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GREEN SYNTHESIS OF METAL NANOPARTICLES USING INDIGENOUS INDIAN MEDICINAL PLANTS: SUSTAINABLE STRATEGIES FOR ANTIMICROBIAL THERAPY AND ENVIRONMENTAL REMEDIATION

T. Fathima Thahsin[1,✉], K. Anjitha[2], M. K. Neenu[3], Minnath Beevi[4], and K.R Krishnapriya[2]

[1]Department of Pharmaceutics, Yenepoya Pharmacy College and Research Centre, Yenepoya Deemed to be University, Derlakatte-575018, Mangalore, Karnataka, India
[2]Department of Pharmaceutical Chemistry, Yenepoya Pharmacy College and Research Centre, Yenepoya Deemed to be University, Derlakatte-575018, Mangalore, Karnataka, India
[3]Department of Pharmacognosy, Yenepoya Pharmacy College and Research Centre, Yenepoya Deemed to be University, Derlakatte-575018, Mangalore, Karnataka, India
[4]Department of Pharmacy Practice, Yenepoya Pharmacy College and Research Centre, Yenepoya Deemed to be University, Derlakatte-575018, Mangalore, Karnataka, India
✉Corresponding author: fathimathahsin18@gmail.com

ABSTRACT

Conventional methods for metal nanoparticle synthesis involve hazardous chemicals and high energy consumption, necessitating sustainable alternatives. However, a comprehensive review focusing on indigenous Indian medicinal plants for green nanoparticle synthesis remains limited. This review summarises plant-mediated synthesis mechanisms, characterisation techniques, and the pharmaceutical and environmental applications of metal nanoparticles. Phytochemical-rich plant extracts act as natural reducing and stabilising agents, producing biocompatible nanoparticles with significant antimicrobial activity and potential for wastewater treatment and pollutant remediation. The integration of traditional Indian medicinal knowledge with green nanotechnology offers an eco-friendly and cost-effective approach for sustainable development. Future research should emphasise standardised synthesis protocols, large-scale production, and toxicological evaluation to facilitate clinical and industrial applications. This review supports SDG 12 (Responsible Consumption and Production)**.**

Keywords: Green Synthesis; Metal Nanoparticles; Indigenous Medicinal Plants; Antimicrobial Activity; Environment.

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INTRODUCTION

Nanotechnology has become a developing scientific discipline that brings benefits to multiple fields, including medicine, environmental science and materials engineering.[1] Metal nanoparticles serve as important research objects because they possess special physicochemical characteristics, including their ability to maintain high surface-to-volume ratios, improved catalytic performance and their specific optical characteristics.[2] The properties of these materials make them ideal for use in drug delivery systems, antimicrobial treatments, diagnostic procedures and environmental cleanup applications.[3] The traditional methods used to create metal nanoparticles through chemical reduction and sol-gel processes and physical techniques require the use of dangerous substances, and they need excessive energy, and they produce dangerous waste materials.[4,5] The green process for creating nanoparticles requires biological systems, which include microorganisms and plant extracts, to produce environmentally friendly and budget-friendly nanoparticles.[6,7] Plant extracts contain diverse phytochemicals, which function as both reduction agents and stabilisation agents during the process of forming nanoparticles.[8,9] India maintains a vast collection of medicinal plants which traditional knowledge systems document through their practice of Ayurveda.[10] The native plants contain numerous bioactive compounds, which include flavonoids,

