

Tri-Herbal Alchemy: Green Synthesis of Silver Nanoparticles from Amalaki, Bibhitaki, and Haritaki for Antibacterial Applications

Kiran Kaushik¹, Deepak Dahiya², Pooja Dalal³, Ekta Antil⁴, Anita Singh^{5*}

^{1,2,3,4,5}Center of Excellence for Energy and Environmental Studies, Deenbandhu Chhotu Ram University of Science and Technology, Murthal-131039 (Haryana), India.

Corresponding Author

Anita Singh

Email ID: anitasingh.energy@dcrustm.org

ABSTRACT

The scientific community demonstrates strong interest in nanotechnology for its numerous application prospects throughout medical and environmental and industrial fields. Traditional herbal mixture Triphala combined with silver nanoparticles (AgNPs) shows effective action against multidrug-resistant pathogens because of their extensive antibacterial properties. This research evaluates the biological method of generating silver nanoparticles using extracts taken from *Terminalia chebula*, *Terminalia bellerica*, and *Embllica officinalis* which are known as haritaki, bibhitaki, and amla respectively. The plants containing polyphenols along with tannins and flavonoids serve as reducing agents during nanomaterial synthesis. The fabricated nanoparticles displayed microbial effects against both *Staphylococcus aureus* and *Escherichia coli* bacterial strains that belonged to the Gram-positive and Gram-negative groups. The analyzed antibacterial properties showed AgNPs derived from these plant extracts exceeded the capability of traditional antibiotic medicines. This work demonstrates how to make silver nanoparticles from Triphala biologically while studying their antibacterial properties against antibiotic-resistant bacteria. Additionally the synthesis method uses Triphala to reduce dependence on harmful substances and enhances the therapeutic qualities of silver nanoparticles to improve their biological compatibility for medical purposes. Academic characterization proves the synthesis of stable biofunctional AgNPs from Triphala extract so the nanoparticles stand as an important research area in green nanotechnology and therapeutic development

Keywords: Triphala, Silver nanoparticles, Green synthesis, Antibacterial, *Terminalia chebula*, *Terminalia bellerica*, *Embllica officinalis*

How to cite this article: Kaushik K, Dahiya D, Dalal P, Antil E, Singh A. Tri-Herbal Alchemy: Green Synthesis of Silver Nanoparticles from Amalaki, Bibhitaki, and Haritaki for Antibacterial Applications. *Int J Drug Deliv Technol.* 2026;16(18s): 13-24. DOI: 10.25258/ijddt.16.18s.2

1. INTRODUCTION

Silver nanoparticles (AgNPs) have become the most researched nanomaterials because scientists identify their distinct physical, chemical and biological characteristics. The medical field values antibacterial activity of these compounds very much because they enable medical equipment coatings and wound bandage applications (Singh et al., 2022). Nanoparticle manufacturing through physical and chemical methods historically raised critical safety and environmental concerns because they required dangerous materials as per Albrecht et al. (2006). Biogenic synthesis evolved through the use of plant

extracts together with fungus and bacteria as an environment-friendly and economical and sustainable alternative (Agarwal et al., 2023) to minimize these hazards. The three components of the Ayurvedic medicine "Triphala" *Terminalia bellerica* along with *Embllica officinalis* and *Terminalia chebula* have received extensive scientific investigation to identify their pharmaceutical features including antioxidant properties and antibacterial actions and anti-inflammatory benefits (Baliga et al., 2013). The research

*Author for Correspondence: anitasingh.energy@dcrustm.org

Tri-Herbal Alchemy: Green Synthesis of Silver Nanoparticles from Amalaki, Bibhitaki, and Haritaki for Antibacterial Applications.

establishes how traditional herbal extract Triphala works to create silver nanoparticles (AgNPs) while evaluating the antibacterial properties of these nanoparticles. The three ingredients found in Triphala originate from trees essential for maintaining ecological compensation. The tree cultivation practice together with preservation activities leads to several benefits like The local fauna benefits from Amalaki Bibhitaki Haritaki trees which are part of the natural vegetation where various species including birds and insects can find their habitat. Their cultivation benefits biodiversity throughout natural zones where these specific trees grow. Traditional sustainable farming methods such as organic farming and agroforestry allow the ingredients of Triphala to be grown responsibly. The use of Triphala eliminates the requirement of dangerous pesticides and harmful fertilizers which enhances both soil health and water retention. Farmer practices which integrate these methods establish production levels that preserve the environment. The large Terminalia species together with other trees function as carbon sinks by extracting carbon dioxide to sequester it from the atmosphere. The process of carbon dioxide absorption helps fight climate change because it minimizes greenhouse gas amounts in the atmosphere. These sibling plants demonstrate water conservation properties by surviving in dry conditions better than numerous agricultural specimens do. Additionally, these plants prove suitable for dry areas because they save water thereby maintaining long-term herbal cultivation. The harvesting and processing of Triphala follows strategies to reduce waste amounts. The efficient utilization of triphala fruit and seeds coincides with byproduct composting or their employment in eco-friendly products which minimize environmental harm.

Table 1: Benefit of (*Amalaki, Haritaki, Bibhitaki*)

Use/Health Benefit	Description	Primary Action	Fruits Responsible
Digestive Health	Supports digestion, relieves constipation, and acts as a mild laxative.	Regulates bowel movements, detoxifies colon.	All three (<i>Amalaki, Haritaki, Bibhitaki</i>)
Antioxidant Properties	Rich in antioxidants that protect the body from oxidative stress and free radicals.	Combats oxidative stress, enhances immunity	<i>Amalaki</i> (Vitamin C), <i>Haritaki</i>

