International Journal of Pharmaceutical Research and Applications
Volume 11, Issue 1 Jan - Feb 2026, pp: 806-811 www.ijprajournal.com ISSN: 2456-4494

Green Synthesis of Nanoparticles toward Sustainable Environment-Review Article

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Date of Submission: 01-02-2026 Date of Acceptance: 10-02-2026

ABSTRACT:
Nanotechnology has emerged as a rapidly advancing field with wide-ranging applications in environmental, agricultural, and biomedical sciences. Among various fabrication techniques, green synthesis of nanoparticles has gained significant attention as an eco-friendly and sustainable alternative to conventional physical and chemical methods. Green synthesis employs biological resources such as plant extracts, microorganisms, enzymes, and agro-waste as natural reducing and stabilizing agents, thereby eliminating the use of toxic chemicals and minimizing environmental hazards. This approach offers advantages including cost-effectiveness, low energy consumption, biocompatibility, and reduced production of harmful byproducts. Green-synthesized nanoparticles exhibit unique physicochemical properties such as high surface area, enhanced reactivity, and improved stability, making them suitable for applications in wastewater treatment, pollutant degradation, drug delivery, antimicrobial agents, agriculture, biosensors, and catalysis. Despite these benefits, challenges such as scalability, reproducibility, control over particle size and morphology, and regulatory concerns remain major obstacles for large-scale industrial application. Therefore, further research is required to optimize synthesis parameters, understand underlying mechanisms, and ensure environmental and human safety. Overall, green synthesis of nanoparticles represents a promising and sustainable strategy for advancing nanotechnology while supporting environmental protection and sustainable development abstract.
Keywords: Green synthesis, Nanoparticles, Sustainable nano technology, Plant-mediated synthesis, Biogenic nanoparticles, Environmental remediation, Antimicrobial activity, Waste water treatment, Eco-friendly synthesis, Biomedical applications, Metal oxide nanoparticles, Biosensors, Catalysis, Drug delivery, Phytochemicals

I. INTRODUCTION

Green synthesis of nanoparticles has emerged as a sustainable and eco-friendly alternative to conventional physical and chemical synthesis methods. Traditional approaches often involve toxic chemicals, high energy consumption, and generate hazardous by-products, whereas green synthesis utilizes biological resources such as plant extracts, microorganisms, enzymes, and agricultural waste as natural reducing and stabilizing agents. These biological entities not only reduce metal ions efficiently but also improve biocompatibility and environmental safety. Due to these advantages, green synthesis has gained significant attention in environmental remediation, biomedical applications, agriculture, and catalysis [1-3.]Green synthesis is safer for the environment (Kataria and Garg et al.), non-polluting (Alsammarraie et al.), non-hazardous (Devi et al.), and more sustainable (Nasrallah and Mohammad Samajadi et al.) than other synthesis techniques. However, there are issues with reaction time, raw material extraction, and producing high-quality products. For example, the raw material is hard to find (Turunc et al.), preparation takes a long time (Subramaniyam et al.), and the produced particle size is very uniform (Gao et al.)

