

Sustainable Bimetallic Nanoparticles: Synthesis Approaches and Their Medicinal and Catalytic Activities

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Abstract

A novel category of materials has been exclusively studied *i.e* bimetallic nanoparticles (BNPs), which have manifested more embellished performance than their monometallic counterparts. In recent years, the universe witnessed an explosion of inventions and applications of BNPs, as they have much enhanced molecular stability, reactivity, reaction selectivity, and potency in biomedical, industrial and environmental remediation due to their distinctive physicochemical properties. Researchers have proposed various nanoparticle synthesis procedures, but most of them involve expensive and harmful chemicals. Being a significant obstacle to scientific progress, eco-friendly, sustainable approaches are more appreciable for nanomaterials production with minimum environmental impact. This review examines sustainable physical and green synthesis methods for bimetallic nanoparticles, as well as their medicinal and catalytic applications.

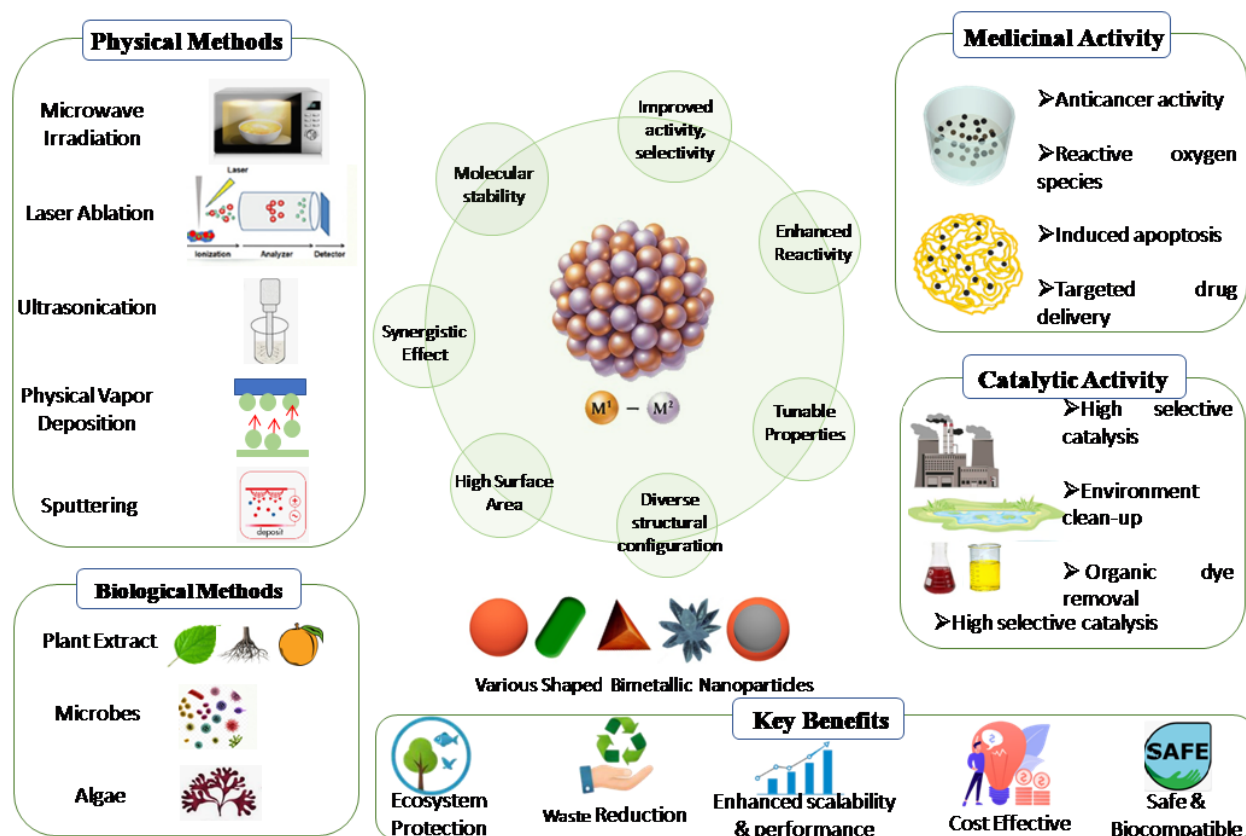
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Introduction