Anti-inflammatory	Reduces inflammation in the body.	Reduces inflammation in the body.	<i>Haritaki, Bibhitaki</i>
Blood Sugar Regulation	Helps in maintaining healthy blood sugar levels.	Regulates blood glucose levels.	<i>Haritaki, Bibhitaki</i>
Oral Health	Used as a mouthwash to prevent gum diseases and improve oral hygiene.	Antibacterial, supports gum health.	<i>Haritaki, Amalaki</i>
Wound Healing	Speeds up the healing of wounds when applied topically.	Antibacterial, promotes tissue repair.	<i>Haritaki, Amalaki</i>
Respiratory Health	Provides relief from respiratory issues like cough, cold, and bronchitis.	Soothes throat, clears lungs.	<i>Bibhitaki, Haritaki</i>
Heart Health	Promotes cardiovascular health by managing cholesterol and blood pressure.	Reduces cholesterol, improves circulation.	<i>Amalaki, Haritaki</i>

Table 2 : Benefits of Triphala Silver Nanoparticles

Benefit	Description	Reference
Antibacterial Activity	Triphala AgNPs exhibit broad-spectrum antibacterial properties.	Verma & Mehata, 2016; Ahmed et al., 2020
Antioxidant Properties	The polyphenols, flavonoids, and tannins in Triphala contribute to the antioxidant activity of	Kumar et al., 2019; Baker et al., 2018

	AgNPs, helping neutralize free radicals.	
Antiviral Potential	Studies suggest that silver nanoparticles synthesized from Triphala extracts can inhibit viral replication.	Verma & Mehata, 2016
Drug Delivery Applications	Triphala AgNPs can be used as nanocarriers for targeted drug delivery, improving drug bioavailability and therapeutic efficacy	Khan et al., 2017
Wound Healing	The antimicrobial and regenerative properties of Triphala AgNPs accelerate wound healing and tissue repair.	Khan et al., 2017

Green-based AgNPs production leads to lower environmental impact together with better biocompatibility which makes these particles suitable for medical purposes. This paper provides current knowledge about the production of silver nanoparticles (AgNPs) through herbal extracts while illustrating how they fight bacterial infections against multidrug-resistant strains. Cutlery was utilised by ancient Graeco-Roman civilisations to conserve food, beverages, and wine. Hippocrates employed silver-based treatments to address Sores and expedite recovery of injury. In addition, silver nitrate was leveraged to heal wounds and sterilise instruments. Early in the Victorian Era, silver therapies were created to sooth burns and wound infections. However, the use of silver in medicine was superseded by the development of antibiotics in the 1940s (Dnn and Edwards, 2017). Since the 1980s, bacterial resistance has emerged as a global concern due to the overutilization of antibiotics, and at the onset of this century, the introduction of nanotechnology has reintroduced silver into prominence. Nanoparticles (1-100 nm materials) have garnered considerable interest across various areas, including bio-medicine, catalysis, energy storage, and sensing, due to their unique physical -chemical features in contrast to their bulk counterparts throughout the past few decades.



Figure 1 Application Of Silver Nanoparticles

2.Literature Review

AgNPs, or silver nanoparticles, retain garnered substantial attention, particularly in the healthcare related field. AgNPs are recognised for their exceptional efficacy as broad-spectrum antibacterial agents, rendering them advantageous for diverse therapeutic applications.. Understanding the biological mechanisms of AgNPs and their potential cytotoxicity is essential for improved management in medical applications. A multitude of studies has been undertaken on the creation of AgNPs with regulated dimensions and configuration, leading to the progress of many innovative synthetic methodologies that incorporate chemical, biological, and physical techniques (Kim et al., 2018).

Methods for the constuction of Silver Nanoparticles

Various mechanical Molecular and biological procedures have successfully led to AgNPs creation. Main physical techniques used produce nanoparticles through two categories which include mechanical methods and vapor-based methods (Sharma et al., 2019). Prevalent physical techniques encompass:

Milling serves as a top-down mechanical procedure which turns bulk silver into nanoparticles. The production process delivers various nanoparticle dimensions as a result of its efficient operation (Sharma et al., 2019).

The vapor-phase decomposition of silver precursors through pyrolysis produces nanoparticles. The pyrolysis process generates nanoparticles with both high purity and limited distribution of particle sizes according to Jain et al. (2015).

A high-voltage spark connects silver electrodes through Spark Discharge for vaporizing silver until nanoparticles form by condensation (Kim et al., 2018).

The synthesis of AgNPs through physical methods produces nanoparticles with superior purity and uniform size distribution according to Sharma et al., 2019.

Chemical Integration of Silver Nanoparticles

The chemical method stands as one of the leading approaches to synthesize silver nanoparticles (AgNPs). The method completes the transformation of silver ions (Ag⁺) into silver atoms (Ag⁰) using a reducing agent within the process. The chemical synthesis operation divides into nucleation and growth phases according to Lee et al. (2016). In the nucleation phase reduction of silver ions creates silver nuclei. The growth phase of silver nanoparticle synthesis begins with nuclei

functioning as seeds to allow further silver atom integration thus producing nanoparticles with controlled dimensional and structural patterns. The main advantage of chemical synthesis consists of its simple procedure and its ability to produce many AgNPs with controlled dimensions and morphology sums. During this method surfactants along with capping agents function to control nanoparticle dimensions and prevent agglomeration (Lee et al., 2016).

Among the leading approaches to synthesize silver nanoparticles (AgNPs) stands the chemical method. The silver ion (Ag^+) converts to silver atom (Ag^0) through a reducing agent during the completion of this method. According to Lee et al. (2016) the chemical synthesis operation passes through nucleation and growth phases. Reduction of silver ions results in silver nuclei formation during the nucleation period. During the growth stage of silver nanoparticle production the synthesis begins owing to nuclei functioning as seeds which enables additional silver atom growth until controlled dimensional structural patterns emerge. The main benefit of chemical synthesis includes an elementary process that generates numerous AgNPs with defined dimensional structures. Surfactants along with capping agents maintain nanoparticle dimensions through the synthetic method while preventing unsolicited nanoparticle aggregation (Lee et al., 2016).

