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Phyto-fabricated Silver Nanoparticles for Antibacterial and Anticancer Activities: A Review

Jitendra Chourey and Dr. Praveen Tahilani

Department of Pharmacy, Sanjeev Agrawal Global Educational (SAGE) University, Bhopal, M.P., India

Corresponding Author: Jitendra Chourey, Email: Jeetuchourey@gmail.com

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Abstract

Green synthesis of silver nanoparticles (AgNPs) using plant-based materials has gained significant attention in recent years due to its eco-friendly, cost-effective, and sustainable approach. This review explores the recent advancements in the phyto-fabrication of AgNPs, highlighting their potential applications in antibacterial and anticancer therapies. Plant extracts serve as natural reducing and stabilizing agents, leading to the formation of nanoparticles with enhanced biological properties. The antibacterial activity of these nanoparticles is attributed to their ability to disrupt microbial membranes, generate reactive oxygen species, and interfere with cellular functions. In the context of cancer treatment, phyto-synthesized AgNPs have shown promising results in inducing apoptosis, inhibiting tumor growth, and enhancing drug delivery. This review consolidates findings from recent studies to provide a comprehensive understanding of the synthesis methods, characterization techniques, and therapeutic mechanisms of action, along with discussing current challenges and future perspectives in clinical translation.

*Keywords:*Green nanotechnology, Apoptosis, Reactive oxygen species, Plant extracts, Biocompatibility, Nanomedicine.

1. Introduction

Silver nanoparticles (AgNPs), generally measuring between 1 and 100 nanometers in diameter, have attracted widespread scientific interest due to their distinct physicochemical properties and varied nanostructures, making them ideal for numerous biomedical applications (Almatroudi, 2020). Their notable antimicrobial and anticancer activities, combined with their wound healing capabilities and low production cost, make them valuable assets in therapeutic practices. Traditionally, AgNPs have been synthesized using chemical and physical methods, which often rely on toxic substances and high energy inputs, raising concerns regarding environmental safety and health implications (Verma et al., 2023a).

Recent trends have shifted toward green solution approaches, particularly phyto-fabrication, which utilizes plant-based extracts as both reducing and stabilizing agents (Aljeldah et al., 2023). This eco-friendly method reduces reliance on harmful chemicals and leverages the natural biocompatibility of plant-derived compounds, improving the biomedical suitability of the synthesized nanoparticles (Verma et al., 2023). In phyto-fabrication, silver ions are reduced to nanoparticles by mixing plant extracts with silver nitrate ($AgNO_3$), and the color change to brown or yellowish hues indicates successful nanoparticle formation (Vanlalveni et al., 2021; Abdelrahman & Basha, 2025; Velidandi et al., 2020).

The synthesis process is influenced by several parameters, including pH, temperature, reactant concentrations, light exposure, duration of reaction, and the specific phytochemical content of the plant extract (Nayak and Begur, 2023). These plant-based methods are advantageous due to their scalability, low cost, and elimination of microbial cultures (Krishnan et al., 2016). Phytochemicals such as flavonoids, alkaloids, and terpenoids aid in both reducing silver ions and stabilizing the nanoparticles, preventing their aggregation and enhancing long-term stability (Sumitha et al., 2018). By carefully adjusting the synthesis conditions, researchers can regulate the shape, size, and biological activity of the resulting nanoparticles.

Thorough characterization of these green-synthesized AgNPs is essential to understand their physical and chemical traits, which influence their biological performance. Techniques such as

UV-Visible spectroscopy are commonly used to confirm nanoparticle formation by detecting the surface plasmon resonance peak between 400–450 nm. Fourier Transform Infrared Spectroscopy (FTIR) helps identify the functional groups involved in reduction and stabilization (Ezealisiji et al., 2017), while X-ray Diffraction (XRD) provides data on the crystalline structure and phase purity of the nanoparticles. Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) offer direct visualization of nanoparticle morphology and size distribution. Dynamic Light Scattering (DLS) and zeta potential analyses are used to assess particle size distribution and surface charge, respectively—key indicators of nanoparticle stability and biological interaction potential (Mahiuddin et al., 2020).

The synthesis method plays a significant role in defining nanoparticle characteristics such as morphology and surface charge, directly influencing their interactions with biological systems. Phyto-fabricated AgNPs exhibit strong antimicrobial effects through multiple mechanisms, including damaging bacterial membranes, generating reactive oxygen species (ROS), and disrupting cellular components such as DNA and proteins. These effects can inhibit bacterial replication and biofilm formation, making the nanoparticles effective even against antibiotic-resistant strains (Mousavi &Naghsh, 2021). Green-synthesized AgNPs have shown antimicrobial efficacy against pathogens like *Staphylococcus aureus*, *Streptococcus pyogenes*, *Salmonella spp.*, and *Bacillus amyloliquefaciens* (Ghiuță et al., 2021), and have demonstrated particular effectiveness against multidrug-resistant *Staphylococcus epidermidis* (Thomas et al., 2014) (Figure 1).

