ,  $44^\circ$ ,  $64^\circ$ , and  $77^\circ$ , corresponding to the (111), (200), (220), and (311) planes of facecentered cubic (fcc) silver [27]. The average crystallite size, commonly between 15 and 45 nm, can be calculated using the Debye–Scherrer equation, with variations influenced by synthesis parameters. Reports have consistently shown that plant-mediated synthesis using extracts from *Azadirachta indica*, *Eucalyptus hybrida*, and *Polyalthia longifolia* produces well-defined crystalline nanoparticles exhibiting distinct Bragg reflections indicative of pure metallic silver.

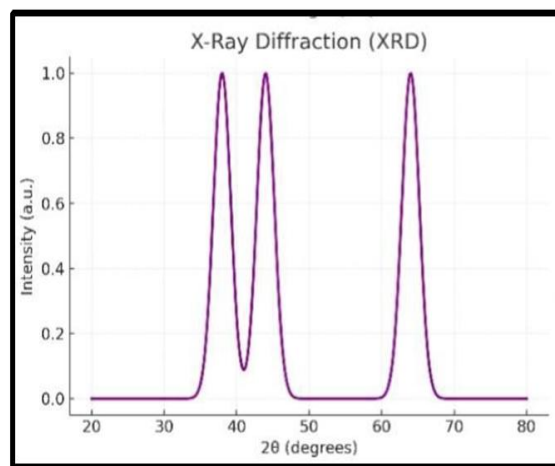


Figure 4:- Graph Of X-RAY Diffraction

✓ Purpose: XRD is utilized to determine the crystalline structure, phase purity, and average crystallite size of synthesized AgNPs.

✓ Typical Diffraction Peaks ( $2\theta$ ):

$38^\circ \rightarrow (111)$

$44^\circ \rightarrow (200)$

$64^\circ \rightarrow (220)$

$77^\circ \rightarrow (311)$

✓ Results: These diffraction peaks correspond to the face-centered cubic (fcc) lattice structure of metallic silver. The crystallite size, estimated using the Debye–Scherrer equation, typically falls within the 15–45 nm range.

✓ Example: XRD analysis of AgNPs synthesized from *Azadirachta indica* and *Eucalyptus hybrida* extracts revealed well-defined Bragg reflections indicative of a crystalline structure.

❖ Scanning Electron Microscopy

SEM analysis provides detailed insights into the surface morphology, size, and structural characteristics of AgNPs, with biosynthesized nanoparticles typically appearing as spherical or near-spherical structures ranging from 20 to 100 nm [28]. SEM images of AgNPs produced using *Syzygium aromaticum* and *Cleome viscosa* leaf extracts reveal uniform particle shapes with minimal aggregation, highlighting the stabilizing role of plant-derived biomolecules. These natural compounds help maintain shape consistency and prevent excessive clustering, contributing to the formation of well-dispersed and stable nanoparticles.

✓ Purpose: SEM provides information about the morphology, surface characteristics, and particle size distribution of AgNPs.

✓ Observation: The synthesized nanoparticles are predominantly spherical or quasispherical, with average diameters ranging from 20 to 100 nm. Biological reducing agents aid in achieving uniform distribution and minimal aggregation.

✓ Example: SEM micrographs of AgNPs derived from *Syzygium aromaticum* and *Cleome viscosa* extracts confirmed their spherical morphology and homogeneous dispersion [29].

❖ High-Resolution Transmission Electron Microscopy (HRTEM)

High-resolution transmission electron microscopy (HRTEM) enables detailed visualization of the size, shape, and internal structure of silver nanoparticles at

the nanometer scale. Typically, HRTEM images show well-dispersed, spherical AgNPs with diameters between 15 and 30 nm, while lattice fringes and SAED patterns confirm their face-centred cubic (fcc) crystalline structure. These findings, when correlated with UV–Vis spectral data, validate the successful synthesis, morphology, and stability of green synthesized AgNPs.

✓ Purpose: HRTEM is utilised to obtain high-resolution information on the shape, size, and lattice structure of AgNPs at the nanoscale.