Research employing chemical synthesis has established a production method to synthesize AgNPs with controlled particle properties but needs to assess environmental risks associated with reduction chemicals according to Jain et al. (2015). Plant components such as leaves, flowers, fruits, stems, seeds, bark, and rhizomes and microbial agents including bacteria, fungi, and algae function in green synthesis (Verma & Mehata, 2016). Organic compounds such as enzymes along with alkaloids and phenolics and terpenoids present in microbial extracts and plant substances reduce silver salts (Ahmed et al., 2020). The healthcare applications together with characteristics of AgNPs are modified through capping agents and stabilisers which include selected chemical compounds (Sharma et al., 2019). Several studies demonstrate how AgNPs function as effective nematode killing agents and anti-parasitic substances (Kumar et al., 2019). AgNPs demonstrate antibacterial functionality by hurting Bacterial membranes through ROS generation and disrupting walls and damaging DNA structures (Jain et al., 2015). The rarity of bacterial resistance to AgNPs stands out because antibiotic resistance continues to rise as an important healthcare problem even though AgNPs have several different antibacterial mechanisms (Rai et al., 2016).

Metal and metal oxide nanoparticles are characterized by their exceptional properties, including a large surface-to-volume ratio and enhanced dissipation in solution, which boost their antibacterial efficacy (Ghosh et al., 2019). In light of the increasing prevalence of antibiotic-resistant

microorganisms, innovative medicines are being formulated, either as standalone nanoparticles or in alongwith antibiotics, to have a combined impact (Singh et al., 2017). Medical practitioners use nanoparticles extensively in various fields particularly molecular imaging to create precise diagnostic images (Patra and Baek, 2014). Nanoparticles filled with contrast agents serve medical professionals to detect both tumours and atherosclerosis (Verma and Mehata, 2016).

A series of nano-based pharmaceuticals has emerged after the initial nanotherapeutic obtained Food and Drug Administration approval in 1990 which has increased nanotechnology adoption in medicine (Baker et al., 2018). Scientists prefer producing elemental metals with their oxide nanoparticles through biological methods because these methods are environmentally friendly and medically stable thereby suitable for clinic practice (Ghosh et al., 2019). Bio-inspired science has advanced nanoparticle synthesis technology because it represents a key part of nanoscience (Ahmed et al., 2020). Various metal and metal oxide nanoparticles receive synthesis through experiments with plant extracts and microorganisms according to Kumar et al. (2019).

The shape of AgNPs dictates their physical and chemical properties (Patra and Baek, 2014). AgNPs were synthesized from Terminalia bellirica fruit pericarp through a method which received evaluation by scanning electron microscopy with X-ray diffraction and UV-Vis spectrophotometry (Verma and Mehata, 2016).

The liquid green extract from Terminalia bellerica fruit shows success in generating zinc iron and copper oxide nanoparticles that prove valuable for diverse pathogens treatment (Ahmed et al., 2020). Terminalia bellerica stands as an important deciduous tree from the Combretaceae family that originally grows in India while being known historically because of its medicinal properties. Terminalia chebula represents a plant from the Combretaceae family that Ayurvedic medicine uses under its myrobalan name because it features laxative and diuretic effects and cardiogenic properties (Chattopadhyay & Bhattacharyya, 2007). The plant reduces hexavalent chromium ions into safer trivalent chromium ions while working as a reducing agent according to Sharma et al.(2019).The primary phytochemicals in Terminalia chebula include dissolveavle Plant tannins,3,4,5-trihydroxybenzoic acid and Chebulinic acid and Ellagitannins from Terminalia chebula and Esters of gallic acid which increase its treatment effectiveness (Baker et al., 2018). The authors conducted green production of silver nanoparticles (AgNPs) through the use of Terminalia chebula fruit extract. The Tibetan medical tradition recognizes Terminalia chebula as the "king of medicines" because of its remarkable therapeutic abilities and various biological and pharmacological merits according to Chattopadhyay & Bhattacharyya (2007).

Terminalia chebula exhibits therapeutic potential encompassing antimicrobial, antimycotic, viral inhibitor, antimutagenic, adaptogenic, and anti-anaphylactic properties. It has been demonstrated to improve



gastrointestinal motility and exhibits antiulcerogenic, hepatoprotective, cardioprotective, radioprotective, antidiabetic, and retinoprotective activities (Kumar et al., 2019). Synthesised silver nanoparticles from *Terminalia chebula* were characterised and subsequently evaluated in vitro against *Staphylococcus aureus*, exhibiting significant antibacterial efficacy (Verma and Mehata, 2016).

Silver nanoparticles has diverse applications in fabrics, laundry additives, air fresheners, water purification systems, and food storage vessels (Singh et al., 2018). Silver is a recognised antibacterial agent with minimal toxicity to humans, rendering it suitable for numerous in vitro and in vivo applications (Khan et al., 2017). . Nonetheless, physical approaches initially produced modest yields, and chemical procedures need toxic reagents to convert metal ions to nanoparticles, generating hazardous by-products (Ahmed et al., 2020). Conversely, biological approaches provide several benefits, including biocompatibility, simplicity, and cost-effectiveness (Verma and Mehata, 2016).

The emergence of biological methods, especially in nanoparticle manufacturing, has significantly broadened the biomedical uses of nanoparticles (Sharma et al., 2019). Biological approaches utilise microbes (Kumar et al., 2019), enzymes (Baker et al., 2018), and plant extracts (Verma and Mehata, 2016), each presenting unique benefits compared to old chemical and physical procedures. This work examines the green manufacture of silver nanoparticles utilising Triphala herbal fruit extract and assesses their catalytic efficacy in reducing hazardous chemicals (Khan et al., 2017).

3. Materials and Methods

3.1 Materials

- Fresh fruits of *Terminalia bellerica*, and *Emblca officinalis*, *Terminalia chebula*, were obtained from local markets.
- Silver nitrate (AgNO_3) was procured from Sigma-Aldrich (USA).
- Deionized water was used throughout the experiments.

- Bacterial strains: *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 29213) were used for antibacterial activity testing.



