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*Full Length Research Article*

## **Trimetallic Nanoparticles: A Review of Current Developments and Applications**

Debasmita Sardar

Department of Chemistry, Rabindra Mahavidyalaya, Champadanga, Hooghly-712401, West Bengal, India

Email: [debasmitasardar07@gmail.com](mailto:debasmitasardar07@gmail.com)

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### **Abstract**

*Nanotechnology has driven the development of innovative products that are transforming how we address societal challenges in energy, environment and health. Current large-scale nanomaterial synthesis relies mainly on chemical and physical methods, which are environmentally harmful, energy-intensive and expensive. There is a critical need to design sustainable nanomaterials using renewable resources while minimizing societal impact. Integrating sustainability principles with nanotechnology facilitates the creation of advanced, eco-friendly nanomaterials. Trimetallic nanoparticles (TNPs) are among these vital materials, offering unique properties derived from the synergistic interactions of three distinct metals. This review highlights recent scenario of trimetallic nanoparticles and nanocomposite synthesis including chemical, physical and green synthesis methods and their applications.*

**Keywords:** *Tri-metallic nanoparticles, chemical synthesis, physical synthesis, green synthesis, plant-based synthesis, applications.*

### **1. Introduction**

Nanoparticles, with their unique physical and chemical properties, have garnered significant attention across diverse fields due to their minuscule size, which is less than 100 nms. Nanotechnology has emerged as a dynamic and interdisciplinary field of science over the past few decades. Nanomaterials, with their unique physicochemical properties, have found applications in diverse innovative fields [1,2] and have significantly contributed to the commercial revolution, leading to the development of hundreds of new products. Metal-based nanostructures, with their high surface area, energy and chemical reactivity, have been utilized in environmental remediation, electronics, gene therapy, drug delivery and resource sustainability [3]. Metal nanoparticles are classified as either monometallic or multimetallic (bimetallic, trimetallic and so on) depending on the number of metals or metal oxides present. Combining noble metals yields synergistic effects [4], amplified at the nanoscale, leading to bimetallic nanoparticles with better catalytic performance than single metals. Combining metals into nanoparticles leverages multimetallic synergy, resulting in enhanced activity and multifunctionality for diverse applications [5]. In recent years, trimetallic nanoparticles (TNPs) are now a major focus of study. Ongoing research in this area is expected to further expand their applications and impact various fields of science and technology [6,7]. To enhance their catalytic

potential, nano-scientists are working to fine-tune the size and morphology of multimetallic nanoparticles, specifically core/shell structures [8], hybrid [9,10] and alloys [11]. The synthesis of those nanoparticles is commonly categorized into physical, chemical and biological approaches. Till date physical, chemical and biological methods are the three main routes to synthesis TNPs. While physical and chemical methods for producing TNPs are often expensive and environmentally harmful. To address these concerns, we seek eco-friendly alternatives. Plant based green synthesis serves as an example of an environmentally friendly approach.

Certain synthetic methods suffer from drawbacks such as the use of hazardous chemicals (reducing/capping agents, toxic solvents) [12] and require energy-intensive [13], time-consuming and costly processes, leading to toxic byproducts, waste and hazardous materials. Moreover, conventional physicochemical techniques are often requiring specialized equipment operating under high energy, pressure, or temperature conditions. Growing concerns exist about the safety and long-term toxicity of nanoparticles in biological systems, which need to be addressed [14]. The development of greener, sustainable synthetic methods is favoured for their safety, eco-friendliness, and cost-effectiveness [15]. In TNPs synthesis, green chemistry principles encourage the use of non-toxic solvents chemical reagents as reducing/capping agents. Green synthesis is the game changer of the traditional nanoparticle production method. It ditches harsh chemicals and high energy for eco-friendly resources and gentler conditions, minimizing waste and environmental impact [16]. Additionally, green synthesis often yields nanoparticles with enhanced biocompatibility, making them suitable for various biomedical and environmental applications [17].