II. GREEN SYNTHESIS OF NANOPARTICLES FROM DIFFERENT RESOURCES:

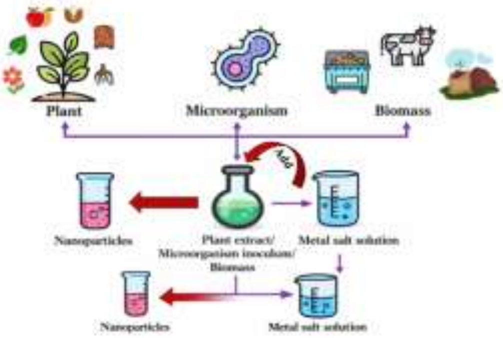

Figure 1. Schematic representation of the green synthesis of nanoparticles

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Plant-mediated synthesis is one of the most widely explored green synthesis approaches because plant extracts are rich in phytochemicals such as flavonoids, polyphenols, terpenoids, alkaloids, proteins, and carbohydrates. These biomolecules act simultaneously as reducing, capping, and stabilizing agents during nanoparticle formation. The diversity and easy availability of plant species enable controlled synthesis of nanoparticles with varied sizes, shapes, and morphologies. Compared to microbial synthesis, plant-based synthesis is faster, cost-effective, non-pathogenic, and suitable for large-scale production [4-14]. Because bacteria have the ability to reduce metal ions, they can produce nanomaterials (NPs). Numerous microorganisms are used to create metal nanoparticles kinds. The biological creation of metal or metal oxide nanoparticles (NPs) using fungus is another effective technique with a distinctive form. Fungi are biological agents used to create NPs. Compared to bacteria, fungi produce more nanoparticles. One cell makes up the microorganism known as yeast. Yeast is classified into 1500 species. Scientists have used many NPs to create yeast.

III. EFFECT OF DIFFERENT PARAMETERS ON THE SYNTHESIS OF NANOMATERIALS BY GREEN METHOD:

A change in pH has an impact on the green synthesis of the solution. Higher pH levels of 8 and 10 in solutions are known to result in polyhedron-shaped, fine, closely spaced, stable AgNPs with an average size of 15 nm. Nanoparticles grown in low pH (2, 4, and 6) solutions started to lose their stability on the tenth day of the experiment, and there was a wide range in particle sizes. W. Handayani et al. investigated the impact of pH on the production of silver nanoparticles in another investigation. Using leaf extracts from Pometia pinnata (Matoa), silver nanoparticles (NPs) with a diameter of 20–60 nm at pH 4 and 15 nm at pH 10 were created.

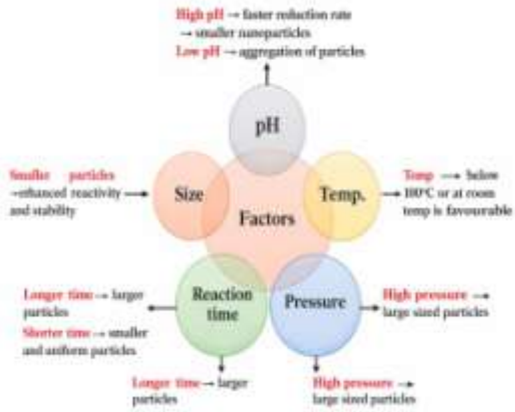

Figure 2. Various factors affecting the green synthesis of nanoparticles

pH is a critical parameter influencing the size, shape, stability, and yield of green-synthesized nanoparticles. Studies have shown that acidic conditions generally lead to the formation of larger and less stable nanoparticles, whereas alkaline conditions favor the formation of smaller, uniformly distributed, and stable nanoparticles. Changes in pH affect the ionization state of functional groups present in plant extracts, thereby influencing metal ion reduction and nucleation processes. Optimal pH ranges between 6 and 11 have been reported to produce fine-structured and stable nanoparticles, particularly for silver and gold nanoparticles [15-22]

IV. APPLICATIONS OF GREEN SYNTHESIZED NANOPARTICLES:

It has been demonstrated that NPs added to food can improve its nutritional value and processing efficiency without sacrificing its quality. These are effective bioremediation agents and are used in wastewater treatment. Nanotechnology is a crucial strategy for solving a number of problems. The production of gold (Au) nanoparticles is useful for the development of effective antibacterial drugs due to their non-toxic behaviour, functionalisation potential, polyvalent effects, and photo-thermal activity .The antibacterial qualities of zinc oxide (ZnO), copper oxide (CuO), and iron oxide (Fe_2O_3) nanoparticles against gram-positive bacteria like Bacillus subtilis and Staphylococcus aureus as well as gram-negative bacteria like Escherichia coli and Pseudomonas aeruginosa were investigated by Azam et al. .Consequently, ZnO NPs have the strongest antimicrobial characteristics. The increased capacity of metal nanoparticles (NPs), notably metal oxide NPs, to photocatalytically degrade different pollution dyes is acknowledged. Silver nanoparticles made from Z. armatum leaf extract have been used to break down a number of contaminant dyes