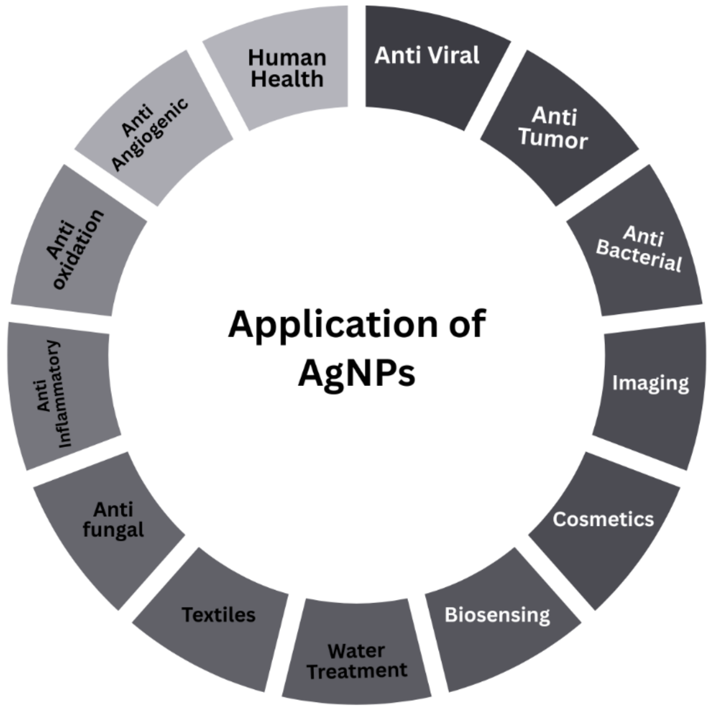

Figure 1: Application of Nanoparticle

When used at low concentrations, AgNpsare generally non-toxic to human cells, making them suitable for medical applications such as infection control in burn care, surgical implants, catheters, dental materials, and skin treatments (Ruttkay-Nedecký et al., 2018).

In addition to their antimicrobial uses, phyto-fabricated AgNps show promising anticancer activity. They can induce programmed cell death (apoptosis) in cancer cells by disrupting mitochondrial functions, leading to the release of cytochrome c and activation of caspase enzymes. These nanoparticles can also cause cell cycle arrest and oxidative DNA damage, further inhibiting cancer cell growth. A major advantage of AgNPs in cancer treatment is their selective cytotoxicity—targeting malignant cells while causing minimal harm to healthy cells. In this review we included fabrication of Nanoparticle by green methods, mechanism, factors that are responsible for increasing for efficiency of AgNPs.

2. Phyto-fabrication of Silver Nanoparticles

The rapidly advancing field of nanotechnology has increasingly focused on the synthesis of AgNPsdue to their distinctive physicochemical characteristics and versatile applications across various sectors, including healthcare, catalysis, and environmental management (Abdelrahman &

Basha, 2025; Ahmad et al., 2020; Almatroudi, 2020). Among the different synthesis techniques, green synthesis or phyto-fabrication has gained prominence as an effective alternative to traditional physical and chemical methods. This eco-conscious approach is not only cost-efficient but also environmentally sustainable (Murali et al., 2019; Shyam et al., 2020).

The widespread use of silver is primarily attributed to its well-documented antibacterial and antioxidant properties (Bantho et al., 2023). In phyto-fabrication, plant extracts rich in naturally occurring biomolecules act as both reducing and stabilizing agents, thus negating the use of toxic chemicals and energy-demanding procedures (Folorunso, 2019). Rooted in the principles of green chemistry, nanobiotechnology represents a promising frontier with significant potential for producing novel materials that support human health, environmental sustainability, and industrial innovation (Bamal et al., 2021). In table 1 incorporated name of plant used for phyto fabrication of AgNPs, and their applications in biomedical science.