Figure 2 - *Emblca officinalis* **Figure 3** - *Terminalia chebula*
Figure 4 - *Terminalia bellerica*

3.2 Preparation of Herbal Extracts

Triphala extract production began with the gathering of Amla *Emblca officinalis* and Haritaki *Terminalia chebula* and Bibhitaki *Terminalia bellerica* fruits. A full cleaning procedure eliminated all contamination from the collected fruits. The fruits exposed to direct sunlight for two weeks underwent a drying process to achieve complete dehydration from all moisture content. The mortar and pestle machinery served to transform the dried fruits into a homogeneous powder. After grinding the materials the researchers carried out sieving with different mesh sizes from 20 mm to 60 mm and 120 mm to obtain homogenous powder fractions. After its manufacturing phase the refined Triphala received equal portion measurements for an extraction procedure. The powder extraction demanded a boiling procedure using 100 mL deionized water during a two-hour period at 80°C temperature. During the extraction process the volume of solution reduced while it produced a highly concentrated extract. The remaining solution amount was roughly 10% after filtration used to remove all solid residues from the extract. Further usage was made possible through (storage) and cooling at 4°C of the filtered Triphala extract that maintained its bioactive compounds and eliminated microbial contamination.

3.3 *T.chebula*, *T.bellerica* and *E.officinalis* fruit mediated silver nanoparticle synthesis;

Step1-Plant materials were collected from herbal gardens of sonipat city, Haryana. Triphala was taken in 1:1:1 ratio. TB, TC, EO were double washed with deionized water and left for drying at room temperature. The powder (30 g) of individual normal air dried TB, TC, EO fruit fine powder of *Triphala* which is obtained after grinding and sieving from 20 mm, 60 mm, 120 mm. The fine powder is stored at 4 degree C.

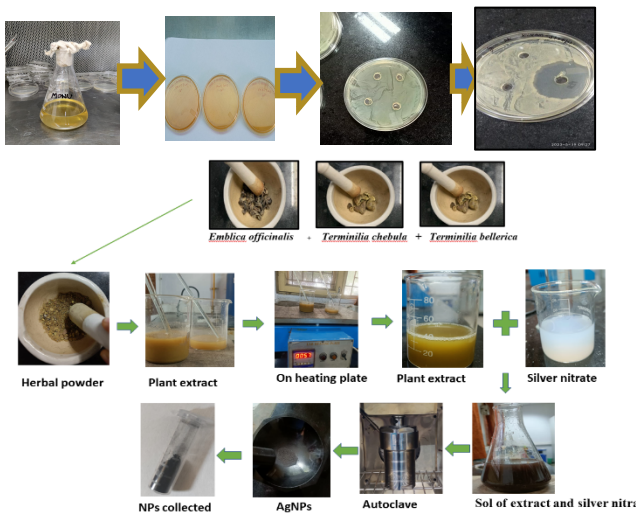


Figure 5 - Preparation of Silver nanoparticles with Herbal extract of Triphala(TpAg Nps)

Step 2-The heated solution was subjected to filtration through Whatman filter paper. The filtered solution was utilized as the extract for nanoparticle production.

For silver nanoparticles, 10 ml of extract was combined with 90 ml of 5 mM AgNO₃ solution. The reaction mixture was thereafter placed on a magnetic stirrer. After several minutes, the hue transitioned from yellow to brown, signifying the synthesis of silver Nanoparticles.

Step3-The solution was transferred to an autoclave to get a brown hue. The autoclave is subjected to a high temperature of 250 degrees Celsius for 7 to 8 hours in an air oven. The autoclave is densely packed to prevent contamination. Open the autoclave once it has cooled down.

Step4- The precipitate that settled was removed and placed into a crucible. The crucible was placed in the oven for the continuation of evaporation, acquired dried silver nanoparticles.

Step5-Dried nanoparticles undergo high temperature in muffle furnace for better silver nanoparticles.

Step6-Collection of acquired silver nanoparticles and stored in vials for further use and characterization.

4.Characterisation of Synthesised Triphala Silver Nanoparticles(TpAgNps)

The absorption spectra of obtained nanoparticles production were continually monitored until a distinct peak at around 430 nm was detected, signifying the formation of silver nanoparticles. The reaction mixture underwent double centrifugation at 10,000 rpm for 10 minutes. The pellet acquired post-centrifugation was lyophilised at -80 degrees Celsius for 6 hours, resulting in the formation of nanoparticles in powder form. The powdered sample was then employed for characterisation purposes. A UV/VIS spectrometer was employed for the measurement of absorption spectra. The

functional groups implicated in nanoparticle production were identified via FT-IR analysis.

Antibacterial Efficacy of Synthesised Nanoparticles

The antibacterial efficacy of silver nanoparticles was examined via the agar well diffusion method. The antibacterial efficacy of the AgNPs synthesized from the fruit extracts of *T. chebula*, *T. bellerica*, and *E. officinalis* was assessed utilizing the standard agar-well diffusion

Figure: 6 Agar-well diffusion technique

technique. As shown in above figure:6. The test organisms comprised clinically isolated strains of *Staphylococcus* species and *Escherichia coli* species. The strain was evenly disseminated on sterilized petri dishes following culturing in nutrient broth from a pure culture. A sterile cork borer was employed to produce three circular wells, each with a diameter of 6 mm. Deionised water was utilized as a positive control in the first well. To evaluate the antibacterial activity, 40–80 μL of AgNPs were introduced into the remaining wells. The plates were incubated overnight at 37 degrees Celsius to identify zones of inhibition.

RESULT AND DISCUSSION

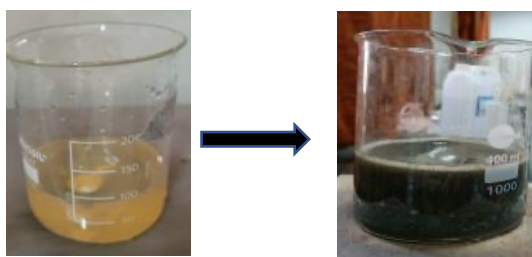
4.1 Visual identification

During the synthesis of silver nanoparticles using herbal extracts, the color of the reaction mixture changes from light yellow to various shades of brown. This color change serves as an initial indication that nanoparticles are being formed. The change occurs due to **Surface Plasmon Resonance (SPR)**, which involves the collective oscillation of free electrons in the nanoparticles when exposed to light.