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alkaloids, tannins, terpenoids and phenolic acids.[11] The phytoconstituents enable green synthesis through their ability to transform metal ions into nanoparticles while also maintaining particle stability without needing dangerous substances.[12,13] The process of plant-based nanoparticle synthesis starts with metal ion reduction, which leads to the formation of stable nanoparticles through nucleation and growth.[14] The reduction process, which occurs through hydroxyl, carbonyl and amine groups, starts from plant biomolecules.[15] The method decreases environmental damage while it improves the human compatibility of the produced nanoparticles.[16] The process of nanoparticle characterisation needs to be completed because it enables researchers to measure nanoparticles' dimensions and their patterns of movement, their spatial organisation, and their capacity to maintain their structure.[17] The scientists use UV–Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) as their primary research tools.[18,19] Green-synthesised nanoparticles demonstrate the ability to clean up environmental damage, and they also serve as biomedical solutions. The system performs successfully by treating wastewater, breaking down pollutants, and eliminating heavy metal contaminants.[20,21] The system's environmental challenges, which result from industrial development, can be solved through its catalytic and adsorptive abilities.[22] Green synthesis processes operate according to sustainable development principles because they decrease hazardous chemical usage while they encourage the utilisation of sustainable energy resources.[23] The reproducibility and scalability of the process face obstacles that stem from the changing nature of plant materials and the absence of standardised procedures.[24,25] Although numerous studies have reported the green synthesis of metal nanoparticles using medicinal plants, a comprehensive review focusing specifically on indigenous Indian medicinal plants and their integrated pharmaceutical and environmental applications remains limited. Therefore, the present review aims to critically summarise recent advances in plant-mediated metal nanoparticle synthesis, characterisation techniques, antimicrobial properties, and environmental remediation. This review also highlights current challenges and future research opportunities while supporting the United Nations Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being) through the development of safer antimicrobial nanomaterials and SDG 12 (Responsible Consumption and Production) by promoting eco-friendly synthesis methods that minimise hazardous chemicals and encourage sustainable utilisation of natural resources. The review provides an extensive examination of green synthesis methods that use indigenous Indian medicinal plant extracts to create metal nanoparticles and describes the methods of synthesis, the processes of testing, and the various ways to use the nanoparticles to fight against microbes and to protect the environment.

Role of Indigenous Medicinal Plants in Nanoparticle Synthesis

The green synthesis process for metal nanoparticles depends on indigenous medicinal plants because those plants contain numerous phytochemical compounds which are found throughout their geographical distribution.[26] Plant extracts contain a diverse range of phytoconstituents including flavonoids, alkaloids, terpenoids, phenolic acids, proteins, and polysaccharides.[27] The compounds function as both reducing agents and stabilising agents, which enable the production of nanoparticles. The functional groups, which include hydroxyl, carbonyl and amine groups, allow metal ions to be reduced into their respective nanoparticles.[28] The biomolecules adsorb on the nanoparticle surface, which results in two effects: prevention of aggregation and improvement of stability.[29] The main benefit of using medicinal plant extracts for medicinal purposes results from their ability to eliminate the harmful substances that conventional synthesis methods require.[30] The plant-based synthesis method achieves fast results without needing the high temperature and pressure and sterile conditions that microbial synthesis requires.[31] Indian indigenous medicinal plants have demonstrated their effectiveness for creating metal nanoparticles through their use in various extraction methods. The plant *Azadirachta indica* (Neem) has been studied extensively for its ability to produce silver nanoparticles, which demonstrate strong antibacterial effects.[32] The plant *Ocimum sanctum* (Tulsi) produces gold and silver nanoparticles because of its abundant phenolic compounds and essential oils.[33] The plant *Curcuma longa* (Turmeric) uses its curcumin content to function as a potent reducing agent, which creates stable nanoparticles that show heightened biological effects.[34] The plants Aloe vera and *Mangifera indica* (Mango) and *Terminalia chebula* have been studied for their

ability to produce nanoparticles which show strong potential to be used in biomedical and environmental fields.[35] The selection of plant species determines the characteristics of nanoparticles that are produced because plants have distinct phytochemical profiles that differ in composition.[36,37] Medicinal plants produce nanoparticles, while their biological effects improve the existing nanoparticle properties. Plant-mediated nanoparticles gain special value for their use in pharmaceutical applications because of their combined effects.[38,39] Among the indigenous medicinal plants, *Azadirachta indica* (Neem) has been most extensively investigated because of its rich phytochemical composition, including flavonoids, terpenoids, azadirachtin, nimbin, and phenolic compounds, which efficiently reduce and stabilise metal nanoparticles[40-43]. Compared with many other medicinal plants, Neem-mediated nanoparticles generally exhibit better stability, smaller particle size, and enhanced antimicrobial activity, making them a preferred source for sustainable green nanoparticle synthesis.[44,45]

Table-1: Indigenous Medicinal Plants Used in Green Synthesis of Metal Nanoparticles and Their Applications