Table 1: Phyto fabrication of AgNPs and their applications in biomedical science

S. No.	Plant Name	Method of synthesis	Biomedical applications	Reference
1	Coffee arabica leaf extract	Aqueous extract decreases Ag^+ to Ag^0 in minutes; identified by UV Vis, FTIR, TEM; diameter ~5–20 nm	For biosensing of L cysteine; high sensitivity, low detection limit; antimicrobial activity	Haridas et al., 2022
2	*Curcuma longa* flower extract	Green synthesis through flower extract; ascertained spherical ~5 nm through UV Vis, XRD, HR TEM	Excellent antibacterial activity against Mycobacterium smegmatis, S. aureus, K. pneumoniae	Rajak et al., 2023
3	*Trillium govanianum* rhizome	Phytochemical reduction by rhizome extract; completely biocompatible; comprehensive in vitro & in silico studies	Antioxidant, antimicrobial and anticancer activity; docking insights with molecular targets	Rehman et al., 2025
4	*Champia parvula* (red seaweed)	Seaweed mediated extraction employed for reducing Ag^+;	Cytotoxicity and antimicrobial against human pathogens	Viswanathan et al., 2024

		complete characterization of nanoparticles		
5	*Lonicera japonica* leaves	Leaf extract employed as reducing/capping agent to prepare AgNPs	Anti inflammatory and antimicrobial activity	Zhang et al., 2022
6	*Punica granatum* peel waste	Peel waste extract lowers Ag^{+}; low cost and eco friendly	Inhibition of foodborne pathogens; possible therapeutic application	Farouk et al., 2023
7	*Cyanobacterium Synechocystis* sp.	Biosynthesis with cyanobacterial extracellular metabolites	Antimicrobial and diabetic wound healing activity	Younis et al., 2022
8	*Graesiellaemersonii* (microalga)	Utilization of extracellular polymeric substances to lower silver ions; green fermentation	Antimicrobial biomedicine and applications in the environment	Do et al., 2025
9	*Durantaerecta*	Leaf extract application for synthesis of AgNPs	Antimicrobial applications	Verma et al., 2025

2.1 Mechanism of Synthesis

The green synthesis of AgNPsthrough phyto-fabrication relies heavily on the bioactive compounds present in plant extracts, which play a dual role—reducing silver ions (Ag^{+}) to metallic silver and simultaneously stabilizing the formed nanoparticles to prevent clumping or aggregation (Sumitha et al., 2018). This method generally entails carefully blending an aqueous plant extract with a silver nitrate ($AgNO_3$) solution, where the plant biomolecules act on the silver precursor under specific reaction conditions to initiate and sustain the reduction process (Krishnan et al., 2016).

A visible shift in color—commonly to brown or yellow—often signals the successful formation of silver nanoparticles. This color change arises due to surface plasmon resonance (SPR), which occurs as the conduction electrons on the nanoparticle surface resonate with light (Ezealisiji et al., 2017). Although widely used, the exact biochemical mechanism by which plant materials reduce metal ions remains incompletely understood, warranting continued scientific investigation (Babu & Prabu, 2011).

Compounds such as flavonoids, terpenoids, proteins, and polysaccharides within the plant extract are recognized as key contributors to the reduction process, as they donate electrons that convert silver ions to their neutral atomic form (Sandhya &Kalaiselvam, 2019). These atoms undergo nucleation followed by particle growth, ultimately leading to the development of stable nanoparticles (Mittal et al., 2014). These biomolecules also serve as capping agents, effectively coating the nanoparticles and preventing their agglomeration, thus enhancing their stability over time (Mittal et al., 2013; Thomas & Mathew, 2019).

This method aligns closely with green chemistry ideals, favoring the use of non-toxic, biocompatible substances while minimizing ecological harm (Trivedi et al., 2022; (Nayak and Begur, 2023). Unlike conventional physical and chemical techniques, which often require hazardous reagents and significant energy input, the phyto-fabrication route presents a safer and more sustainable alternative (Rawat et al., 2018).

2.2 Factors Influencing Synthesis

The phyto-synthesis of silver nanoparticles is a multifaceted process influenced by numerous variables, all of which play vital roles in determining the morphology, size, stability, and overall yield of the nanoparticles (Antonio-Pérez et al., 2023). Gaining a deep understanding of these parameters and optimizing them is essential for producing nanoparticles with desired properties and for ensuring consistency across experiments.

Key factors influencing the synthesis include the concentrations of plant extract and silver nitrate, reaction temperature, pH, and duration of the reaction. The amount of plant extract affects the availability of phytochemicals acting as reducing agents—higher concentrations may accelerate the reduction process and often result in the formation of smaller nanoparticles. Similarly, the silver nitrate concentration defines the supply of silver ions and directly influences the quantity of nanoparticles formed (Vanlalveni et al., 2021).

Temperature significantly affects reaction kinetics: while elevated temperatures can hasten reduction, they may also promote nanoparticle aggregation. Meanwhile, pH alters both the redox behavior of the extract and the surface charge of nanoparticles, which can impact their colloidal stability and tendency to aggregate (Kumar et al., 2019). Reaction time dictates the progression of silver ion reduction; extended durations may lead to larger particles and increased size variability.