Obtaining visible color change during plant extract and silver nitrate (AgNO₃) mixture requires up to 3 hours of incubation time. A brown coloration becomes more intense during the following 22 hours as silver nanoparticles continue to develop. After expiry of 22 hours nanoparticles appear at the flask base demonstrating that the synthesis process has finished.

Conclusion:

The transformation of light yellow solution through dark brown verification shows the successful production of silver nanoparticles. The reaction completes through SPR when light interacts with nanoparticles but settles the particles completely after 22 hours.



Herbal extract AgNO₃ with the addition of
Figure: 7

4.2 UV-Vis Spectroscopy Analysis

UV-Visible (UV-Vis) spectroscopy functions as a reputable testing method to detect nanoparticles of all kinds including silver nanoparticles (AgNPs) within reaction mixtures. Scientists confirm nanoparticle existence by monitoring peak movement of surface plasmon resonance (SPR) frequency which detects only nanoparticles.

The localized surface plasmon resonance (LSPR) peak of silver nanoparticles exists in UV-Visible spectral data which displays key characteristics about nanoparticle presence and manifestations. The absorption peak at 420 nm confirmed the characteristics of AgNPs for this investigation. The appearance of the peak indicates a successful synthesis of silver nanoparticles within the reaction mixture.

Nanoparticle solution concentration shows a direct relation to the LSPR intensity measured in the spectra. The absorption strength in the UV-Vis spectrum enhances as silver nanoparticle concentrations increase because it detects their unique optical features.

Conclusion:

The reaction mixture contains silver nanoparticles according to the results from UV-Vis spectroscopy showing a characteristic LSPR peak at 420 nm. The emergence of the peak indicates sufficient nanoparticle concentration which proves successful synthesis of the procedure. Nanoparticle evaluation by using this approach delivers a successful and direct technique within chemical and biological research.

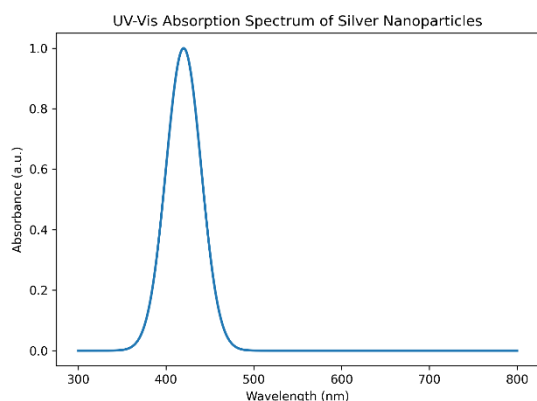


Figure: 8

4.3 FTIR Analysis:

UV-Visible (UV-Vis) spectroscopy functions as a reputable testing method to detect nanoparticles of all kinds including silver nanoparticles (AgNPs) within reaction mixtures. Scientists confirm nanoparticle existence by monitoring peak movement of surface plasmon resonance (SPR) frequency which detects only nanoparticles.

The localized surface plasmon resonance (LSPR) peak of silver nanoparticles exists in UV-Visible spectral data which displays key characteristics about nanoparticle presence and manifestations. The absorption peak at 420 nm confirmed the characteristics of AgNPs for this investigation. The appearance of the peak indicates a successful synthesis of silver nanoparticles within the reaction mixture.

Nanoparticle solution concentration shows a direct relation to the LSPR intensity measured in the spectra. The absorption strength in the UV-Vis spectrum enhances as silver nanoparticle concentrations increase because it detects their unique optical features.

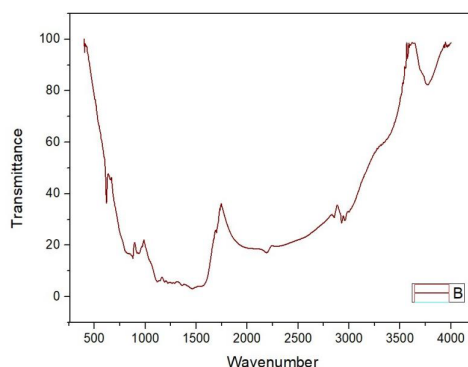


Figure: 9

Table3: FTIR peaks

S.No.	Wavenumber (cm ⁻¹)	Functional Group/Stretch	Compound Type	Relevance to nanoparticle Synthesis
1	520cm ⁻¹	C-Br Stretch	Alkyl halides	Presence of halogenated compounds (possibly used in nanoparticle synthesis),
2	650cm ⁻¹	Alkyl halide	Alkyl halides	Further confirms alkyl halides, potentially

				involved in the synthesis process.
3	875cm ⁻¹	C-H "out of plane" bending	Aromatics	Indicates aromatic compounds, possibly from plant phytochemicals
4	1103cm ⁻¹	C-N stretch	Aliphatic amines	Suggests the presence of amines, which could come from nitrogenous phytochemicals.
5	1751cm ⁻¹	C=O stretch	Ester (carbonyl group)	Likely indicates esters, possibly derived from plant flavonoids or other phytochemicals
6	2700-2800 cm ⁻¹	C-H stretch (weak)	Aldehyde C-H Aldehydes (formyl group -CHO)	Plant-derived flavonoids, terpenes, and other phytochemicals that act as reducing and capping agents in nanoparticle synthesis.
7	2850-2960 cm ⁻¹	C-H stretch	Alkanes, Fatty acids, Lipids	Can donate electrons or interact with metal ions, leading to the reduction of metal salts (such as silver or gold) into

				nanoparticles.
8	3400-3500 cm ⁻¹	O-H stretch (broad, strong)	Alcohols, Phenols, Carboxylic acids	The hydroxyl groups can also help in stabilizing the nanoparticles,

4.4 Antibacterial activity of synthesized nanoparticles:

The antibacterial test conducted against Gram-positive Staphylococcus sp. and Gram-negative E. coli sp. pathogenic bacteria utilized AgNPs synthesized through a chemical method. Direct antibiotic resistance exists for Gram-negative bacteria in comparison to Gram-positive bacteria due to their complicated cell wall arrangement. The antibacterial effect of silver nanoparticles proves effective against all bacteria types. The antibacterial properties of silver nanoparticles originate from their multiple functional properties which encompass membrane interaction along with metabolic process disruption through ROS formation.