Plant Name (Scientific Name)	Common Name	Phytochemicals Involved	Types of Nanoparticles Synthesised	Key Applications
Azadirachta indica	Neem	Flavonoids, Terpenoids, Phenolics	Silver nanoparticles (AgNPs)	Antibacterial, Antifungal
Ocimum sanctum	Tulsi	Phenolic compounds, Essential oils	Gold (AuNPs), Silver nanoparticles	Antimicrobial, Antioxidant
Curcuma longa	Turmeric	Curcumin, Polyphenols	Silver nanoparticles	Anti-inflammatory, Antimicrobial
Aloe vera	Aloe vera	Polysaccharides, Vitamins, Enzymes	Silver, Gold nanoparticles	Wound healing, Antimicrobial
Mangifera indica	Mango	Mangiferin, Phenolic acids	Silver nanoparticles	Antioxidant, Environmental applications
Terminalia chebula	Haritaki	Tannins, Flavonoids	Silver nanoparticles	Antimicrobial, Antioxidant
Cymbopogon citratus	Lemongrass	Citral, Terpenoids	Gold nanoparticles	Antibacterial, Catalytic activity
Moringa oleifera	Drumstick tree	Proteins, Flavonoids	Silver nanoparticles	Water purification, Antimicrobial

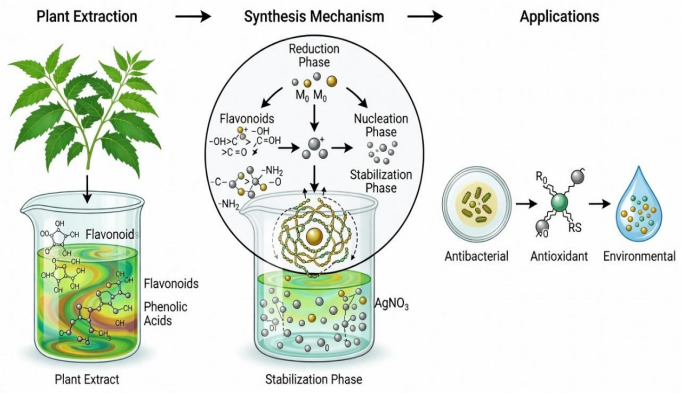

Fig.-1: Schematic Illustration of the Green Synthesis of Silver Nanoparticles Mediated by Plant Extracts

Mechanism of Green Synthesis of Metal Nanoparticles

The green synthesis of metal nanoparticles using plant extracts is a complex biochemical process that needs multiple steps to complete, which include metal ion reduction, nucleation and growth and stabilisation.[46] This method depends on the natural capacity of phytochemicals found in plant extracts to function as both reducing agents and capping agents, which removes the requirement for hazardous chemicals.[47]

Reduction of Metal Ions

The first step in nanoparticle synthesis involves the reduction of metal ions such as Ag^{+}, Au^{3+}, and Cu^{2+} into their corresponding zero-valent metal atoms (Ag^{0}, Au^{0}, Cu^{0}). The reduction process occurs through the action of phytochemicals that exist in plant extracts and include flavonoids, phenolic acids, terpenoids and alkaloids.[48] The compounds achieve this by donating electrons to metal ions, which results in their reduction. The process depends on functional groups, which include hydroxyl (-OH), carbonyl (C=O) and amine ($-NH_2$) groups.[49] Flavonoids undergo oxidation through electron transfer, which results in metal ion reduction to form nanoparticles.[50]

Nucleation and Growth

Metal atoms reach their first stage of development when they start nucleation, which results in tiny atom groups becoming permanent nucleation sites. The nuclei function as starting points for the subsequent extension of nanoparticle growth.[51]

During the growth phase, metal atoms build up on the existing nuclei, which results in nanoparticles that have specific shape and size. The size and shape of nanoparticles are influenced by several factors such as:

•Concentration of plant extract
•Metal ion concentration
•Temperature
•pH of the reaction medium

Higher concentrations of reducing agents generally lead to rapid nucleation and formation of smaller nanoparticles, while slower reduction rates may result in larger particles.[52]

Stabilisation (Capping Mechanism)

The process of stabilisation prevents the aggregation of nanoparticles, which acts as an essential procedure. Phytochemicals present in plant extracts adsorb onto the surface of nanoparticles and act as capping agents.[53] The biomolecules create a protective shell that surrounds the nanoparticles by means of hydrogen bonding and van der Waals forces, together with electrostatic interactions.[54] The process of capping provides two benefits because it stabilises the nanoparticles while improving their biocompatibility and functional capabilities.[55]

Role of pH and Temperature

The synthesis process depends on reaction conditions, which include pH and temperature.

pH

Alkaline conditions generally produce faster reduction results, which create smaller and more stable nanoparticles.