Beyond these core parameters, other influences include the species of plant used, the method employed for extract preparation, and the specific phytochemicals present, all of which can affect nanoparticle characteristics (Khan & Ali, 2020). To efficiently fine-tune these variables, researchers often turn to response surface methodology (RSM)—a statistical approach that optimizes conditions with minimal experimental trials (Ibrahim et al., 2021). Through careful adjustment of these factors, it becomes possible to custom-engineer silver nanoparticles tailored to meet the demands of specific biomedical or industrial applications (Dada et al., 2018).

3. Characterization of Phyto-synthesized Silver Nanoparticles

Characterizing silver nanoparticles synthesized via phyto-fabrication is essential for evaluating their physicochemical properties and determining their suitability for targeted applications (Abdelrahman & Basha, 2025). A range of analytical tools is employed to investigate various aspects of these nanoparticles, including their structural formation, stability, morphology, and surface attributes (Patil &Chougale, 2021). These characterization techniques are crucial in assessing the quality and functionality of the nanoparticles, especially for their use in sectors like biomedicine, catalysis, and environmental protection (Ezealisiji et al., 2017; Rajeshkumar et al., 2019).

Furthermore, understanding how nanoparticles are synthesized, how they are stabilized by plant-derived compounds, and how they behave under different environmental or biological conditions is critical for data comparison across systems, development of structure-activity relationships, and advancing predictive toxicology models (Reidy et al., 2013) (Table 2).

Table: 2 Analytical Techniques for Characterization

Technique	**Principle**	**Information Provided**	**Application in Nanoparticle Characterization**	**Reference**
UV-Visible Spectroscopy	Absorption of light in UV-Vis region	Optical properties, Surface Plasmon Resonance (SPR)	Confirms synthesis, monitors stability and aggregation	Badi'ah et al., 2019; Calderón-Jiménez et al., 2017; Amirjani et al., 2019; González-Castillo et al., 2015
DLS	Measures light scattering by particles in suspension	Particle size distribution, zeta potential	Determines hydrodynamic size and colloidal stability	Bruna et al., 2021
FTIR	Absorption of IR radiation by chemical bonds	Functional groups, surface chemistry	Identifies capping agents or functionalization of nanoparticles	Torras & Roig, 2020
XRD	Diffraction pattern from crystalline structures	Crystallinity, phase identification, particle size	Determines crystal structure and average crystallite size	Patel et al., 2016
SEM	Electron beam scans sample surface	Surface morphology, particle size	Provides high-resolution surface images	Karthiga et al., 2020

TEM	Electron beam transmitted through sample	Size, shape, crystal structure	High-resolution imaging and structural analysis	Bharti et al., 2015; Sao et al., 2024
EDX/EDS	X-rays emitted by atoms upon electron bombardment	Elemental composition	Confirms elemental presence in nanoparticles	Verma et al., 2023; Deshpande et al., 2024
Zeta Potential Analysis	Measures electrophoretic mobility	Surface charge, colloidal stability	Evaluates stability and dispersion in solution	Patil and Chougale, 2021

5. Antibacterial Activity of Phyto-Fabricated Silver Nanoparticles

The use of silver as an antimicrobial agent dates back centuries (Kędziora et al., 2018; Ruttkay-Nedecký et al., 2018). However, the discovery and widespread adoption of antibiotics in the 20th century overshadowed its medical use (Li et al., 2020). The growing threat of antibiotic resistance in recent decades has revived interest in silver, especially in its nanoparticle form, as a potent antibacterial material (Franci et al., 2015).

AgNPs display remarkable antibacterial potential due to their nanoscale size and high reactivity, making them effective against a broad range of Gram-positive: *Staphylococcus aureus*(Bantho et al., 2023), *Bacillus subtilis*(More et al., 2023), *Streptococcus pyogenes*(Vardanyan et al., 2015), *Listeria monocytogenes*(Mousavi &Naghsh, 2021), *Enterococcus faecalis*(Panáček et al., 2015)and Gram-negative bacteria: *Escherichia coli*(Chen et al., 2020), *Pseudomonas aeruginosa*(Ren et al., 2009), *Klebsiella pneumoniae*(Normani et al., 2021), *Salmonella typhimurium*(Kaiser et al., 2023), *Proteus vulgaris*(El-Sayed et al., 2023)(Gurunathan et al., 2014).