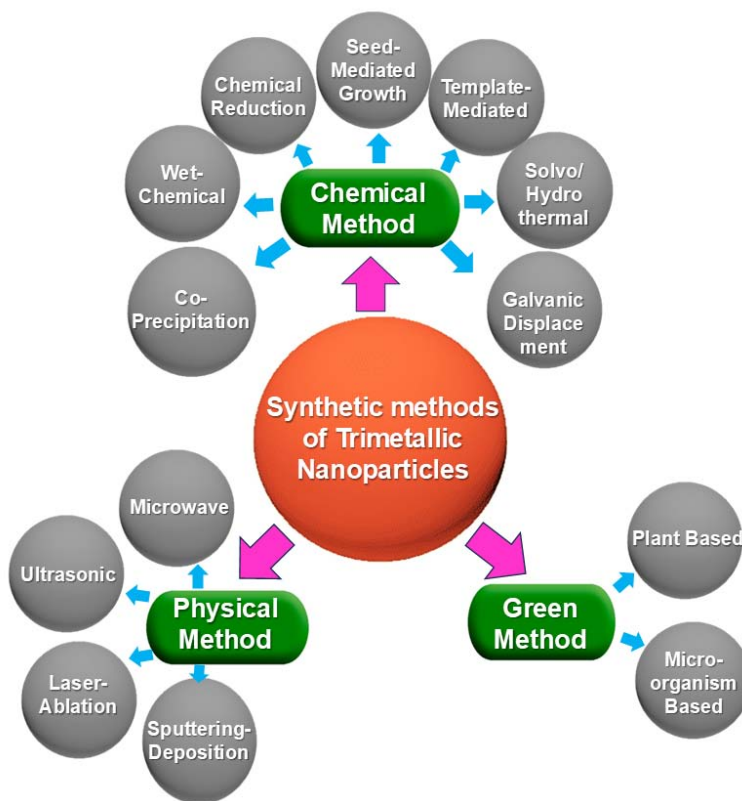
Plant based green synthesis of chemicals and natural product extracts offer sustainable and facile routes for nanostructure fabrication. Plant extracts containing large variety of antioxidants and secondary metabolites serve as both reducing and stabilizing agents in the synthesis of nanoparticles [18]. These special molecules (biomolecules) work together like a well-oiled machine to shield the plant's cellular components from harmful oxygen molecules. Interestingly, this protective mechanism also facilitates turning metal ions into nanoparticles. The extracts from various plant parts such as leaves, stems, barks, roots, seeds and fruits have been employed for the synthesis of trimetallic nanoparticles [19].

TNPs primarily consist of a combination of three distinct metals respectively. Literature reports manifest that TNPs exhibit superior characteristics in comparison to monometallic or bimetallic counterparts. They offer enhanced properties like heightened catalytic activity [20,21], increased antibacterial efficacy [22] and enhanced sensitivity as cancer cell sensor [9,23]. These advantageous attributes stem from the synergistic or multifunctional effects achieved through the incorporation of multi-metals within trimetallic NPs [23]. For effective and safe use in medical and environmental applications, nanoparticle size and toxicity must be controlled. Size

optimizes performance, while toxicity reduction ensures safety. This report presents the physical, chemical and biological approaches [scheme 1] for synthesizing TNPs and their applications. This review uniquely focuses on TNPs, highlighting their specific properties and applications, which are often overlooked. It also emphasizes green synthesis through microorganisms and plant extracts, addressing the need for sustainable nanotechnology.

## 2. Trimetallic Nanoparticles

TNPs combining three metals at nanoscale, offer unique properties and synergistic effects beyond mono- or bimetallic systems, enhancing catalytic, stability, optical and electronic behaviours. TNPs commonly adopt alloy or core-shell structures. Alloys, with homogeneous metal mixing, provide strong synergistic effects and enhanced properties. Core-shell structures, including triple core-shells, feature layered metals with the middle layer acting primarily as an interlayer, having limited influence on size/shape. Triple core-shells enable independent tuning of core and shell properties, with the outer shell protecting the core or enhancing specific functions.