✓ Observation: The nanoparticles generally display a spherical, monodispersed morphology with diameters ranging from 15 to 30 nm. The presence of lattice fringes and selected area electron diffraction (SAED) rings confirms their crystalline facecentered cubic (fcc) structure [30].

✓ Correlation: The HRTEM results show strong agreement with UV–Vis and XRD analyses, collectively confirming the successful synthesis of silver nanoparticles.

## XII.MODE OF ACTION OF NANOSILVER

The antimicrobial activity of silver nanoparticles (AgNPs) begins with their attachment to the negatively charged microbial cell membrane through electrostatic interactions. This contact disrupts membrane integrity, increasing permeability and causing leakage of essential intracellular components. Additionally, silver ions released from AgNPs penetrate the cell and bind to thiol (-SH) groups in membrane proteins, impairing respiratory enzymes and electron transport [30]. This disruption leads to loss of membrane potential, oxidative imbalance, and eventual cell lysis. Gram-negative bacteria, with their thinner peptidoglycan layers, are generally more vulnerable to these effects than Gram-positive bacteria.

### Interaction with The Cell Membrane

The antimicrobial activity of silver nanoparticles (AgNPs) begins with their attachment to the negatively charged microbial cell membrane through electrostatic interactions. This contact disrupts membrane integrity, increasing permeability and causing leakage of essential intracellular components. Additionally, silver ions released from AgNPs

penetrate the cell and bind to thiol (-SH) groups in membrane proteins, impairing respiratory enzymes and electron transport [30]. This disruption leads to loss of membrane potential, oxidative imbalance, and eventual cell lysis. Gram-negative bacteria, with their thinner peptidoglycan layers, are generally more vulnerable to these effects than Gram-positive bacteria.

#### Generation of Reactive Oxygen Species (ROS)

Silver nanoparticles (AgNPs) exert antimicrobial effects by generating reactive oxygen species (ROS) such as superoxide ( $O_2^-$ ), hydroxyl radicals ( $\bullet OH$ ), and hydrogen peroxide ( $H_2O_2$ ) [31]. The buildup of these ROS induces oxidative stress in microbial cells, leading to damage of lipids, proteins, and nucleic acids [32]. This oxidative stress disrupts mitochondrial activity, inactivates vital respiratory enzymes, and degrades genetic material, resulting in metabolic failure, inhibited replication, and ultimately, cell death.

#### Interaction with DNA and Proteins

Silver nanoparticles (AgNPs) and their released ions can directly disrupt genetic and protein structures within cells. Silver ions ( $Ag^+$ ) bind to DNA bases and phosphate backbones, causing DNA condensation and inhibiting replication and transcription by blocking RNA polymerase activity [33]. Additionally,  $Ag^+$  ions interact strongly with thiol groups in enzymes and structural proteins, inducing conformational changes that lead to enzyme inactivation. These interactions interfere with essential cellular signalling and metabolic processes, ultimately suppressing cell growth and leading to cell death [34].

#### Antifungal Mechanism

Silver nanoparticles (AgNPs) exhibit potent antifungal activity by interacting directly with fungal cell wall components such as ergosterol and chitin, leading to membrane destabilization, increased permeability, and leakage of cellular contents. They also disrupt mitochondrial respiration, decrease ATP production, and induce oxidative stress through reactive oxygen species (ROS) generation, collectively inhibiting fungal growth and metabolism. Studies have demonstrated the strong antifungal efficacy of AgNPs against *Candida albicans*, *Aspergillus niger*, and

*Fusarium oxysporum*, highlighting their promise as effective alternative antifungal agents [35-36].

#### Antiviral Activity

Silver nanoparticles (AgNPs) exhibit strong antiviral activity against both DNA and RNA viruses by inhibiting viral attachment, fusion, and replication [37]. They interact with viral envelope glycoproteins, such as gp120 in HIV-1, preventing the virus from binding to host cell receptors and entering target cells. Additionally, AgNPs can disrupt viral genetic material and inhibit polymerase activity, effectively blocking replication. These multifaceted antiviral mechanisms make AgNPs promising candidates for use in antiviral coatings, disinfectant surfaces, and nanocarrier-based drug delivery systems.