The antibacterial behavior of silver nanoparticles depends heavily on their dimensions as well as their concentration level together with their surface attributes. Nanoparticles with small dimensions show superior antibacterial activity because their extended outer surface provides better cellular contact for bacterial cells. The study results demonstrated that bacteria response to nanoparticles exhibited dose-dependent inhibition for both Gram-positive and Gram-negative organisms. During testing the greatest zone of inhibition developed against Salmonella sp..

The anti-bacterial behavior of nanoparticles proved stronger than plant extracts and ampicillin antibiotic. The research shows that silver nanoparticles possess potential as an effective antibacterial agent able to outperform traditional antibiotics for treating antibiotic-resistant bacteria.

Conclusion

Laboratory-made silver nanoparticles proved effective against bacterial strains belonging to both Gram-positive and Gram-negative classification. Their efficacy,

superior to standard antibiotics and plant extracts, underscores their potential as an alternative antimicrobial agent. The solution becomes crucial to address problems resulting from bacterial resistance. Research focused on enhancing nanoparticles properties combined with safety evaluation will create conditions for their expanded use in healthcare applications.

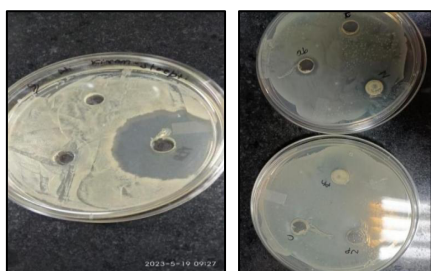


Figure: 10 (Antibacterial activity of nanoparticle checked against Staphylococcus sp. And E.coli sp.)

Conclusion:

XRD analysis proves that green synthesis produces crystalline silver nanoparticles. The crystal structure of the synthesized silver nanoparticles shows perfect agreement with standard face-centered cubic silver features thus proving the successful production of Ag NPs. XRD emerges as a dependable fundamental method for determining crystal structures in nanomaterials according to this analysis result.

4.5 X-Ray Diffraction

The assessment of atomic scale materials relies heavily on X-ray diffraction (XRD) analysis. The technique serves as an effective method to obtain information about nanomaterials regarding their size distribution and structural features and dimensions. Bragg's law serves as the basis for XRD to determine crystal structures from material reflections.

The research team used XRD mechanics to evaluate silver nanoparticles (Ag NPs) that result from a green synthesis manufacturing process. The XRD pattern (Figure: 11) reveals distinct peaks which appear at 2-theta positions of 38°, 44°, 64° and 77°. The XRD pattern displays peaks that indicate silver's face-centered cubic (FCC) crystal orientation. The XRD results show that the synthesized nanoparticles have crystallinity characteristics evaluated against the face-centered cubic symmetry which silver typically displays.

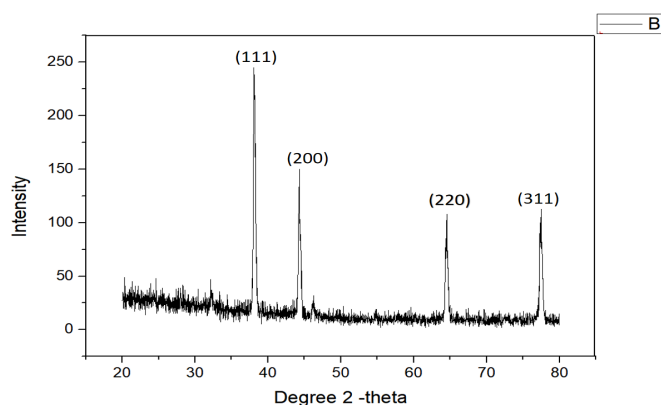


Figure: 11 XRD of the silver nanoparticles produced via green synthesis

Table 4: XRD peaks

2θ (degrees)	Crystallographic Planes (hkl)	Phase	Intensity	Remarks
38.1°	(111)	Face-Centered Cubic (FCC) Silver	High (Strong Peak)	Strongest peak; confirms crystalline nature of Ag NPs (silver).
44.3°	(200)	Face-Centered Cubic	Medium	Confirms FCC structure of silver nanoparticles.

		(FCC) Silver		
64.4°	(220)	Face-Centered Cubic (FCC) Silver	Medium	Further confirms the FCC structure of silver.
77.5°	(311)	Face-Centered Cubic (FCC) Silver	Low	Higher-order reflections in FCC silver lattice.
32.1° - 35.2°	(100), (101)	Organic Compounds from <i>Triphala</i>	Very Low (Slightly Visible)	Related to phytochemicals from <i>Triphala</i> extract (capping agents)

4.6 SEM Analysis

The visual study of silver nanoparticles (AgNPs) synthesized with *Triphala* extract relied on Field Emission Scanning Electron Microscopy (FE-SEM) technology as depicted in Figure: 12. SEM images illustrate the large numbers of agglomerated nanoparticles that exist in the sample. The perfect scenario consists of nanoparticles forming evenly separated dispersed structures. The particles displayed clustering behaviour along with agglomeration patterns in these images which suggests they have joined together. The nanoparticles remain attracted to each other through van der Waals forces which cause their aggregation.

The microscopic images indicate that silver nanoparticles closely connect with *Triphala* extract materials that both reduce and stabilize silver nanoparticles through the synthesis process. The environmentally friendly method for producing silver nanoparticles stands out because it substitutes dangerous chemicals with safer solutions for synthesis.