Nanotechnology has turned up as one of the most dynamic and fast-paced multidisciplinary fields, creating remarkable prospects for the generation of functional materials with tailored properties (Lim *et al.*, 2018). Nanoparticles, defined by the size range from 1 to 100 nm, are novel materials that have distinct physical and chemical properties and are distinct either from their bulk materials or from the smallest atoms due to their high surface-to-volume ratio. Scientists find nanomaterials more alluring due to the presence of tunable surface characteristics and also they have found widespread application in various fields such as drug delivery (Ponchel & Cauchois, 2017), environmental remediation, energy conversion (Kumar *et al.*, 2022) and catalysis (Lim *et al.*, 2018). Nowadays, researchers have paid attention to metallic nanoparticles among the diverse range of nanomaterials, due to their remarkable magnetic & optical (Srinoi *et al.*, 2018), electrical, catalytic, and biological properties (Thakur & Thakur, 2022). There are three methods—physical, chemical, and biological—to produce metal nanoparticles, which are different from the others in terms of efficiency, cost, environmental impact (Kabir *et al.*, 2018), and scalability. Engaging with toxic (Awasthi & Sharma, 2022) and harmful chemicals, consuming high-energy, environmentally unsafe by-products, and decreasing the acceptability of conventional chemical methods are significant concerns. Sustainable methods, such as physical routes (Krishnia *et al.*, 2022) like microwave irradiation, ultrasonication, and laser ablation, rely on the application of physical energy for nanoparticle synthesis, while biological routes (Salem & Fouda, 2020) that physical routes (Krishnia *et al.*, 2022) such as microwave irradiation, ultrasonication, and laser ablation rely on the application of physical energy for nanoparticle synthesis, and biological routes (Salem & Fouda, 2020) which involve microorganisms are gaining popularity as renewable (Larrañaga-Tapia *et al.*, 2024) and eco-friendly alternatives. They both reduce or eliminate the need for chemical reactions. Here, biological methods exploit plant extracts and other biological agents such as microorganisms (e.g., bacteria, fungi, and yeast) as reducing and stabilizing agents (Salem & Fouda, 2020). Both preparative methods have become highly demanding for the production of sustainable nanomaterials due to attributes such as low cost, biocompatibility, scalability, and minimal environmental impact.

Due to the synergistic and integrated effects attributable to the different metals forming the bimetallic nanoparticle (BNP), BNPs outperform monometallic counterparts in terms of catalytic activities and features

such as stability, biocompatibility, and even therapeutic efficacy. This is very important for applications in catalytic processes and biomedicine. In the biomedical field, BNPs show remarkable anti-cancer activities by producing reactive oxygen species, triggering apoptosis, and specifically exhibiting cytotoxic properties to cancer cells. In addition, their high catalytic efficiency has been applied to pollutant degradation in environmental remediation and various chemical transformation processes. The combination of the synergistic effect and tunable structure leading to enhanced therapeutic and catalytic activities makes BNPs essential materials for future sustainable nanotechnology. This review paper outlines the latest developments in green BNP fabrication processes and discusses their medicinal and catalytic applications.



Scheme 1: Bimetallic Nanoparticles Sustainable Synthesis Procedure and their Applications

Bimetallic Nanoparticles:

The combination of two metals at the nanoscale imparts distinct properties to BNPs; furthermore, synergistic effects (Hao *et al.*, 2024) render them more effective than single-metal systems, enhancing their catalytic, stability-related, optical, and electronic characteristics. BNPs adopt spherical (Długosz *et al.*, 2021), rod-shaped (Elsayed *et al.*, 2022), wire (Tsuiji, 2017), alloy (Abbaspour & Norouz-Sarvestani, 2013) or core-shell (Jiang *et al.*, 2019), flower (Odoom-Wubah *et al.*, 2017), star shape (Censabella *et al.*, 2019) of formation.