Temperature

Elevated temperature speeds up chemical reactions, which results in quicker nanoparticle production, yet it can also impact particle stability. The control of nanoparticle properties requires researchers to optimise these specific parameters.[56]

Reaction Pathways and Phytochemical Involvement

The specific method of creating nanoparticles through the synthesis process depends on which plant extract scientists select for their work. Different phytochemicals participate in redox reactions and stabilisation processes.[57] For instance:

Phenolic compounds → act as electron donors
Proteins and enzymes → assist in stabilisation
Sugars and polysaccharides → contribute to both reduction and capping

Plant-mediated synthesis achieves high efficiency through its multi-component system, yet it creates complex operational challenges.[58,59]

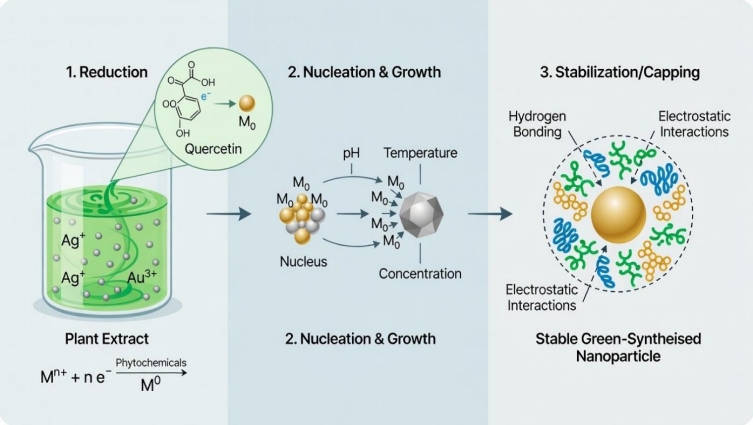

Fig.-2: Phytochemical Mediated Synthesis and Stabilisation of Metallic Nanoparticles

Challenges in Understanding Mechanism

The research has been conducted extensively, but scientists have not yet discovered all biochemical pathways that plants use to create nanoparticles.[60] The identification of specific reduction and stabilisation molecules becomes challenging because plant materials contain different bioactive compounds.[61] The scientific field needs advanced analytical methods together with molecular studies to achieve a better understanding of these mechanisms at the basic level.[62,63] The process of green metal nanoparticle synthesis occurs through a combined mechanism that depends on the phytochemical content to produce reduction, nucleation, growth and stabilisation effects.[64] The method offers an environmentally friendly and effective method to create nanoparticles which can be used in pharmaceutical and environmental fields.[65]

Characterisation of Metal Nanoparticles

The process of characterising metal nanoparticles establishes which metal nanoparticles must be studied because their characteristics determine their use in biological and environmental fields. The synthesised nanoparticles require accurate measurement of their size, shape, surface morphology, crystallinity and stability to achieve reproducibility and functional performance.[66] Multiple analytical methods are used to study the plant-based nanoparticles because each method reveals distinct details about their structural and chemical characteristics.

UV–Visible Spectroscopy

Another technique commonly used in identifying the formation of metal nanoparticles is that of UV visible spectroscopy. This is so since metal nanoparticles exhibit a distinct absorption peak due to the surface plasmon resonance (SPR) effect. For example, silver nanoparticles typically show an absorption peak around 400–450 nm, while gold nanoparticles exhibit peaks in the range of 500–550 nm. The position and intensity of the SPR peak provide information about particle size, shape, and concentration.[67]

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis is used by researchers for the identification of functional groups present in the plant extract used for the synthesis of nanoparticles. The presence of peaks corresponding to hydroxyl, carbonyl, and amine groups indicates the role of phytochemicals such as phenols, proteins, and flavonoids in nanoparticle synthesis. FTIR also helps in confirming the capping of nanoparticles by biomolecules, which enhances their stability and biocompatibility.[68]

Scanning Electron Microscopy (SEM)

The scanning electron microscope provides high-resolution images of the surface morphology and particle size of the nanoparticles. The scanning electron microscope system produces detailed images through its electron beam that scans across the specimen's surface. This analysis enables researchers to identify three main characteristics of a sample, which include its three-dimensional shape, which can be spherical, triangular or rod-shaped, its surface texture and its aggregation state. The scanning electron

microscope method of analysis provides surface details, but it cannot deliver exact internal structural information.[69]

Transmission Electron Microscopy (TEM)