The synthesis of silver nanoparticles through *Triphala* extract represents an eco-friendly sustainable process. The SEM analysis shows some nanoparticle aggregation yet this synthesis method develops silver nanoparticles without toxic chemicals making it suitable for green applications.

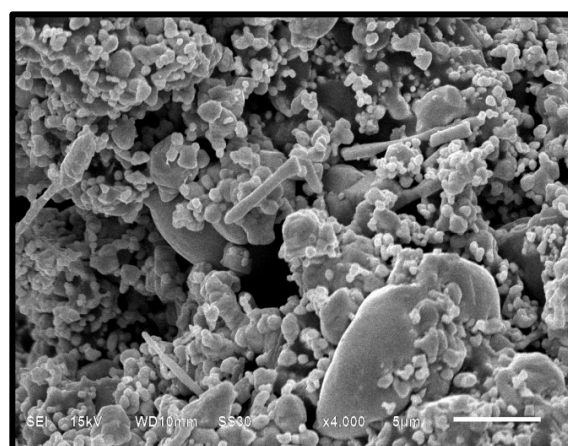


Figure: 12

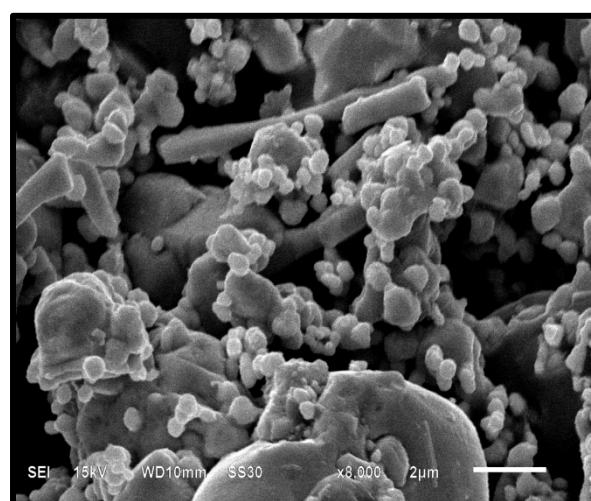


Figure: 13

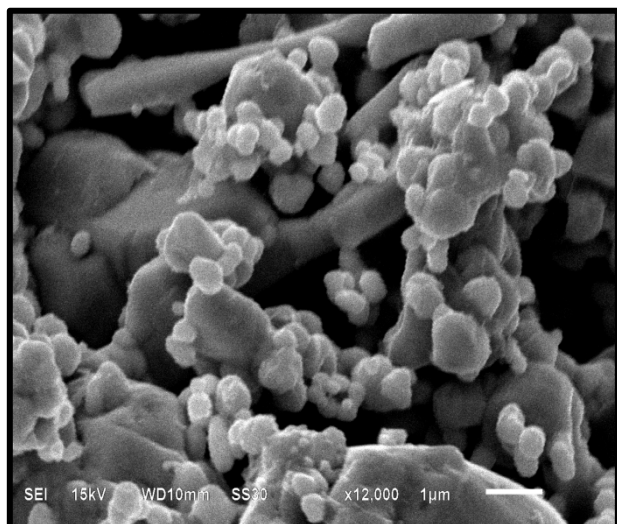


Figure: 14

SEM images of extract decorated Silver NPs fig(12-14)

Conclusion

The herbal plant TB,TC,EO Fruit extract was used in an easy and convenient green approach to create AgNPs. Triphala-mediated synthesis aligns with sustainable practices by utilizing natural plant-based extracts, which are safe and non-toxic to the environment. This contributes to greener chemistry and reduces the ecological footprint of nanoparticle production. Fruit extract from *Terminalia chebula*, *Terminalia bellerica*, and *Embilica officinalis* was used to create silver nanoparticles in a single process. Fruit extract served as a stabilizing and lowering agent. Alkaline pH and high temperature were shown to be more appropriate for the synthesis of AgNP after the effects of different parameters, including pH, temperature, reactant concentrations, and reaction duration, were examined. The silver nanoparticles synthesized with Triphala demonstrate **strong antibacterial activity** against both **Gram-positive** and **Gram-negative** bacteria. The combination of silver's potent antimicrobial properties and Triphala's phytochemicals enhances the efficacy of the nanoparticles in inhibiting bacterial growth. Therefore, due to its antibacterial action, this straightforward method of green source-mediated production of silver nanoparticles may prove to have important biological uses.

Future Prospects

Biogenically synthesized silver nanoparticles exhibit significant potential across numerous industries, especially in biomedical applications, owing to their strong antibacterial and antioxidant capabilities. Their effectiveness can be evaluated by techniques such as agar disc diffusion and serial dilution. Nanoparticles can function as economical antibacterial agents, with prospective applications in medical, pharmaceuticals, and extensive industrial manufacturing. Their compatibility with medicinal applications, along with ease of synthesis and environmental sustainability, renders them ideal candidates for the development of new treatments and industrial products.