Scheme 1- Methodologies for the synthesis of trimetallic nanoparticles

## 2.1. Chemical Synthesis of Trimetallic Nanoparticles

Chemical methods for synthesizing metal nanoparticles involve using chemical reactions to reduce metal ions from metal precursors into corresponding metal nanoparticles. These methods frequently incorporate stabilizing agents to regulate particle size and prevent them from clumping together. Some common chemical methods (Table 1) are chemical reduction, co-precipitation, thermal decomposition, wet-chemical, sol-gel, solvothermal, microemulsion, polyol, electrochemical, sonochemical synthesis.

### 2.1.1. Chemical Reduction

This is the most common method, using a reducing agent to convert metal ions into metal atoms. The reducing agent and metal precursor are mixed in a solution, and the reaction is allowed to proceed until nanoparticles of the desired size and shape are formed. Trimetallic FeCoNi boride oxides immobilized on polypyrrole/reduced graphene oxide nanosheets [20], Au/Pt/Pd [21], CuZnFe oxide [22] NPs, AuPtPd [24], Sn-Zn-Cu alloy [25], (Ni-Cu)@Ag [26], Au-Ni-Co [27], Fe-Ag-Pd [28], Fe-Co-Ni alloy [29], Pt-Pd-Rh [30] TNPs were synthesized by one step reduction.

### 2.1.2. Co-reduction Method

The co-reduction method is a chemical technique for synthesizing bimetallic or multimetallic nanoparticles by simultaneously reducing multiple metal precursors in one reaction, enabling efficient formation of alloyed or core-shell structures. Au@Ag@Pt [31], Ag-Cu-Ni trimetallic nanocomposites [32], AgCuPt nanoparticles [33], PtPdCu nanocrystals [34], FePtAu nanoparticles [35], Au@PdPt nanoparticles [36] have been synthesized by co-reduction method.

### 2.1.3. Wet-Chemical Method

The wet chemical method synthesizes nanoparticles through reactions in a liquid medium by mixing metal precursors with reducing agents and stabilizers. Reaction conditions like pH, temperature, and concentration are adjusted to control nanoparticle size and shape. Using the wet chemical method, researchers have synthesized Au core-Pt/Pd shell nanorod [37], AuAgCu Alloy nanoparticles [38], Au/PtCu nanowires [39] have been synthesized. T. Pal *et al.* manifested a wet-chemical approach to synthesis dog-bone shaped Au core-Pt/Pd shell nanorod decorated reduced graphene oxide (rGO) nanosheets (GMTs) for efficient ethanol electrooxidation. The method utilizes the electrostatic attraction between positively charged cetyltrimethylammonium (CTA)-capped Au nanorod and the negatively charged groups on graphene oxide (GO) [37].

### 2.1.4. Template Mediated Synthesis

In addition to other methods, template-directed synthesis in an aqueous environment provides a versatile pathway for creating nanoparticles with tailored size, shape, and structure, where a pre-formed template guides the formation of nanoparticles with controlled size, shape, and structure has been reported. Well-

defined trimetallic AuPtPd alloy nanowires at room temperature were demonstrated by Dong *et al.* [40].

### **2.1.5. Co-precipitation Method**

The synthesis of CuO-NiO-ZnO nanoparticles [41], Co-Zr-Sb nanoparticles [42], Fe-Ni-Zn and Fe-Co-Zn nanoparticles [43] was accomplished through the co-precipitation technique where metal ions are precipitated using a precipitating agent, followed by nucleation and growth of nanoparticles.

### **2.1.6. Sol-gel Method**

A colloidal solution (sol) containing metal precursors undergoes hydrolysis and condensation to form a gel, followed by drying and calcination. Gupta *et al.* reported synthesis of Ag/ZnO/TiO<sub>2</sub> trimetallic bifunctional nanofibers by sol-gel method [44].

### **2.1.7. Seed-mediated Growth Method**

Here pre-existing nanoparticles ("seeds") act as templates, enabling precise control over nanomaterial growth by directing material deposition. This method yields nanoparticles such as Au-Ag@Pt [45], PtAu@Ag nanoparticles [46], Au@Pd@Pt nanoparticles [47], Au-Pd-Ag nanocrystals [48] demonstrating its versatility.

