International Journal of Scientific Research in Science and Technology
Available online at : www.ijsrst.com
Print ISSN: 2395-6011 | Online ISSN: 2395-602X
doi : https://doi.org/10.32628/IJSRST

A Review on Biological Routes to Palladium Nanoparticle Synthesis: A Path toward Sustainable Nanomaterials

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ARTICLEINFO

Article History:
Published : 27 January 2025

Publication Issue :
Volume 12, Issue 10
January-February 2025

Page Number :
31-36

ABSTRACT

Biogenic synthesis of palladium nanoparticles (PdNPs) has emerged as an eco-friendly and sustainable alternative to conventional chemical and physical synthesis methods. This green approach utilizes biological entities such as bacteria, fungi, algae, and plant extracts, which act as reducing and stabilizing agents through biomolecules like proteins, enzymes, and metabolites. Biogenic PdNPs exhibit unique physicochemical properties, including high catalytic activity, biocompatibility, and enhanced stability, making them promising for applications in catalysis, biomedicine, environmental remediation, and energy storage. This review provides a simple overview of the biological methods used for PdNP synthesis, their key properties, and potential applications. Additionally, challenges in large-scale production and future research directions are discussed to enhance the efficiency and applicability of biogenic PdNPs.

Keywords: Nanoparticles, Biomolecules, Catalysis.

I. INTRODUCTION

Nanobiotechnology is the technology that deals with the nanosized material within biogenic formations, which is more popular for the formation of nanoparticles for the protection of the environment from hazardous chemicals within emerging research [1,2]. Therefore, different nanomaterials have been formed such as carbons, metals, polymers, composites, chalcogenides, and are being investigated for much utilization [3]. Nanotechnology allows scientists to manipulate the characteristics of materials through manipulating molecular scale, which has led to a slew of new applications for nanostructures.

Palladium can manufacture different kinds of geometrical shapes due to its face-centered cubic metal structure, and for crystalline production, it achieves rapid reduction rates through manipulating thermodynamics, a shift in the amount of palladium seed aggregation caused by slower reduction changes the formation to a kinetically mediated phase [4]. The crystallinity of palladium seeds plays a major role in the controlling of structure and form of the final product [5]. The investigations of nanoparticles, and in particular nanomaterials clusters in terms of physical and chemical properties as a function of size and structure [6]. Palladium nanoparticles made up from plants [7], fungi [8], bacteria [9]. Nanotechnology has revolutionized various scientific disciplines, with PdNPs playing a crucial role due to their exceptional catalytic, electronic, and antimicrobial properties. However, conventional PdNP synthesis methods pose environmental hazards and high costs. Palladium nanoparticles have different energetic applications such as catalytic degradation, cancer therapy, drug delivery, chemical, and biological sensors, bioimaging, methane combustion, hydrogen generation and storage, and lithium- ion batteries and are widely covered with the catalytic ability [10, 11].The quest for eco-friendly alternatives has led to the exploration of biological routes, which leverage the reducing and stabilizing properties of biomolecules found in microbes, plants, and other biological entities. Nanoparticles may be used to increase chemical performance and play an essential role in nanocatalysis, but maybe extra importantly. The initial necessities of good electric and thermal conductivity for proper support resources are produced electrochemically and have great stability and surface area.

II. BIOLOGICAL SYNTHESIS OF PALLADIUM NANOPARTICLES

The biological synthesis of palladium nanoparticles (PdNPs) is an eco-friendly and sustainable alternative to conventional chemical and physical synthesis methods. This green approach utilizes microorganisms, plants, and biomolecules to reduce palladium ions (Pd^{2+}) into stable PdNPs under mild conditions, eliminating the need for toxic chemicals and high-energy inputs. The synthesis methods can be broadly classified into microbial, plant-mediated, and biomolecule-assisted synthesis.

2.1. Microbial Synthesis

Microorganisms such as bacteria, fungi, and algae possess biomolecules (e.g., proteins, enzymes, and polysaccharides) that can act as reducing and stabilizing agents for PdNPs. Bacteria, fungi, and algae possess metabolic pathways that facilitate Pd(II) reduction into PdNPs. Some notable microbial systems include:

- **Bacteria:** *Shewanella oneidensis*, *Escherichia coli*, and *Bacillus subtilis* have been reported to reduce Pd(II) into PdNPs through enzymatic processes involving hydrogenases and NADH-dependent mechanisms.
- **Fungi:** *Aspergillus niger* and *Fusarium oxysporum* mediate nanoparticle formation by secreting extracellular enzymes.
- **Algae:** Marine and freshwater algae produce PdNPs via intracellular bioaccumulation and extracellular reduction.