#### Anti-Inflammatory Mechanism

In addition to their antimicrobial effects, silver nanoparticles (AgNPs) exhibit strong anti-inflammatory properties that promote tissue repair and wound healing. They reduce inflammation by suppressing pro-inflammatory cytokines such as TNF- $\alpha$ , IL1 $\beta$ , and IL-6 produced by immune cells, while simultaneously enhancing fibroblast proliferation, collagen synthesis, and tissue regeneration for faster wound closure. Topical nanosilver formulations have shown effectiveness in treating burns, dermatitis, and chronic wounds by combining anti-inflammatory action with sustained antimicrobial protection [38].

### XIII. APPLICATIONS OF SILVER NANOPARTICLES

Green-synthesised silver nanoparticles (AgNPs) have gained significant attention due to their unique physicochemical and biological properties, making them valuable in biomedical, pharmaceutical, environmental, and industrial applications. Their broad-spectrum antibacterial, antifungal, antiviral, antioxidant, and anti-inflammatory activities highlight their potential in therapeutic and diagnostic fields. Moreover, the eco-friendly and biocompatible nature of green-synthesised AgNPs ensures their sustainability and safety, supporting their growing importance in modern medical science.

#### Antibacterial Applications

Silver has long been known for its antibacterial properties, and in nanoparticle form, it demonstrates enhanced antimicrobial efficiency due to its high surface area and controlled release of silver ions ( $\text{Ag}^+$ ) [39]. Silver nanoparticles (AgNPs) effectively inhibit both Gram-positive and Gram-negative bacteria, including *E. coli*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa*, by disrupting cell membranes, inducing oxidative stress, and interfering with DNA replication [39]. When integrated into wound dressings, coatings, and medical devices, AgNPs help prevent infections by reducing bacterial adhesion and biofilm formation. Green-synthesized AgNPs offer similar antibacterial performance to chemically produced ones but with lower cytotoxicity, making them safer for pharmaceutical, disinfectant, and hygiene applications [40].

#### Antifungal Applications

Silver nanoparticles (AgNPs) possess strong antifungal activity against pathogens such as *Candida albicans*, *Aspergillus niger*, and *Fusarium oxysporum*. Their antifungal mechanism involves disrupting cell membrane permeability, inhibiting spore germination, and blocking respiratory enzymes, leading to fungal cell death. AgNPs synthesised using plant extracts like *Aloe vera*, *Euphorbia hirta*, and *Azadirachta indica* have shown high efficacy in clinical and agricultural applications by damaging fungal cell wall components such as chitin and glucan, causing cytoplasmic leakage and oxidative stress. Owing to their broad-spectrum activity and low toxicity, green-synthesised AgNPs are being developed as eco-friendly antifungal agents for use in medicine, food preservation, and crop protection.

#### Antiviral Applications

Silver nanoparticles (AgNPs) exhibit strong antiviral activity against a broad range of DNA and RNA viruses, including HIV, influenza, herpes simplex, and hepatitis B [40]. They inhibit viral attachment, entry, and replication by interacting with viral surface proteins such as the gp120 glycoprotein on HIV-1, thereby preventing binding to host cell receptors [41]. Similarly, AgNPs can block the envelope proteins of herpes and influenza viruses, hindering their penetration into host cells [41]. Owing to these properties, AgNPs are being explored for

antiviral coatings, nasal sprays, disinfectants, and vaccine formulations, with green-synthesised AgNPs offering enhanced safety and a lower risk of resistance development.

#### Wound-Healing and Anti-Inflammatory Applications

Silver nanoparticles (AgNPs) possess potent antimicrobial and anti-inflammatory properties, making them highly effective in wound healing applications. Incorporated into dressings, ointments, and gels, they accelerate recovery by stimulating fibroblast proliferation, promoting collagen synthesis, and enhancing angiogenesis. AgNPs also reduce inflammation by downregulating mediators such as  $\text{TNF-}\alpha$  and IL-6, leading to less pain and swelling. Clinical studies have shown that nanosilver creams promote faster healing of burns, ulcers, and surgical wounds while minimising infection. Compared to conventional silver-based formulations, green-synthesised AgNPs offer superior biocompatibility, sustained antimicrobial activity, and minimal tissue irritation, making them ideal for advanced wound care [42].