The shape and structural arrangement of BNPs play a critical role in regulating nanoparticle activity rates and determining their optical, catalytic, electrical, and biomedical properties (Srinoi *et al.*, 2018). The surface-to-volume ratio, which is fundamentally influenced by nanoparticle shape, governs these activity rates. Distinct nanoparticle morphologies possess unique surface energies, active sites, and crystal planes, all of which significantly affect their effectiveness in applications such as cancer prevention and catalysis.

Physical Synthesis of Bimetallic Nanoparticles:

When conventional chemical synthesis or biological agents are not used to synthesize nanoparticles, physical methods (Nyabadza *et al.*, 2023a), which rely on the "top-down" approach, come to the fore. These methods generally produce high-purity nanoparticles with controlled structure and shape.

Microwave Assisted Synthesis: The microwave-assisted method of BNP synthesis, a physical process, offers a fast, productive, and controllable procedure. This method 1) ensures rapid and uniform heating, which accelerates the reaction rate and provides superior control over nanoparticle nucleation and growth 2) maintains consistency in the particle size and morphology of the nanocomposites; 3) enhances process efficiency, including high selectivity and yield and 4) promotes energy efficiency by enabling faster heating compared to conventional heating methods.

CuPd, CuRh, AuPd, AuRh, PtRh, PdRh, AuPt bimetallic nanoalloys (Abdelsayed *et al.*, 2009) have been prepared by microwave irradiation method. Core-shell AuPd nanoparticles (Harpeness & Gedanken, 2004) and Ag-Rh BNPs (Pande *et al.*, 2018) have been synthesized by the microwave-assisted polyol reduction method.

Laser ablation Process:

Laser ablation is a facile and eco-friendly physical method in which a high-energized laser beam is applied to a solid metal target immersed in a liquid, gas, or vacuum; this causes the emission of atoms and the direct formation of BNPs (Nyabadza *et al.*, 2023b).

Ultrasonication Process:

A simple and fast physical method used for BNPs (Kan *et al.*, 2003), preparation employs high-frequency ultrasound waves, generating localized high temperatures to promote BNPs generation. Because this method uses very few harmful chemicals or stabilizing agents, it produces high-purity products with strong potential and lowers negative effects on the environment.

Physical Vapor Deposition (PVD):

In the Physical Vapor Deposition (PVD) method, BNPs are formed on a substrate by vaporizing a solid source and subsequently condensing and depositing the vapor; resulting in high-purity, defect-free nanostructures (Beyene *et al.*, 2012).

Sputtering:

Sputtering is a physical process used to achieve high purity and control over composition. To achieve excellent purity and composition control, sputtering in this method energetic ions strike a bulk metal target, ejecting atoms that condense into BNPs (Nguyen *et al.*, 2017).

Electrical Explosion of Wire (EEW):

The 'Electrical Explosion of Wire' (EEW) method, also known as 'Pulsed Wire Discharge' (PWD) is a highly effective 'top-down' physical technique for producing high-purity nanomaterial. During this process, a high-density current pulse is applied to a thin metal wire, resulting in rapid Joule heating. The solid wire is converted into a high-pressure plasma and vapor state, after some time, the vapor rapidly condenses to form nanoparticles (Suliz *et al.*, 2022; Pervikov *et al.*, 2020).

Arc Discharge Method:

In this physical synthesis method, a high-temperature (3000–6000°C) plasma arc is generated between two metal electrodes by inducing the electrical breakdown of gas via the 'arc discharge' process. The intense heat turns the anode material into vapor. After some time, the vapor condenses in an inert gas atmosphere, such as helium or argon, to form BNPs (Qu *et al.*, 2020).