2.2. Plant-Mediated Synthesis

The biological fabrication of palladium nanoparticles during the aforementioned process required complex experimental techniques in the physical method, a large amount of reducing agents, and a medium in the chemical method. As a result, a simple approach for selecting artificial processing that uses environmentally beneficial resources must be developed. Furthermore, biological approaches offer a wider range of resources, such as reducing agents and better control over the size and form of the nanoparticles.

Palladium Nanoparticles are Phyto-Fabricate Using a Variety of Plants

In biological methods, synthesis of metallic nanoparticles in various shapes and sizes from diverse plant parts such as flower, leaves, roots, fruit, and bark [12]. The sizes and shapes of nanoparticles can be changed through a broad variety of concentration of metal, and concentration of plant extracts in the reaction mixture [13]. In the biology method there are different plant parts used for the synthesis of palladium nanoparticles such as flower, leaves, stem, root, bark, etc.

2.2.1. Flower Extract Mediated Palladium Nanoparticles

A green synthesis of palladium nanoparticles from *Moringa oleifera* flower extract. The SPR peak of synthesized palladium nanoparticles was observed at 460 nm. Palladium nanoparticles are used in a variety of applications, including the reduction of 4-nitrophenol and methylene blue, as well as the Suzuki-coupling reactions in water. Plant extracts containing poly-phenols act as stabilizers of the smaller dimensions of the PdNPs examined by transmission electron microscopy [14].

A green synthesis of palladium nanoparticles from *Hibiscus sabdariffa* flower extract has been developed. When flower extract was added to the palladium ions medium, the color changed gradually from light brown to dark brown, which suggested the palladium nanoparticles production on SPR peak at 420 nm [15]. Under moderate circumstances, TEM analysis of palladium nanoparticles revealed that nanoparticles were spherical in shape with a diameter of around 10 nm and were employed as a heterogeneous catalyst for Suzuki coupling processes [16].

2.2.2. Leaf Extract Mediated Palladium Nanoparticles

Soybean leaf extract used for the production of a green synthesis of palladium nanoparticles. When soybean leaf extract is added to a palladium ion solution, the color of the solution shifts from light orange to dark brown. The existence of palladium ions in the reaction mixture is shown by a peak at420 nm. HRTEM was used to analyze the size and SAED patterns of palladium nanoparticles. HRTEM pictures of PdNPs show that an evenly dispersed spherical shape with a diameter of 15 nm has formed. These biological syntheses of PdNPs can be employed as catalysts, particularly for the breakdown of azo dyes [17].

2.2.3. Root Extract Mediated Palladium Nanoparticles

The use root extract of *Euphorbia condylocarpa* as reducing agents and stabilizers in the biological synthesis of palladium nanoparticles and their catalytic uses in ligand and copper free Sonogashira and Suzuki coupling reactions high yield, simple approach, and reused several times without losing substantial catalytic activity. The UV-Vis spectrum shows a band at 387 nm, which is caused by a transition inside the B ring of the cinnamoyl system. For the phosphine-free Sonogashira and Suzuki coupling processes, *Euphorbia condylocarpa* root extract employed as a reducing agent and stabilizer is a highly efficient, magnetically recoverable, and recyclable catalyst [18].

2.2.4. Dried Fruit Extract Mediated Palladium Nanoparticles

Using the aqueous fruit extract of *Couroupita guianensis* as a powerful biological reducing agent, manufacture palladium nanoparticles. The production of a black precipitate, which has a lower absorbance in UV-Vis spectroscopy, indicated the reduction of PdCl2 solution into their nanoscale. The activity of phenolic components from *C. guianensis* in nanoparticles reduction and surface functionalization is revealed by the FTIR spectrum. HRTEM micrographs of nanoparticles show well- distributed, spherical nanoparticles with an average size of 6 nm. Synthesized palladium nanoparticles have demonstrated outstanding antibacterial efficacy against both gram-negative and gram-positive bacteria. The experiment shows that manufactured nanoparticles are safe to use in biological applications such as in vitro cell viability, anticancer capability and hemocompatibility [19].

2.2.5. Bark Extract Mediated Palladium Nanoparticles

The biological synthesis of palladium nanoparticles used *Terminalia arjuna* bark extract. Palladium chloride PdCl2 used as a precursor for synthesis of palladium nanoparticles. The absorption band at 234 nm of aqueous solution of palladium chloride is caused by charge transfer from the precursor ion to the palladium nanoparticles. The SPR band in the UV-Vis spectrum was found after the addition of bark extract and palladium ions. The SPR band showed the synthesis of palladium nanoparticles. HRTEM analysis of synthesized PdNPs showed was spherical in shape and ranging sizes ~ 16 nm. Synthesized palladium nanoparticles showed excellent catalytic activity for reductive degradation [20].