5.1 Mechanisms of Antibacterial Action

The antimicrobial efficacy of plant-mediated AgNPsarises from multiple, synergistic mechanisms. One of the primary actions is the compromise of bacterial cell membrane integrity. Silver nanoparticles attach to and penetrate the cell wall, causing structural disruptions that lead to leakage of cellular components and eventual cell death (Mousavi &Naghsh, 2021).

Additionally, AgNPs promote the formation of ROS, including hydroxyl radicals, superoxide ions, and hydrogen peroxide. These ROS inflict oxidative damage on proteins, lipids and DNA, ultimately impairing bacterial function and viability (Brown et al., 2012).AgNPscan also bind to bacterial DNA, interfering with replication and transcription processes, which inhibits the production of essential proteins and enzymes (Mousavi &Naghsh, 2021).Moreover, AgNPs can inhibit biofilm formation, which is a major defense mechanism used by bacteria to resist antimicrobial agents. AgNPs reduce the ability of bacteria to form biofilms by preventing surface adherence and matrix development, thereby enhancing their vulnerability(Seetharaman et al., 2024). The broad-spectrum activity and multiple modes of action make phyto-fabricated AgNPsa promising solution against resistant pathogens (Fig 2).

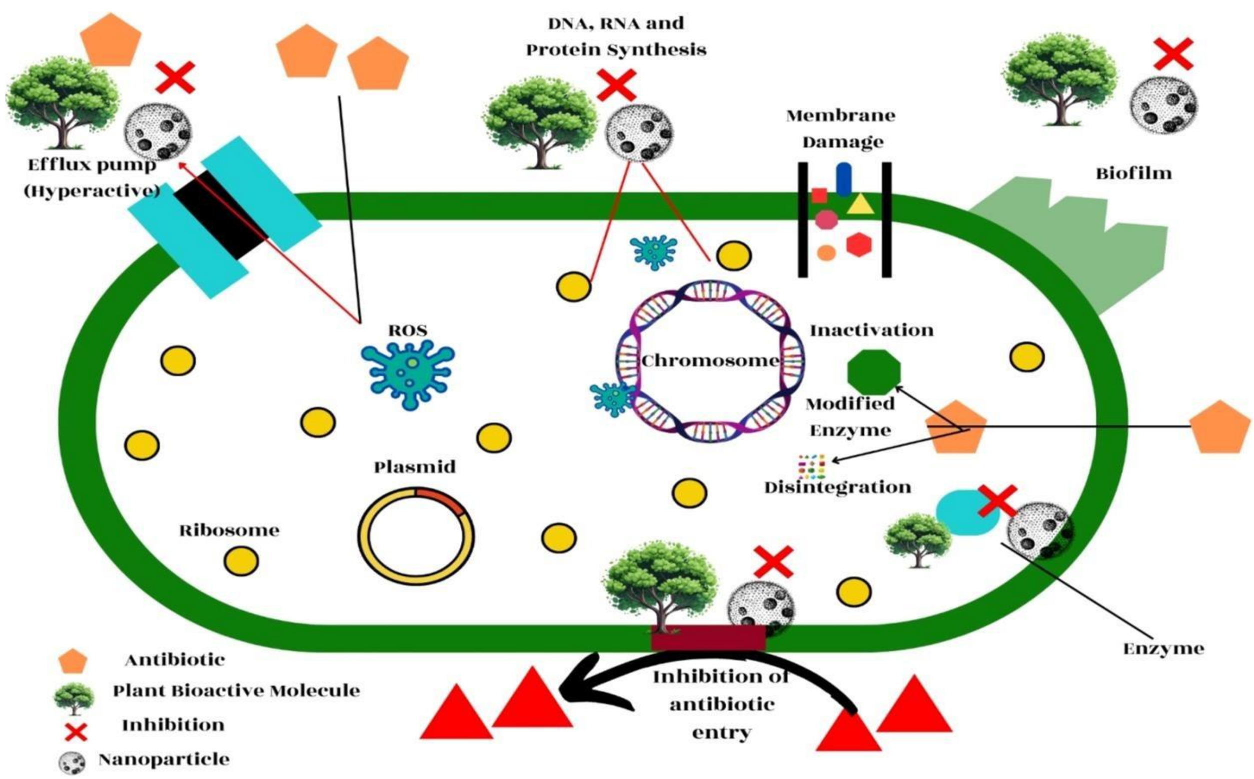

Fig 2: Mechanism of antimicrobial activity (Verma et al., 2025)

6. Anticancer Activity of Phyto-Fabricated Silver Nanoparticles

Developing innovative cancer therapies is essential to overcome the limitations of traditional treatments, such as adverse effects and resistance (Azizi et al., 2017). Nanotechnology, particularly AgNPs, has emerged as a promising platform in oncology (Tunç, 2024). Green synthesis methods utilizing plant extracts provide an eco-friendly and cost-efficient route for nanoparticle production (Almatroudi, 2020), while also offering biocompatibility and versatility in medical applications (Abdelrahman & Basha, 2025).