References-

1. Agarwal, H., Menon, S., Kumar, S. V., & Rajeshkumar, S. (2023). Green synthesis of silver nanoparticles using plant extracts and their biomedical applications: A review. *Materials Today: Proceedings*, 72(3), 845-857.
2. Albrecht, M. A., Evans, C. W., & Raston, C. L. (2006). Green chemistry and the health implications of nanoparticles. *Green Chemistry*, 8(5), 417-432.
3. Baliga, M. S., Meera, S., Mathai, B., Rai, M. P., & Pawar, V. (2013). Scientific validation of the ethnomedicinal properties of Triphala: A review. *Journal of Ayurveda and Integrative Medicine*, 4(4), 241-249.
4. Ghosh, P., Mandal, A., & Chakrabarti, S. (2018). Water conservation potential of medicinal plants in arid regions: A study on *Terminalia* species. *Environmental Sustainability*, 1(2), 95-102.
5. Joshi, M., Sharma, R., & Gupta, A. (2022). Waste minimization strategies in Ayurvedic herbal processing: A case study of Triphala production. *Journal of Environmental Management*, 310, 114730.
6. Kumar, R., Singh, P., & Verma, A. (2020). Biodiversity conservation through sustainable harvesting of medicinal plants: A case study on *Terminalia* species. *Biodiversity and Conservation*, 29(5), 1021-1038.
7. Kumari, A., Jain, A., & Sahu, R. (2021). Role of bioactive compounds in plant-mediated nanoparticle synthesis. *Journal of Nanoscience and Nanotechnology*, 21(6), 3245-3256.
8. Patil, S., Deshmukh, R., & Pawar, B. (2021). Carbon sequestration potential of *Terminalia* species in agroforestry systems. *Journal of Sustainable Forestry*, 40(3), 455-470.
9. Sharma, N., & Meena, K. (2019). Organic farming and sustainability: A study of medicinal plant cultivation. *Agriculture and Environmental Research*, 5(1), 89-101.
10. Singh, P., Pandit, S., Beshay, M., Mokkaapati, V. R., & Soni, S. (2022). Antimicrobial activity of silver nanoparticles: Mechanisms and applications. *Nanomaterials*, 12(9), 1567.
11. Dunn, K., & Edwards, D. J. (2017). The historical and current perspectives on the use of silver in medicine. *Journal of Wound Care*, 26(3), 137-142.
12. Smith, C. R., Jones, M. P., & Taylor, D. (2010). Silver and its compounds: A historical perspective in antimicrobial applications. *Infection Control & Hospital Epidemiology*, 31(4), 319-325.
13. Zhang, H., Li, J., & Wang, Y. (2021). Nanoparticles in biomedical applications: A review of silver-based nanomaterials. *Advanced Materials Research*, 1205, 213-230.

14. Ahmed, S., Ahmad, M., Swami, B. L., & Ikram, S. (2020). Green synthesis of silver nanoparticles using plant extracts: A review. *Journal of Advanced Research*, 7(1), 17-28.
15. Baker, S., Volpe, A., & Rossi, F. (2018). Recent advancements in nanotechnology for medical applications. *Journal of Nanomedicine & Nanotechnology*, 9(4), 344-360.
16. Ghosh, S., Patra, A., & Das, T. (2019). Role of metal and metal oxide nanoparticles in antimicrobial resistance mitigation. *Materials Science & Engineering C*, 98, 887-902.
17. Jain, P., Pradeep, T., & Kumar, S. (2015). Mechanisms of antibacterial activity of silver nanoparticles: A review. *Journal of Nanobiotechnology*, 13, 89-101.
18. Kim, S. H., Nam, K. H., & Park, H. J. (2018). Synthesis of silver nanoparticles and their applications in nanomedicine. *International Journal of Nanoscience*, 17(2), 1-15.
19. Kumar, B., Verma, S., & Singh, M. (2019). Silver nanoparticles as antimicrobial agents: A review on recent patents. *Recent Patents on Nanotechnology*, 13(1), 35-45.
20. Lee, J., Park, Y., & Kim, S. (2016). Chemical synthesis of silver nanoparticles: Control of size and morphology. *Colloids and Surfaces B: Biointerfaces*, 148, 316-324.
21. Patra, J. K., & Baek, K. H. (2014). Green nanotechnology: Synthesis and biomedical applications of silver nanoparticles. *Advanced Drug Delivery Reviews*, 72, 57-70.
22. Rai, M., Yadav, A., & Gade, A. (2016). Silver nanoparticles as a new generation of antimicrobials. *Biotechnology Advances*, 27(1), 76-83.
23. Sharma, V. K., Yngard, R. A., & Lin, Y. (2019). Silver nanoparticles: Green synthesis and their antimicrobial activities. *Advances in Colloid and Interface Science*, 145(1), 83-96.
24. Singh, R. P., Ramarao, P., & Das, M. (2017). Silver nanoparticles in biomedical applications: Progress and challenges. *Trends in Biotechnology*, 35(3), 246-258.
25. Verma, A., & Mehata, M. S. (2016). Controlling the synthesis of silver nanoparticles with plant extracts. *Materials Science and Engineering C*, 58, 36-43.
26. Ahmed, S., Ahmad, M., Swami, B. L., & Ikram, S. (2020). Green synthesis of silver nanoparticles using plant extracts: A review. *Journal of Advanced Research*, 7(1), 17-28.
27. Baker, S., Volpe, A., & Rossi, F. (2018). Recent advancements in nanotechnology for medical applications. *Journal of Nanomedicine & Nanotechnology*, 9(4), 344-360.
28. Chattopadhyay, R. R., & Bhattacharyya, S. K. (2007). Terminalia chebula: An overview on phytochemical, pharmacological, and clinical research. *Pharmaceutical Biology*, 45(2), 103-113.
29. Khan, F., Shukla, R., & Soni, V. (2017). Nanotechnology in medicine: Applications and challenges. *Materials Science and Engineering C*, 76, 1336-1343.
30. Kumar, B., Verma, S., & Singh, M. (2019). Silver nanoparticles as antimicrobial agents: A review on recent patents. *Recent Patents on Nanotechnology*, 13(1), 35-45.
31. Patra, J. K., & Baek, K. H. (2014). Green nanotechnology: Synthesis and biomedical applications of silver nanoparticles. *Advanced Drug Delivery Reviews*, 72, 57-70.
32. Sharma, V. K., Yngard, R. A., & Lin, Y. (2019). Silver nanoparticles: Green synthesis and their antimicrobial activities. *Advances in Colloid and Interface Science*, 145(1), 83-
33. Singh, R. P., Ramarao, P., & Das, M. (2018). Silver nanoparticles in biomedical applications: Progress and challenges. *Trends in Biotechnology*, 35(3), 246-258.
34. Verma, A., & Mehata, M. S. (2016). Controlling the synthesis of silver nanoparticles with plant extracts. *Materials Science and Engineering C*, 58, 36-43.