### **2.1.8. Galvanic displacement Method**

The galvanic displacement method is a spontaneous redox reaction which involves the deposition of a noble metal onto another noble metal substrate due to differences in their electrochemical potentials. Examples of nanoparticles produced using this method include Au@Pd@Ru nanoparticle [49], Ag/Au/Pt nanocages [50], Pt-Au-Ag nanodendrites [51].

### **2.1.9. Solvothermal Process**

Using a solvent in a sealed autoclave at elevated temperature and pressure, the solvothermal process provides a controlled chemical environment for nanoparticle synthesis (*e.g.* PtNiCo alloyed 3D multipods [52]).

### **2.1.10. Hydrothermal Synthesis**

Hydrothermal synthesis is a widely used technique which uses high-pressure and high-temperature conditions in an aqueous solution. PtNiCu Nanoalloy synthesized by this method [53].

### **2.1.11. Oleo-polyol Method**

It chemically reduces metal salts in polyol solvents (such as ethylene glycol or glycerol), enabling controlled synthesis of high-purity metal nanoparticles [54,55]. Here polyols act as both solvent and reducing agent. The process relies on chemical reactions to control the nucleation, growth and stabilization of nanoparticles.

### **2.1.12. Thermal Decomposition Method**

The thermal decomposition method is a chemical process where a compound is heated to a high temperature, causing it to break down into simpler substances (like oxides, gases, or elements). This method yields FePtPd alloy nanowire [56], FePtCu and FePtNi nanorods [57].

### 2.1.13. Microemulsion Method

The microemulsion method is a chemical synthesis technique that uses thermodynamically stable mixtures of oil, water, and surfactants to form nanoscale droplets, which act as nanoreactors for producing nanoparticles with controlled size and shape (*e.g.* Pt-Ru-Co nanoparticles [12]).

Table 1: Trimetallic Nanoparticles Synthesis Using Chemical Method

Nanoparticles Type	Method	Size (nm)	Morphology	Applications	References
FeCoNi nanostructure	One step Chemical Reduction	20-70	Irregular granulated	Electrocatalytic activity towards oxygen evolution reaction (OER)	Song <i>et al.</i> [20]
Au/Pt/Pd Nanoparticles	Chemical Reduction	Average size ~2	Spherical	Catalytic activities in the glucose oxidation	Zhang <i>et al.</i> [21]
CuZnFe Oxide Nanoparticles	Chemical Reduction	Average size 42±2	Agglomerated	Antibacterial activity against <i>E. coli</i> , <i>E. faecalis</i>	Alzahrani <i>et al.</i> [22]
AuPtPd Nanocomposites	Simultaneous reduction	Average size 80-100	Irregular	H <sub>2</sub> O <sub>2</sub> biosensor for cancer detection	Chen <i>et al.</i> [24]
Sn-Zn-Cu Alloy nanoparticles	Chemical reduction	Average size ~20	Core-shell	-----	Ipser <i>et al.</i> [25]
(Ni-Cu)@Ag Nanoparticles	Chemical reduction	Average size ~13.34	Spherical Core-shell	Antibacterial activity	Ahmed <i>et al.</i> [26]
Au-Ni-Co TNP	Chemical reduction	Average size ~57	Rod	Catalyst to purify wastewater in textile industries	Memon <i>et al.</i> [27]
Fe-Ag-Pd Nanoparticles	Seedless chemical reduction	Average size ~160	Hollow capsule like rod	Catalytic activity for degradation of formic acid	Khan <i>et al.</i> [28]
Fe-Co-Ni Alloy nanoparticles	Chemical reduction	Size range 10-50	Distorted polyhedral	Electrocatalytic activities toward OER, HER, and EOR	Khalid <i>et al.</i> [29]
Pt-Pd-Rh Nanoparticles	Chemical reduction by block-co-polymer	Average size ~100	Mesoporous	Electrocatalytic activities toward MOR	Yamauchi <i>et al.</i> [30]
Au@Ag@Pt nanoparticles	Co-reduction	Size range 15-20	Core @multishell	Catalysis	Kaneko <i>et al.</i> [31]
Ag-Cu-Ni TNC	Co-reduction	Size range 105-592	----	Removal of benzene and benzopyrene	Jhanani <i>et al.</i> [32]
AgCuPt Nanoparticles	Co-reduction	Average size 32.89±4.35	Spherical Core-shell	Catalytic activities in the CO <sub>2</sub> reduction	Yu <i>et al.</i> [33]
PtPdCu	Co-	Average	Porous	Electrocatalyst	Yu <i>et al.</i>