Due to their nanoscale size and unique surface properties, AgNPs can efficiently target tumor cells, enhancing drug delivery and therapeutic outcomes (Bantho et al., 2023). They are being explored for roles in infection control, diagnostics, and treatment of diverse cancers (Rai et al., 2014).

6.1 Mechanisms of Anticancer Action

Phyto-synthesized AgNPs exhibit anticancer activity through multiple interconnected mechanisms, enabling selective toxicity towards cancer cells (Aljeldah et al., 2023). One of the primary mechanisms involves mitochondrial dysfunction, which triggers the release of pro-apoptotic proteins and initiates programmed cell death (apoptosis) (Zhang et al., 2025). This pathway is particularly effective in cancer cells, which typically have altered mitochondrial behavior.

6.2 Efficacy Against Cancer Cell Lines

Phyto-fabricated silver nanoparticles have shown considerable anticancer potential through their cytotoxic effects on various cancer cell lines, indicating their promise as broad-spectrum therapeutic agents. These nanoparticles have been evaluated across cell lines of different tissue origins, offering insight into their versatility and effectiveness in treating multiple cancer types. For example, HeLa cells, derived from cervical cancer, have been particularly sensitive, displaying significantly reduced proliferation and viability when treated with phyto-synthesized silver nanoparticles (Rai et al., 2014). Likewise, MCF-7 breast cancer cells exhibited signs of apoptosis and growth inhibition following treatment (Babu et al., 2020).

In studies involving A549 lung carcinoma cells, silver nanoparticles facilitated tumor suppression and induction of cell death, showing strong effects in pulmonary cancer models (Singh et al., 2019). Similarly, HT-29 colon cancer cells responded to these nanoparticles with significant cytotoxic effects, reinforcing their utility in gastrointestinal cancers (Sukri et al., 2021).

The green synthesis of these nanoparticles involves plant-derived compounds acting as reducing and capping agents, preventing particle aggregation while aiding nanoparticle stability (Sumitha et al., 2018). This biologically mediated process offers several advantages including eco-friendliness, cost-efficiency, and compatibility with medical applications (Bantho et al., 2023; Thomas & Mathew, 2019).

To assess anticancer efficacy, various in vitro assays are employed such as the MTT, SRB, clonogenic, and colony formation assays (Jeevanandam et al., 2020). Results from these studies consistently show a dose-dependent reduction in cell viability, indicating that increasing nanoparticle concentrations leads to enhanced cytotoxicity (Alsubki et al., 2021). Remarkably, these nanoparticles are non-toxic to humans at low concentrations while being highly effective against a broad range of microbes and cancer cells (Ahmad et al., 2010).

TEM has verified the presence of nanoparticles within cancer cells, providing evidence of their efficient cellular uptake and interaction with internal structures. In vitro studies also suggest that these nanoparticles can trigger cellular apoptosis, increase oxidative stress, generate reactive oxygen species ROS and cause genotoxic effects (Silván et al., 2018).

6.3 Mechanisms of Anticancer Action

The anticancer efficacy of phyto-synthesized silver nanoparticles arises from a variety of mechanisms operating at both molecular and cellular levels. A primary route is the induction of oxidative stress, where ROS generation leads to disruption of redox homeostasis, ultimately damaging essential cellular structures (Subbaiya & Selvam, 2013). Furthermore, these nanoparticles compromise mitochondrial integrity, resulting in the release of apoptotic signals and the initiation of programmed cell death.

They also cause DNA damage by directly interacting with the genetic material, interfering with DNA replication and repair processes, thereby causing cell cycle arrest and eventual apoptosis. Silver ions, known for their strong antimicrobial effects, exhibit similar interactions in cancer cells by disrupting cellular metabolism (Sangsuwan et al., 2016).