Table 1: Biimetallic Nanoparticles Synthesis Using Physical Method

Nanoparticles Type	Method	Size (nm)	Morphology	Applications	References
Ag-Cu and Cu-Ag BNP	Microwave assisted route	Average size 27-97 & 32-184	Spherical	Antiviral activity	Długosz <i>et al.</i> , 2021
Ag-Ir alloy nanoparticle	Microwave irradiation	Average size 20	Spherical, wire	Catalytic activity	Guo <i>et al.</i> , 2018
Ag-Dy BNP	Microwave method	Average size ~ 10	Spherical	Medicinal activity	Mishra & Kannan, 2016
LA@Au-Ag Nanocluster	Microwave assisted method	Average size 1.96-3.30	-	Medicinal activity	Sharma <i>et al.</i> , 2020
Pd-Pt BNP	Laser ablation process	Average size 10-15	starry sky	Catalytic activity	Censabella <i>et al.</i> , 2019
ZnO-Ag BNP	Laser ablation process	Average size 30-130	Nanorods, Nanosheets	Anticancer activity	Elsayed <i>et al.</i> , 2022
Cu-Fe and Cu-Ni	Laser ablation process	Average size 20 & 34	Spherical	Medicinal activity	Ali <i>et al.</i> , 2023
Ag-Pd, Ag-Au, Ag-Pt BNP	Ultrasonic-assisted route	Average size 20-30, 30, 15	Spherical	Catalytic activity	Marimuthu <i>et al.</i> , 2021
Ag-Cu BNP	Physical vapour deposition	Average size ~7	Dot	Medicinal activity	Hao <i>et al.</i> , 2020
Pd-Au BNP	Plasma Sputtering deposition	-	-	Catalytic activity	Guo <i>et al.</i> , 2011
Ti-Ag and Fe-Ag BNP	Electrical explosion of wire	Average size 70, 70-90	-	Antimicrobial activity	Svarovskaya <i>et al.</i> , 2020
Pt-Ni @MWCNT	Arc Discharge Method	Average size 26.55-27.55	Spherical	Medicinal activity	Bekmezci <i>et al.</i> , 2024

Green Synthesis of Bimetallic Nanoparticles:

In response to the escalating demand for the sustainable synthesis of BNPs, 'green synthesis' (Larrañaga-Tapia *et al.*, 2024), an eco-friendly alternative has appeared to replace traditional physical and chemical methods, which are often energy-intensive, hazardous, costly, and environmentally harmful. Green synthesis, also known as eco-friendly synthesis, utilizes biological materials such as plant extracts, bacteria, fungi, yeast, and algae as reducing and stabilizing agents, thereby eliminating the need for toxic or hazardous chemicals. Bioactive molecules, including polyphenols, flavonoids, proteins, enzymes, and polysaccharides. Plants contain bioactive molecules, including polyphenols, flavonoids, proteins, enzymes, and polysaccharides, which help maintain the structure and stability of nanoparticles., contribute to maintaining nanoparticle structure and stability. This approach enables the sustainable production of biocompatible bimetallic nanoparticles for diverse applications (Kumari *et al.*, 2015).

Eco-friendly Plant Based Green Synthesis:

Bioactive organic molecules extractable from plants, such as flavonoids, phenolic acids, terpenoids, alkaloids, proteins, enzymes, carbohydrates, vitamins, and antioxidants are widely used in the synthesis of BNPs as reducing, stabilizing, and coating agents.

Compared to microbe-based methods, using plants to synthesize nanoparticles is simpler, faster, and more cost-effective. This approach does not need culture media and offers better control over the size and shape of the nanoparticles. Various parts of the plant such as leaves (Elemike *et al.*, 2019), roots (Amina *et al.*, 2020), buds, gum, seeds (Emam, 2019), tubers, and fruit peels, have been used successfully to produce

BNP. Plants are promising option for sustainable synthesis of bimetallic nanoparticles because they contain many phytochemicals. These bioactive molecules can be used on a large scale and are environmentally friendly. Still, there are challenges in fully understanding how nanoparticles form and in making sure production is consistent on a larger scale.

Microbes Based Green Synthesis:

Synthesizing BNPs with the assistance of microorganisms like bacteria (Mollania *et al.*, 2024), fungi (Patel *et al.*, 2025), and yeast (Romero-Núñez *et al.*, 2019) is a promising and eco-friendly method. Using whole microbial cells or their extracellular parts in the right conditions is a sustainable and affordable alternative to traditional synthesis. Microbial-assisted production has several clear benefits, such as:

- Rapid microbial growth and ease of cultivation.
- High adaptability to various environmental conditions.
- Inherent metabolic processes that naturally reduce metal ions into nanoparticles.