TEM serves as an effective method for analysing nanoparticle distribution and internal structure. TEM produces high-resolution images which enable accurate measurement of particle dimensions and their physical shape. The method proves effective for validating the creation of nanoparticles that maintain uniform distribution throughout the space.[70]

X-ray Diffraction (XRD)

X-ray diffraction (XRD) was applied by the authors to investigate crystal properties and phases of the nanoparticles under study. The obtained results contain data concerning the crystal lattice structure and the crystallite size. The standard reference data is used to identify specific metal nanoparticles that are present in the obtained diffraction patterns. The Debye–Scherrer equation is a common method that scientists use to compute average particle dimensions from XRD measurements.[71]

Dynamic Light Scattering (DLS)

DLS is a technique that analyses the hydrodynamic sizes and size distribution of the nanoparticles contained within the colloidal solution. The system delivers data on particle stability and their tendency to form aggregates. This technique works best for testing nanoparticles that scientists developed for biomedical applications because their solution stability must be maintained.[72]

Zeta Potential Analysis

Zeta potential functions as a critical measurement that demonstrates how particles maintain their electrical charge and their ability to withstand environmental conditions.[73]

High positive or negative zeta potential values indicate good stability

Low values indicate that particles will stick together

The zeta potential of plant-based nanoparticles shows stable behaviour because their phytochemical capping agents create protective barriers.

Challenges in Characterisation

The existing advanced techniques face difficulties that prevent correct identification of plant-mediated nanoparticles.[74] The analysis process experiences disruption because of biomolecules present in the sample. The measurement of particle dimensions becomes difficult because the sample exhibits polydispersity. The process of sample preparation results in modifications in the properties of the nanoparticles. The reliable and complete identification of materials needs multiple testing methods according to the established standards.[75]

Antimicrobial Applications

Green-synthesised metal nanoparticles exhibit significant antimicrobial activity against a broad range of microorganisms. Among them, silver nanoparticles (AgNPs) dominate biomedical applications because of their broad-spectrum activity, high surface reactivity, and sustained release of Ag^+ ions. Compared with gold, copper oxide, and iron oxide nanoparticles, AgNPs more effectively disrupt microbial membranes, generate reactive oxygen species, and inhibit DNA replication, making them particularly suitable for wound dressings, antimicrobial coatings, and pharmaceutical formulations.[76,77]

Mechanism of Antimicrobial Action

The antimicrobial properties of metal nanoparticles rely on various mechanisms that make it impossible for microorganisms to develop resistance against them. The primary mechanism of bacterial control operates through microbial cell membrane destruction. Nanoparticles attach to the cell surface of bacteria, which results in physical damage and higher membrane permeability.[78] Microbial cells face oxidative stress through the generation of reactive oxygen species (ROS), which represent another crucial

mechanism. The process causes cellular damage, which affects all cellular components, including lipids, proteins and nucleic acids.[79] The nanoparticles provide a way to enter cells where they bind with key cellular elements, including DNA and enzymes, which results in the disruption of both replication and metabolic activity. Silver nanoparticles specifically release Ag^+ ions, which strengthen their antibacterial power by disrupting the thiol groups present in proteins.[80]

Activity Against Bacteria

Green-synthesised nanoparticles display strong antibacterial effects against both Gram-positive and Gram-negative bacterial strains. Researchers frequently examine the following pathogens:

•*Escherichia coli*
•*Staphylococcus aureus*
•*Pseudomonas aeruginosa*

The distinct cell wall composition of Gram-positive and Gram-negative bacteria determines how effective nanoparticles will be against them. The thinner peptidoglycan layer of Gram-negative bacteria makes them more vulnerable to attack.[81]

Antifungal Activity

Plant-mediated nanoparticles possess two distinct properties, which include antibacterial activity and antifungal activity against:

•*Candida albicans*
•*Aspergillus niger*

The antifungal mechanism achieves its goal through three different processes, which include breaking down cell membranes, blocking spore development, and disrupting the metabolic functions of fungi.[82]

Pharmaceutical Applications

The strong antimicrobial effects of green-synthesised nanoparticles enable their various pharmaceutical applications, which include:

• Wound healing formulations
• Antimicrobial coatings for medical devices
• Drug delivery systems
• Topical antimicrobial agents [83,84]

Recent studies have demonstrated improved control over nanoparticle size, stability, and biological performance through optimisation of phytochemical composition and synthesis conditions, thereby expanding their applications in drug delivery, biosensing, antimicrobial therapy, and environmental remediation.