Nanocrystals	reduction	edge length ~30	cube, dendrites		[34]
FePtAu Nanoparticles	Co-reduction	Average size $42 \pm 2$	Spherical	Catalysis	Sun <i>et al.</i> [35]
Au@PdPt Nanoparticles	Co-reduction	Average size $30.3 \pm 2.0$	Octahedral core-shell	Catalyst against methanol electrooxidation	Han <i>et al.</i> [36]
Au core–Pt/Pd shell nanorod	Wet chemical method	75-90 (length), 25-30 (diameter)	Dog bone shaped	Electrocatalytic efficiency	Pal <i>et al.</i> [37]
AuAgCu Alloy nanoparticles	Wet chemical method	Size range 26-35	Spherical, elongated	Catalysis towards HER	Memon <i>et al.</i> [38]
Au/PtCu Nanowires	Wet chemical method	Lattice spacing 0.23 nm	1D wire with dendritic nanoshell	Electrocatalyst for methanol fuel cell	Wang <i>et al.</i> [39]
AuPtPd Alloy Nanowire	Template mediated method	Average diameter of 10	1D wire	Electrocatalysts for ethanol electrooxidation	Dong <i>et al.</i> [40]
CuO-NiO-ZnO Oxide nanoparticles	Co-precipitation method	Average size $7 \pm 2$	Agglomerated	Antibacterial activity against Escherichia coli & Staphylococcus aureus bacterial strains	Neogi <i>et al.</i> [41]
Co-Zr-Sb Nanoparticles	Co-precipitation method	Average size 18–23	Spherical	Nanomagnetic Catalyst	Gilanizadeh <i>et al.</i> [42]
Fe–Ni–Zn and Fe–Co–Zn Nanoparticles	Co-precipitation method	Average size 19–25.5 & 19.1–30.5	Spherical	Biogas production boosting activity	Nasrullah <i>et al.</i> [43]
Ag/ZnO/TiO <sub>2</sub> Nanofibre	Sol-gel method	Average size 60-170	Fibre shaped	Antibacterial and photocatalytic activity	Gupta <i>et al.</i> [44]
Au–Ag@Pt Nanoparticles	Seed-mediated growth	Size range >100	Urchin shaped	SERS-photothermal-catalytic properties	Sun <i>et al.</i> [45]
PtAu@Ag Nanoparticles	Seed-mediated growth	Average size 40-50	Spherical	Electrocatalysts for the selective oxidation of glycerol	Shen <i>et al.</i> [46]
Au@Pd@Pt Nanoparticles	Seed-mediated growth	Average size ~ 55	Island Cluster	Photo electrocatalytic activity	Tong <i>et al.</i> [47]
Au–Pd–Ag Nanocrystals	Seed-Mediated Co-reduction	Average size ~ 30	octopods, concave cubes	--	Skrabala <i>et al.</i> [48]
Au@Pd@Ru Nanoparticle	Galvanic displacement	Average size ~ 110	Blackberry	Catalytic degradation of azo dye	Patra <i>et al.</i> [49]
Ag/Au/Pt	Galvanic	Average	Porous	SERS detection	Hwang <i>et</i>