AgNPs have emerged as promising nanomaterials in cancer therapy due to their ability to target multiple intracellular and molecular mechanisms. One of the critical intracellular targets of AgNPs is the mitochondria, where they impair ATP production by disrupting the mitochondrial membrane potential and inhibiting the electron transport chain. This leads to a reduction in cellular energy levels, ultimately impairing vital biological functions and triggering apoptotic pathways (Akhter et al., 2021). Furthermore, AgNPs increase ROS generation, which damages cellular components and promotes oxidative stress-mediated cell death (Jeyaraj et al., 2019). In addition to mitochondrial disruption, AgNPs influence key signaling pathways implicated in cancer cell survival and proliferation. Notably, AgNPs downregulate the PI3K/Akt signaling pathway, which is commonly overactive in tumors and plays a role in promoting cell survival, metabolism, and resistance to apoptosis (Gurunathan et al., 2019). Inhibition of this pathway enhances cancer cell sensitivity to apoptosis. AgNPs also modulate the MAPK signaling cascade, particularly the ERK, JNK, and p38 kinases. By inducing oxidative stress, AgNPs activate pro-apoptotic kinases like JNK and p38, leading to DNA damage, cell cycle arrest, and apoptotic cell death (Franci et al., 2015). Additionally, AgNPs are known to activate tumor suppressor proteins such as p53 and caspase-dependent apoptotic pathways, and they may inhibit nuclear factor kappa B (NF-κB), reducing inflammatory responses and tumor invasiveness (Rastogi et al., 2020). These multiple modes of action make AgNPs potent anticancer agents capable of targeting various hallmarks of cancer.

Further, the nanoparticles exhibit an affinity for phosphorus and sulfur groups in DNA, disrupting replication and contributing to their anticancer and antimicrobial potency (Prabhu & Poulose, 2012). Their ability to generate ROS significantly contributes to oxidative stress, a central element in cancer cell apoptosis. Due to their potent bioactivity, silver nanoparticles are now found in numerous commercial and healthcare applications, including cosmetics, wound dressings, textiles, coatings, and food packaging (Li et al., 2020; Zhang & Tanaka, 2014).

7. Phyto-fabricated AgNPs: A Sustainable and Versatile Approach for Biomedical Applications

AgNPs offers a sustainable and safe alternative to traditional chemical approaches(Shyam et al., 2020).This method minimizes environmental impact while producing nanoparticles with enhanced biocompatibility and functional surfaces, which are ideal for medical and pharmaceutical use (Sandhya & Kalaiselvam, 2019). The resulting nanoparticles are not only effective in targeting diseases like cancer but are also adaptable for diagnostics, drug delivery, and infection control, making this an appealing strategy for modern biomedical science.

Table 3:Sustainable and Versatile Approach for Biomedical Applications

Application Area	**Details / Benefit**	**Reference**
Chronic Wound Healing	AgNP-incorporated nanofiber dressings enhance antibacterial activity and accelerate tissue regeneration in diabetic and burn wounds.	Sabarees et al. (2022)
Antimicrobial Therapy	AgNPs exhibit broad-spectrum activity against multidrug-resistant bacteria and biofilms.	González-Fernández et al. (2025)
Biofilm Disruption	Effective in preventing or disrupting microbial biofilms in chronic infections and on medical devices.	Sabarees et al. (2022)
Anticancer Potential	Induce apoptosis in cancer cells via ROS generation and modulation of signaling pathways (PI3K/Akt, MAPK).	Pasparakis (2022)
Clinical Trials in Dermatology & ENT	Phase I/II trials of AgNP hydrosols and topical formulations for chronic rhinosinusitis and plantar warts show	Dias et al., (2025)

	efficacy and good tolerability.	
Antiviral Applications	Inactivation of viruses such as SARS-CoV-2 and herpes viruses via binding to viral proteins and blocking entry.	Pasparakis, (2022)
Anti-Inflammatory Effects	AgNPs reduce pro-inflammatory cytokines (IL-6, TNF-α) and support tissue compatibility in wound healing.	Afkhami et al., 2023
Antimycobacterial Nanosystems	Silver-loaded mesoporous silica nanoparticles effective against *Mycobacterium tuberculosis* cell envelope.	Montalvo-Quiros et al. (2021)

8. Advantages of Phyto-Fabricated AgNPs

8.1 Eco-Friendly and Non-Toxic Synthesis Process

The phyto-fabrication of silver nanoparticles (AgNPs) employs plant-derived biomolecules as both reducing and stabilizing agents, offering a green alternative to conventional chemical and physical synthesis methods. Traditional methods often rely on hazardous reagents like sodium borohydride or hydrazine, which can produce toxic byproducts harmful to both humans and the environment. In contrast, plant extracts are rich in secondary metabolites such as phenolics, flavonoids, terpenoids, alkaloids, and proteins that mediate the bioreduction of Ag^{+} ions to Ag^{0} nanoparticles under ambient conditions (Iravani, 2011; Ahmed et al., 2016).