Environmental Applications

The combination of rapid industrial growth and urban development has created major environmental pollution problems which especially impact water resources through contamination from heavy metals, dyes, and organic pollutants. The traditional methods of treatment face problems because they become costly when their treatment results in poor performance and creates additional hazardous waste materials. The green-synthesised metal nanoparticles function as effective sustainable solutions for environmental remediation because their unique properties enable them to perform catalytic functions, adsorb substances, and kill microorganisms.[85]

Wastewater Treatment

The environmental field benefits from metal nanoparticles through their application in wastewater treatment processes. Industrial wastewater discharge contains hazardous heavy metal pollutants which include lead, mercury, cadmium, and arsenic. Studies show that green-synthesised silver, iron, and zinc oxide nanoparticles achieve high efficiency in contaminant removal through their adsorption and reduction mechanisms. Their large surface area enhances interaction with pollutants, leading to improved removal efficiency.[86]

Degradation of Organic Pollutants

Metal nanoparticles serve as catalysts for the breakdown of dangerous organic substances, which include dyes, pesticides, and phenolic compounds. The textile industry uses nanoparticles to break down dyes, which include methylene blue and rhodamine B, that exist in their wastewater. The redox reactions of toxic materials become faster through the catalytic properties of nanoparticles, which transform those materials into safer substances.[87]

Water Purification and Disinfection

The antimicrobial properties of green-synthesised nanoparticles enable their use as efficient water purification solutions. The solution disinfects water by removing all pathogenic microorganisms, which guarantees the production of safe drinking water. Silver nanoparticles exhibit excellent antibacterial characteristics that have made them quite common in filters. The addition of nanoparticles to membranes and filters results in improved performance and longer-lasting products.

Removal of Heavy Metals

Nanoparticles exhibit strong affinity toward heavy metal ions, which enables their removal from polluted water sources. The mechanisms involved in the process include the following methods of operation:

•Adsorption onto nanoparticle surface
•Reduction of metal ions to less toxic forms
•Ion exchange processes

Iron nanoparticles demonstrate high efficiency in extracting chromium and arsenic contaminants from water systems.[88]

Air Pollution Control

Green-synthesised nanoparticles function as air purification materials. The materials serve as catalysts that remove both toxic gases and volatile organic compounds (VOCs). The metal oxide nanoparticles function as pollution degradation agents because they eliminate atmospheric pollutants, which results in better air quality.[89]

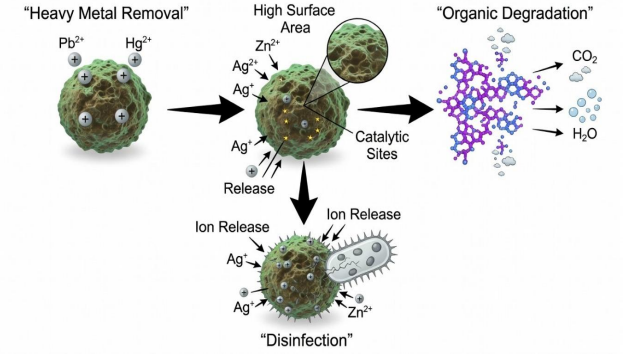

Fig.-3: Environmental Applications

Environmental Monitoring

Nanoparticles have gained popularity in environmental sensing and monitoring because they provide high sensitivity and selectivity. They can detect:

•Heavy metals
•Toxic chemicals
•Biological contaminants

The system allows for timely detection of pollutants, which supports efficient environmental management.

Challenges and Limitations

The following three challenges need to be solved because they prevent the full potential of the technology from being realised:

•Environmental conditions cause instability problems for nanoparticles
•Non-target organisms face danger from potential toxic effects
•Large-scale implementation presents significant operational challenges

The research must be conducted to assess environmental effects that persist over time and to create methods that ensure safe application of the technology. Despite these advantages, green synthesis faces challenges including variability in plant phytochemical composition, lack of standardised protocols, batch-to-batch inconsistency, and limited toxicological data. These limitations affect reproducibility and restrict large-scale industrial production of plant-mediated nanoparticles.[90]