#### Anticancer and Antioxidant Applications

Recent studies have revealed the anticancer potential of silver nanoparticles (AgNPs), which can generate reactive oxygen species (ROS), induce mitochondrial damage, and trigger apoptosis in cancer cells. Green-synthesised AgNPs have shown cytotoxic effects against various cancer cell lines, including HeLa, MCF-7, A549, and HepG2, primarily through oxidative stress and DNA fragmentation. Additionally, phytochemicals present in plant-based AgNPs enhance their antioxidant activity, enabling free radical neutralisation and reduction of oxidative damage. The combined antioxidant and anticancer effects make AgNPs promising candidates for targeted drug delivery and advanced therapeutic nanomedicine [43-44].

#### Environmental and Industrial Applications

Beyond biomedical applications, silver nanoparticles (AgNPs) are widely utilised in environmental and industrial fields. They serve as antimicrobial agents in water purification systems, effectively eliminating microorganisms and organic pollutants, and are incorporated into fabrics, paints, and coatings to provide long-lasting antibacterial protection [45].

Additionally, their exceptional optical and electrical properties make them valuable for biosensors, diagnostic devices, electronics, fuel cells, and renewable energy technologies. The adoption of green synthesis methods for these purposes reduces environmental toxicity and aligns with the principles of sustainable nanotechnology.

#### XIV.FUTURE PERSPECTIVES AND CHALLENGES

Despite considerable progress in the green synthesis of silver nanoparticles (AgNPs), several scientific and technological challenges continue to hinder their large-scale application. One major issue is achieving reproducibility and scalability, as natural variations in biological extracts can lead to inconsistencies in nanoparticle size, morphology, and stability. Standardised extraction procedures and optimised synthesis parameters are essential to ensure uniformity in industrial production [46]. Additionally, the precise mechanisms underlying nanoparticle formation remain poorly understood, despite the identification of key biomolecules such as phenolics, proteins, and polysaccharides; advanced analytical and computational approaches are needed to elucidate these molecular interactions. Concerns regarding toxicity and biosafety also persist, as the long-term biological effects, tissue accumulation, and environmental impact of biosynthesised AgNPs are not yet fully established, necessitating comprehensive *in vivo* studies and regulatory evaluation. The absence of standardised characterisation protocols further complicates data comparability across studies. Establishing universal methodologies for synthesis, purification, and analysis would enhance consistency and industrial feasibility [46]. Nonetheless, green-synthesised AgNPs exhibit strong potential in pharmaceuticals, particularly in drug delivery, tissue engineering, and antimicrobial coatings. Future research should focus on developing hybrid nanocomposites incorporating polymers, liposomes, or bioactive compounds to improve therapeutic efficacy and minimise microbial resistance. Ensuring sustainability through eco-friendly synthesis, waste reduction, and the use of renewable biological materials, alongside interdisciplinary collaboration, will be crucial for advancing safe and environmentally responsible nanomedicine.

#### XV.CONCLUSION

The green synthesis of silver nanoparticles (AgNPs) represents a sustainable, cost-effective, and environmentally friendly alternative to conventional chemical and physical methods. Plant-based synthesis, in particular, offers significant advantages due to the abundance of natural phytochemicals that function as both reducing and stabilizing agents, enabling the formation of stable, biocompatible nanoparticles with controlled size and morphology. Comprehensive characterization through UV-Vis spectroscopy, FTIR, XRD, SEM, and TEM confirms the successful formation of crystalline, well-dispersed AgNPs with potent biological activity. Green-synthesised AgNPs exhibit remarkable antimicrobial, antifungal, antiviral, antioxidant, anti-inflammatory, and anticancer properties, highlighting their broad potential in biomedical, pharmaceutical, environmental, and industrial applications. Despite challenges related to reproducibility, large-scale production, and long-term safety, continued research, standardization of synthesis protocols, and interdisciplinary advancements will strengthen their future utility. Overall, green synthesis holds great promise for advancing safe, effective, and sustainable nanotechnology-based solutions.

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