Nanocages	displacement	size ~ 70	nanocage	activity	<i>al.</i> [50]
Pt-Au-Ag Nanodendrites	Galvanic displacement	--	Dendrites	Catalysis in methanol oxidation reaction	Chung <i>et al.</i> [51]
PtNiCo alloyed 3D multipods	Solvothermal process	Size range 30.6-75.4	Hollow	Catalysis towards HER	Wang <i>et al.</i> [52]
PtNiCu Nanoalloy	Hydrothermal Synthesis	Average size ~ 40	Porous	Electrocatalysis toward methanol oxidation	Yuan <i>et al.</i> [53]
Sr <sub>0.3</sub> Mg <sub>0.7</sub> Fe <sub>2</sub> O <sub>4</sub> Nanocubes	Oleo polyol method	Average size ~ 63±5	Cubic	Dye removal ability	Ahmad <i>et al.</i> [54]
Ni/Cu/Ag Nanoparticles	Polyol assisted method	Average size ~ 44	Spherical	Nonlinear Optical activity in optoelectronics	Chandrasekhar <i>al.</i> [55]
FePtPd alloy Nanowire	Thermal decomposition	diameter ~2.5 & length <100	Wire	Catalysis in methanol oxidation reaction	Sun <i>et al.</i> [56]
FePtCu FePtNi Nanorods	Thermal decomposition	Average length 20 ± 2 & average diameter 2 ± 0.2	Rod	Catalysis in oxygen reduction reaction	Sun <i>et al.</i> [57]
Pt-Ru-Co Nanoparticles	Micro-emulsion	Average Size 2.7 ± 0.6	Monodispersed	Catalysis in methanol oxidation reaction	Zhang <i>et al.</i> [12]

## 2.2. Physical Synthesis of Trimetallic Nanoparticles

Physical methods (Table 2) like microwave irradiation, ultrasonication, and laser ablation utilize physical forces to synthesize nanoparticles, avoiding chemical reactions. This approach typically yields high-purity nanoparticles, eliminating the need for stabilizing agents and preventing chemical byproduct formation. Compared to chemical synthesis, physical methods offer several advantages: high purity, minimizing contamination and byproducts; enhanced sustainability, reducing chemical waste and environmental impact; simplified synthesis with fewer variables; precise structural control, enabling unique, defect-controlled nanostructures; and solvent-free processing, facilitating clean, dry synthesis.

### 2.2.1. Microwave Synthesis

Microwave heating offers a rapid, efficient, and controllable method for nanocomposite synthesis. It provides 1) fast and uniform heating which leads to quicker reaction times and better control 2) enhanced control over size and morphology of nanocomposites, 3) Improved efficiency with high selectivity and yield, 4) reduced processing time with achieving rapid temperature increases compared to traditional heating and lastly dielectric heating which facilitating uniform internal heating, nucleation, and crystallization. AuPtAg nanofluid [58], AuPtAg

nanocomposites [59], La/Cu/Zr nanoparticles [60] and La/Cu/Zr/carbon quantum dots [61] have been synthesised using microwave method whereas PdRuNi@GO has been formed by microwave assisted polyol method [62].

### 2.2.2. Ultrasonication Process

Ultrasonication, a physical method for nanoparticle synthesis (PtAuRu nanocrystals [63]) which employs high-frequency ultrasound waves, offers several key benefits: high purity due to the absence of chemical stabilizers, scalability for large-scale production, and an eco-friendly process with minimal hazardous chemical use.

### 2.2.3. Laser ablation Process

A simple and green method, by irradiating a solid target material with a high-energy laser in a liquid, gas, or vacuum environment. Laser ablation method enables the direct creation of nanostructures, including trimetallic nanoparticles ( $\text{Al}_2\text{O}_3@\text{AgAu}$  nanoparticles [64]), from bulk materials, without any added surfactants or chemicals.

### 2.2.4. Sputtering Deposition Process

A physical vapor deposition (PVD) technique where high-energy ions eject atoms from a target, which then deposit as thin films or nanoparticles onto a substrate. CNTs-PdAu/Pt nanoparticles [13] was synthesised via this method.