In this process, the nanoparticles can build up inside the microbial cells or be released outside. This makes microbe-based synthesis a simple, affordable, and eco-friendly way to make high-quality BNPs.

Algae Based Green Synthesis:

Algae are well known for their role in making nanoparticles and are seen as a promising biological source for green synthesis of biogenic nanoparticles (BNPs) (González-Ballesteros *et al.*, 2018; Chaudhary *et al.*, 2020). This method is considered eco-friendly because algae contain many natural reducing and stabilizing agents, i.e., bioactive compounds, such as secondary metabolites, proteins, peptides, polysaccharides, and pigments. Algae exhibit rapid growth, are straightforward to cultivate and harvest, and can be produced on a large scale at relatively low cost, which makes them suitable for sustainable nanoparticle production. As some of the oldest and most widespread photosynthetic organisms, algae are capable of absorbing metal ions and converting them into nanoparticles, providing an efficient and environmentally friendly method for BNP production (Chugh *et al.*, 2021).

Table 2: Green Synthesis of Bimetallic Nanoparticles

Nanoparticles Type	Source	Size (nm)	Morphology	Applications	References
Ag-Au	Stigmaphyllonovatum (amazonvine) leaf	Average size ~15	Spherical	Anticancer activity	Elemike <i>et al.</i> , 2019
Pd-Pt	<i>Cinnamomum camphora</i> (C. camphora) leaf	Average size 20-60	Flower	Electro-Catalytic Performance	Odoom-Wubah <i>et al.</i> , 2017
Ag-Cu	<i>Rheum emodi</i> Root	Average size 40-50	Spherical	Anticancer activity	Sharma <i>et al.</i> , 2021
Au-Pt	<i>Syzygium aromaticum</i> bud	Average size <3	Spherical	Catalytic activity	Sharma <i>et al.</i> , 2020
Ag-Pd, Au-Pd	Kondagogu gum	Average size 2-40	Spherical	Catalytic activity	Velpula <i>et al.</i> , 2021
Cu-Mn	Pumpkin Seed	Average size ~50	Spherical	Anticancer Efficacy	Alafaleq <i>et al.</i> , 2023
Pt-Pd	<i>Dioscorea bulbifera</i> tuber	Average size 10-25	Spherical	Anticancer activity	Ghosh <i>et al.</i> , 2015
Ag-Cu	Banana peel	-	-	Catalytic activity	Su <i>et al.</i> , 2025
Au-Ag	<i>Escherichia coli</i> bacteria	Average size ~23.01	Core-shell	Medicinal activity	Jiang <i>et al.</i> , 2019
Fe & ZnO Nanoparticles	Daedalea Mushroom	Average size ~16.8	Irregular	Antifungal activity	Kamal <i>et al.</i> , 2023

Applications:

Nanoparticles show a lot of promise in biomedicine. Because they are small, have a large surface area, and can be adjusted in different ways, they interact well with biological systems at both the cellular and molecular levels. Among them, bimetallic nanoparticles have demonstrated enhanced efficacy through synergistic effects between constituent metals. Here two potentities, i.e., medicinal and catalytic activities, have been highlighted.

Medicinal Applications:

Bimetallic nanoparticles exhibit significant therapeutic potential, particularly in anticancer, antimicrobial, antioxidant and anti-inflammatory applications. For instance, *Staphylococcus aureus* ("staph") and *Candida albicans* are types of bacteria and yeast that are commonly found in the bodies of healthy individuals. Although usually harmless, it can cause infections ranging from minor skin lesions to severe, life-threatening conditions when it enters the body through cuts, wounds or immune system weakens. Ag-Cu and Cu-Ag BNPs (Długosz *et al.*, 2021) and Ag-Cu BNPs (Sharma *et al.*, 2021) exhibited antimicrobial activity against those microbes. Ag-Cu and Cu-Ag BNPs (Długosz *et al.*, 2021) have shown antiviral efficacy against Human alphaherpes virus 1 & 2 (HHV-1/HSV-1 & HHV-2/HSV-2) which are contagious DNA viruses of the Herpesviridae family. Those viruses can establish lifelong infections with painful sores, blisters, are characterized by recurrent lesions and asymptomatic viral shedding. Many bimetallic nanoparticles (BNPs) have demonstrated enhanced biocompatibility and therapeutic efficacy against cervical cancer (HeLa) (Elemike *et al.*, 2019) and colorectal cancer (HCT116) cells, HT-29 cells, breast cancer cell lines (MDA-MB-231) (Alafaleq *et al.*, 2023). LA@Au-Ag nanoclusters (Sharma *et al.*, 2020) showed antimicrobial activity against Gram-negative bacteria, while Ti-Ag and Fe-Ag bimetallic nanoparticles (Svarovskaya *et al.*, 2020) demonstrated potent activity against methicillin-resistant *Staphylococcus aureus* (MRSA), both are highly pathogenic antibiotic-resistant bacterium. Accurate determination of uric acid (UA) in urine is crucial for diagnosing urinary system disorders. Pt-Ni@MWCNT nanocomposites (Bekmezci *et al.*, 2024) have been employed as sensitive sensors for the detection of UA at low concentration levels.

Catalytic Applications:

The growing environmental threat posed by organic dye pollution from industries such as textiles, paper, and food processing necessitates the development of innovative remediation strategies. Green-synthesized bimetallic nanoparticles serve as highly efficient catalysts for stability and selectivity. They have been extensively employed in oxidation, reduction, hydrogenation of different pollutants via catalytic reactions. These nanoparticles play a vital role in the degradation of organic pollutants, wastewater treatment, and the synthesis of valuable chemical products. Their superior catalytic performance contributes to the development of sustainable and environmentally friendly chemical processes. Several BNPs show catalytic efficiency for hydrogenation reaction (Guo *et al.*, 2018) to produce industrial application, to build electronic device (Censabella *et al.*, 2019), for methane (asphyxiant) combustion (Guo *et al.*, 2011) and for corrosion inhibition at oil field (Su *et al.*, 2025). Some BNPs (Marimuthu *et al.*, 2021) demonstrated degradation of 4-nitrophenol, which is highly toxic and carcinogenic industrial pollutant for environmental remediation.

Future Perspectives and Challenges

Sustainable BNPs have emerged as promising nanomaterials due to their enhanced medicinal and catalytic properties, coupled with environmentally friendly green synthesis approaches. Despite proficient progress, challenges remain in achieving reproducible and scalable green synthesis, precise control over nanoparticle composition and morphology, and a clear understanding of the mechanisms underlying metal-metal synergistic effects.

Despite its advantages, physical synthesis has several limitations, including high initial equipment costs, potential safety risks associated with improper handling of reaction vessels, long-term toxicity,

biocompatibility, high energy consumption and difficulties in real-time monitoring of reaction progress. Additionally, the process often requires chemical precursors and stabilizing agents, which may reduce its overall sustainability. Green synthesis faces challenges like limited control over size and shape, problems with scaling up, inconsistent results, complicated purification, and differences in biological sources. To use nanoparticles in catalytic applications, we need to make them more stable, reusable, and effective in real-world conditions. There is also very few information about how BNPs affect the environment, so more detailed in vivo and environmental studies are necessary.

Future research should focus on creating clear guidelines for "green synthesis" (eco-friendly synthesis) methods that use different biological resources. It should also work to better explain how structure affects effectiveness and improve safety assessment standards.

Conclusion

Bimetallic nanoparticles (BNPs) have played a key role in advancing nanotechnology because of their unique properties and wide range of uses in biomedicine, catalysis, and environmental cleanup. This review covers details of the green and sustainable method of BNP synthesis using both physical and biological methods, their classification, and their applications in medicine and catalysis. It highlights what makes BNPs special and the different ways they can be used. Recently, using green or eco-friendly synthesis methods along with physical techniques has become a promising and sustainable way to produce BNPs. Physical synthesis methods also tend to have less environmental impact and create less waste than traditional chemical approaches.

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