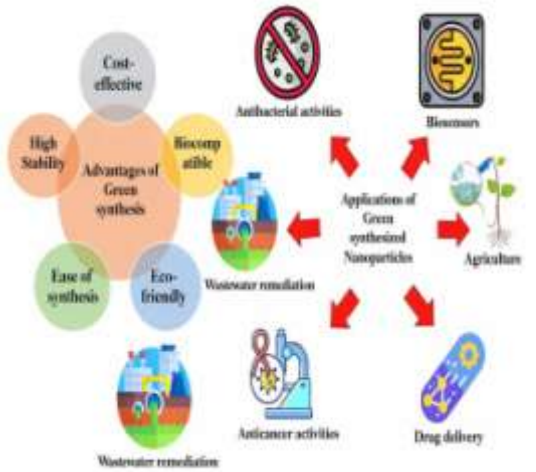

Figure 3. Advantages and applications of green-synthesized nanoparticles.

Green-synthesized nanoparticles have found extensive applications in diverse fields such as medicine, agriculture, environmental remediation, energy storage, and sensing technologies. In biomedical applications, nanoparticles are used for drug delivery, antimicrobial therapy, cancer treatment, imaging, and biosensing due to their small size and enhanced surface reactivity. In environmental applications, nanoparticles play a vital role in wastewater treatment, dye degradation, heavy-metal removal, and pollutant detoxification. Additionally, green nanoparticles have shown promising antimicrobial, antioxidant, and catalytic properties, making them valuable materials for sustainable technological development [23-39]

V. LIMITATIONS OF GREEN SYNTHESIS:

Due to time restrictions, using raw components in actual production may be challenging. Another challenge is identifying the precise biomolecules that decrease and stabilise metal nanoparticles from their precursor.It is easy to maintain optimal conditions for the production of nanoparticles from biowaste at the small-scale laboratory level. However, it is challenging to maintain optimal conditions for the large-scale synthesis of nanoparticles from biowaste, where biowaste degradation is a problem that needs to be addressed. The optimal temperature for a number of greener synthetic techniques is extremely high, and the synthesis process is time-consuming and energy-intensive, potentially harmful to the environment. The procedure doesn't always adhere to sustainable synthesis requirements, even though it starts with ecologically benign elements

Despite its advantages, green synthesis of nanoparticles faces several limitations, including poor control over particle size and morphology, low yield, difficulty in identifying exact reducing biomolecules, and challenges in large-scale industrial production. Variability in plant extract composition and reaction conditions also affects reproducibility. Future research should focus on understanding synthesis mechanisms, optimizing reaction parameters, improving scalability, and assessing long-term environmental and human safety. Advancements in green nanotechnology are expected to bridge laboratory-scale research and industrial-scale applications while supporting sustainable development goals [40-42]

VI. CONCLUSION AND FUTURE PERSPECTIVE:

An important development in the realm of nanoscience is the creation of NPs using plant extracts. This study provides a current, comprehensive overview of the research conducted in this field while highlighting the advantages and potential applications of this eco-friendly strategy. Plant-mediated synthesis is a sustainable alternative to conventional chemical methods since it uses plant extracts as stabilising and reducing agents for the synthesis of nanoparticles. These advantages include cost-effectiveness, scalability, and the lack of hazardous contaminants. Making use of sustainable plant-based resources facilitates regulated synthesis processes and yields nanoparticles with enhanced stability and size uniformity that are perfect for a variety of applications.

Furthermore, the plant-based bio-inspired nanoparticles offer intriguing pharmacological properties including eco-friendliness and nanosize, which make them very helpful for directing the targeting of certain cells and for a variety of medicinal sectors. Drug delivery, disease control, agriculture, bioremediation, and other industrial purposes are a few further possibilities.

Even though the green approach of manufacturing NPs shows a lot of potential, there are a number of issues and areas that require further research. To further understand the connection between metal salt concentration and nanoparticle generation, as well as to optimise parameters to address polydispersity, more research is required. Understanding the chemical components, production process, and function of biological nanoparticles is crucial for their optimal application. In order to effectively use biological NPs' biomedical applications, it is also crucial to carry out scientific studies and research to solve issues with their excretion, distribution profile, clearance, biological compatibility, and availability

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