Sustainability and Future Perspectives

Modern scientific research has made sustainability an essential requirement for all research work, especially in chemistry research, pharmaceutical research and environmental science research. The green synthesis of metal nanoparticles through indigenous medicinal plant extracts demonstrates green chemistry principles which aim to decrease hazardous materials, improve energy efficiency and protect natural resources.[91] Plant-mediated nanoparticle synthesis offers several sustainability advantages over conventional methods. The process completely removes dangerous reducing agents and harmful organic solvents, which results in decreased environmental pollution and decreased health hazards. The system operates with low energy consumption and works effectively at standard pressure and temperature, which results in decreased total expenses for manufacturing.[92] The system utilises renewable plant materials which create eco-friendly alternatives and protect natural biodiversity. The system uses indigenous Indian knowledge systems to develop modern nanotechnology, which provides a new way to connect traditional practices with present scientific progress. Scientists have confirmed that traditional medicinal plants, which Ayurveda and other traditional systems have used for centuries, serve both as nanoparticle synthesis materials and therapeutic agents.[93] The scientific value of traditional knowledge increases through this process, which leads to its worldwide acceptance and practical application. The full potential of green-synthesised nanoparticles remains unachievable because there are multiple challenges that must be solved first. The main challenge exists because there are no established standards for preparing plant extracts. The extraction methods, together with seasonal changes and geographical location differences, cause variations in phytochemical composition, which results in inconsistent nanoparticle synthesis results. The development of standardised protocols is an essential requirement that establishes both reproducibility and scalability. The production of nanoparticles at industrial scale presents major challenges for scientists to solve. The laboratory synthesis process operates with relative ease, but industrial applications encounter difficulties that arise from maintaining product stability and achieving uniformity while minimising operational costs. The existing challenges require organisations to implement advanced technologies together with optimisation strategies.[94] Detailed research needs to occur for toxicological assessment because it represents a crucial research area. There is little understanding of the effects of plant-derived nanoparticles on humans and the environment in the long term, despite the belief that these substances pose fewer risks than those created chemically. Comprehensive studies on biocompatibility, biodistribution, and environmental impact are necessary before their widespread application.[95] The research should proceed to develop hybrid methods which combine green synthesis methods with advanced nanotechnology methods to create improved operational performance. Researchers can use computational modelling together with artificial intelligence technology to study synthesis mechanisms while they find optimal reaction conditions.[96] The progress of this discipline depends on scientists from different fields working together with chemists, pharmacologists, environmental scientists and traditional medicine specialists.[97] Industrial translation of green-synthesised nanoparticles requires standardised extraction methods, quality control, scalable production, and regulatory approval to ensure consistent product quality and safety. Furthermore, artificial intelligence (AI) and machine learning offer new opportunities to optimise synthesis conditions, predict nanoparticle properties, and accelerate the design of sustainable nanomaterials for pharmaceutical and environmental applications.[98]

CONCLUSION

Green synthesis of metal nanoparticles using indigenous Indian medicinal plant extracts has emerged as an eco-friendly and sustainable alternative to conventional synthesis methods. Plant-derived phytochemicals function as natural reducing and stabilising agents, enabling the production of biocompatible nanoparticles with significant antimicrobial and environmental applications. The reviewed

studies demonstrate that these nanoparticles exhibit promising antimicrobial activity against diverse pathogens and considerable potential in wastewater treatment and pollutant degradation, highlighting their scientific contribution to sustainable pharmaceutical and environmental technologies. The combination of traditional Indian knowledge systems with contemporary nanotechnology creates an innovative method for producing environmentally safe and budget-friendly solutions. Despite these advantages, challenges including lack of standardised synthesis protocols, difficulties in large-scale production, and limited toxicological data continue to restrict clinical and industrial translation. Therefore, future research should focus on process standardisation, comprehensive safety evaluation, and scalable manufacturing to facilitate practical applications. Overall, plant-mediated nanoparticle synthesis represents an important step toward sustainable nanotechnology and supports the United Nations Sustainable Development Goals, particularly SDG-3 (Good Health and Well-being) through safer healthcare applications and SDG-12 (Responsible Consumption and Production) by promoting environmentally responsible synthesis and efficient use of natural resources.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-12: Responsible consumption and production*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

T.Fathima Thahsin http://orchid.org/0009000205157886
K.Anjitha http://orchid.org/0009000438158062
M.K. Neenu http://orchid.org/0009000165779292
Minnath Beevi http://orchid.org/0009000678448309
K.R. Krishnapriya http://orchid.org/0009000979087391

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