This biosynthetic approach eliminates the need for high temperature, pressure, and toxic solvents, thereby minimizing environmental burden and occupational hazards. The phytochemicals not only reduce silver ions but also stabilize the nanoparticles, preventing agglomeration without the need for synthetic capping agents. Furthermore, these AgNPs demonstrate lower cytotoxicity and improved biocompatibility when compared to chemically synthesized counterparts, which is critical for biomedical applications such as antimicrobial agents, wound healing, and drug delivery systems (Moezzi et al., 2012; Mittal et al., 2021).

The eco-friendly profile of phyto-fabricated AgNPs is further enhanced by the use of renewable plant materials, often including agricultural or medicinal plant waste, making the process cost-effective and sustainable(Velidandi et al., 2020). Notably, the reaction often occurs in aqueous media, thus avoiding organic solvents, which are typically volatile and environmentally damaging.

8.2 Cost-Effective and Scalable Production

A significant cost advantage over conventional synthesis techniques, primarily due to the utilization of readily available plant materials—often agricultural waste, medicinal herbs, or common leaves, stems, and roots—as bioreducing and stabilizing agents. This not only reduces the cost of raw materials but also simplifies the synthesis process by eliminating the need for expensive chemical precursors, hazardous solvents, and sophisticated instrumentation (Mittal et al., 2013).

The scalability of green synthesis is facilitated by its ambient condition requirements—typically room temperature and atmospheric pressure—which makes the process energy-efficient and adaptable to large-scale batch production. Unlike physical methods (e.g., laser ablation, evaporation–condensation) or chemical methods (e.g., using sodium borohydride or hydrazine), phyto-synthesis can be easily scaled up using standard bioreactors or even stirred tank setups with minimal environmental constraints (Kumar et al., 2020).

Moreover, the one-pot synthesis process eliminates the need for multiple purification steps or post-synthesis modifications. The biomolecules in the plant extract act both as reducing and capping agents, thus reducing labor and process costs. The green method has also been shown to yield nanoparticles with desirable shapes, sizes, and biological activities, suitable for diverse applications like antibacterial coatings, drug carriers, cancer therapeutics, and biosensors (Rai et al., 2021).

Phyto-fabrication of AgNPs offers a cost-efficient production route due to the abundance and affordability of plant materials (Wahab et al., 2021). It eliminates the need for expensive and toxic reducing agents, significantly reducing the overall cost of nanoparticle synthesis. Rooted in the principles of green chemistry, this method supports the development of products that benefit healthcare, environmental conservation, and industrial growth. Its scalability also makes it suitable for extensive use, particularly in low-resource environments, thus encouraging innovation and broader applications (Bamal et al., 2021).

8.3 Biocompatibility and Biomedical Suitability

AgNPs synthesized through phyto-fabrication exhibit superior biocompatibility owing to the natural capping agents from plants, which reduce cytotoxic effects and improve interaction with biological systems (Simon et al., 2022). Their reduced risk of adverse biological responses makes them ideal candidates for medical applications such as drug delivery systems, imaging agents, and therapeutic tools. Additionally, their strong antimicrobial properties enhance their value in pharmaceutical formulations. Their environmental compatibility also extends their utility beyond medicine, including applications in sustainable agriculture.

8.4 Potential for Targeted Therapy

One of the most promising aspects of phyto-fabricated AgNPs is their potential for targeted therapy, particularly in oncology and infectious disease treatment. Due to their small size, high surface area, and biofunctionalization capability, AgNPs can be engineered to target specific cells or tissues, enhancing therapeutic efficacy while minimizing side effects.

AgNPs are naturally biocompatible and can be conjugated with targeting ligands, such as antibodies, peptides, folic acid, or aptamers. These ligands help direct the nanoparticles to specific receptors overexpressed on tumor cells or infected tissues (Gurunathan et al., 2019). Additionally, the phytochemicals present in the plant extracts (such as flavonoids, alkaloids, and terpenoids) often retain bioactivity in the final AgNP formulation, further contributing to the selective cytotoxicity against cancer cells or pathogens (Singh et al., 2021).

Furthermore, AgNPs have been shown to disrupt intracellular signaling pathways, such as PI3K/Akt and MAPK, that are crucial in cancer cell proliferation, metastasis, and survival. They can also induce mitochondrial dysfunction, ROS production, and DNA fragmentation, leading to apoptosis in targeted cells (Chugh et al., 2020).

Compared to conventional chemotherapy, AgNP-based targeted therapy offers multiple advantages:Reduced systemic toxicity(Singh et al., 2019); Lower drug resistance(Sao et al., 2023); Enhanced accumulation in tumor tissue via the Enhanced Permeability and Retention

(EPR) effect(Kumari et al., 2022); Possibility of dual action (therapeutic and diagnostic – theranostics)

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