III. ADVANTAGES OF BIOLOGICAL SYNTHESIS

Biological synthesis offers a sustainable and environmentally friendly alternative to traditional chemical and physical synthesis methods for nanomaterials, pharmaceuticals, and industrial compounds. It avoids hazardous chemicals commonly used in chemical synthesis (e.g., reducing agents like sodium borohydride). Generates minimal toxic byproducts, reducing environmental pollution. Biodegradable biomolecules act as natural stabilizers, eliminating the need for synthetic surfactants. Operates at ambient temperature and pressure, unlike chemical methods that require high temperatures and energy-intensive processes. Utilizes biological materials such as plant extracts, microbial cultures, and enzymes, which are renewable and naturally replenished. Follows the principles of green chemistry by minimizing waste generation and optimizing resource efficiency. Produces biocompatible materials, making them suitable for biomedical and pharmaceutical applications. Reduces risks of toxicity and environmental harm associated with chemically synthesized nanoparticles. Prevents contamination of water bodies and soil by eliminating harmful solvents and heavy metal residues. Can be used in eco-friendly bioremediation strategies to remove pollutants from the environment [21]. Biological synthesis represents a cleaner, safer, and more sustainable method for producing nanomaterials and industrial compounds. By reducing environmental impact and conserving natural resources, it aligns with global efforts toward green technology and eco-friendly industrial practices.

IV. APPLICATIONS OF BIOSYNTHESIZED PDNPS

- **Catalysis:** Palladium nanoparticles (PdNPs) are widely utilized in catalysis due to their exceptional catalytic efficiency, stability, and surface reactivity. They play a key role in organic synthesis, facilitating hydrogenation, cross-coupling reactions (e.g., Suzuki, Heck, and Sonogashira), and carbon-carbon bond formation with high selectivity [22]. In environmental catalysis, PdNPs aid in pollutant degradation and water purification by promoting redox reactions. Their electrocatalytic properties enhance fuel cell performance, particularly in hydrogen oxidation and oxygen reduction reactions. Additionally, PdNPs contribute to sustainable energy by catalyzing CO_2 reduction and hydrogen production, making them valuable for green chemistry, energy conversion, and industrial catalytic processes.
- **Biomedical Applications:** Palladium nanoparticles (PdNPs) have diverse biomedical applications due to their excellent catalytic, photothermal, and biocompatible properties [23]. They are used in targeted drug delivery systems, enabling controlled and responsive drug release. In cancer therapy, PdNPs facilitate photothermal therapy (PTT) and photodynamic therapy (PDT) for selective tumor destruction. Their catalytic activity enhances bioorthogonal reactions for in vivo drug activation. PdNPs also improve biosensing technologies for detecting disease biomarkers with high sensitivity. Additionally, their antimicrobial properties make them effective against bacterial and viral infections, while their role in regenerative medicine aids wound healing and tissue repair, offering promising advancements in healthcare.

- **Environmental Remediation:** Palladium nanoparticles (PdNPs) play a vital role in environmental remediation due to their outstanding catalytic properties and high surface reactivity. They are widely used in wastewater treatment for the degradation of organic pollutants, such as dyes, pesticides, and pharmaceutical residues, through advanced oxidation and reduction processes [24]. PdNPs also facilitate the catalytic reduction of toxic heavy metals like hexavalent chromium (Cr^{6+}) and lead (Pb^{2+}), converting them into less harmful forms. In air purification, PdNPs serve as efficient catalysts in automobile exhaust treatment, helping to remove carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). Their role in hydrogenation and dechlorination reactions further supports the removal of environmental contaminants, such as chlorinated hydrocarbons and persistent organic pollutants. Additionally, PdNPs contribute to sustainable energy solutions by promoting CO_2 reduction and hydrogen production, making them valuable for both pollution control and green energy applications.

V. CONCLUSION

In conclusion, biological routes for palladium nanoparticle (PdNP) synthesis offer a sustainable and eco-friendly alternative to conventional chemical and physical methods. By leveraging biomolecules from plants, microorganisms, and other natural sources, these green synthesis approaches minimize toxic byproducts, reduce energy consumption, and enhance biocompatibility. Additionally, biologically synthesized PdNPs exhibit remarkable catalytic, biomedical, and environmental remediation potential, further reinforcing their significance in sustainable nanotechnology. Despite challenges such as scalability and precise control over nanoparticle properties, ongoing research and advancements in bioengineering hold promise for optimizing these methods. Embracing biological synthesis pathways can drive the development of greener, more efficient nanomaterials for diverse applications.

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