Table 2: Trimetallic Nanoparticles Synthesis Using Physical Method

Nanoparticles Type	Method	Size (nm)	Morphology	Applications	References
AuPtAg Nanofluid	Microwave assisted route	Average size 20-40	Spherical, triangle and ellipsoidal	Antibacterial activity	Dey <i>et al.</i> [58]
AuPtAg Nanocomposites	Microwave irradiation	Average size 20	Spherical, wire	SERS activity	Karhikeyan <i>et al.</i> [59]
La/Cu/Zr Nanoparticles	Microwave method	Average size < 20	Spherical	Purification of waste water containing antibiotic	Sharma <i>et al.</i> [60]
La/Cu/Zr/carbon quantum dots	Microwave method	Average size ~40	Fibrous	Photocatalytic activity	Sharma <i>et al.</i> [61]
PdRuNi@GO	Microwave assisted polyol method	Average size 3.78 ± 0.43	Random	Catalytic activity towards HER	Sen <i>et al.</i> [62]
PtAuRu Nanocrystal	Ultrasonic-assisted route	65- 85 (average size 77)	Spherical	Electrocatalysts for electrooxidation of liquid fuel	Du <i>et al.</i> [63]
$\text{Al}_2\text{O}_3@\text{AgAu}$ Nanoparticles	Nanosecond pulse laser ablation	Average size 15	Alloy	Catalytic reduction of 4-nitrophenol to 4-aminophenol	Soni <i>et al.</i> [64]
CNTs-PdAu/Pt Nanoparticles	Sputtering deposition	Average size ~3	Spherical	Electrocatalytic activity	Cai <i>et al.</i> [13]

### 2.3. Green Synthesis of Trimetallic Nanoparticles

Traditional methods like physical or chemical methods for nanomaterial synthesis are costly, complex, time-consuming and environmentally harmful, generating toxic byproducts and requiring high energy input. Green synthesis or biological synthesis are often synonymous. Both represent the most cost-effective and environmentally sustainable approach to synthesizing TNPs. Green synthesis offers a sustainable alternative, using natural sources like plant extracts or microorganisms as reducing and stabilizing agents, eliminating hazardous chemicals. This biocompatible approach (Table 3) produces eco-friendly and safer nanomaterials. Besides plant extracts, multimetallic nanoparticles can be produced using environmentally friendly methods that utilize microbes such as algae, bacteria, yeast, fungi where reductase enzymes, proteins, peptides, electron shuttle quinones and exopolysaccharides act as stabilising agents.

#### 2.3.1 Eco-friendly Plant Based Green Synthesis of Trimetallic Nanoparticles

Natural extracts from plant components, such as flavonoids, phenolic acids, terpenoids, carbohydrates, alkaloids, enzymes, proteins, vitamins and antioxidants, serve as reducing, stabilizing and capping agents in the production of TNPs and alloys [65]. These bio-renewable sources hold significant promise for the green synthesis of TNPs, alloys. This method also eliminates the need for bacterial culture media, enabling faster synthesis and improved control over nanoparticle size and morphology. Nevertheless, challenges persist, including the need to understand the precise mechanisms of TNP formation, scale up production processes, and achieve consistent outcomes. Table 3 summarizes plant-based green synthesis methods for TNPs. Different plant parts, such as leaves [19,66,69,75,78,79,80,81,84,86,87,88], bud [67], gum [68], seeds [70,73], roots [71,72,82], tuber [83] and fruits peel [85,94], have been used to synthesize TNPs. Plants provide a readily available, cost-effective, and scalable source for nanoparticle synthesis, rich in secondary metabolites and with purifying potential. Careful biological synthesis ensures the production of stable, well-characterized nanoparticles. In 2007, a pioneering study demonstrated the synthesis of Au/Ag/Cu alloy trimetallic nanoparticles using *Brassica juncea* seed extract [73]. This research marked one of the earliest instances of employing a natural extract to introduce three noble metals to create such complex nanostructures.

#### 2.3.2 Fungi Based Green Synthesis of Trimetallic Nanoparticles

Biofabrication of TNPs, utilizing fungi, is another biological technique for producing nanoparticles. Microbial cells offer the advantages of rapid growth, simple maintenance, and adaptability to diverse environments. Microbes, through both extracellular and intracellular processes, can transform inorganic precursors into nanoparticles tolerating high metal concentrations [89]. They absorb and enzymatically reduce metal ions from their surroundings. Fungi, similarly, produce nanoparticles either inside or outside their cells. Fungi release extracellular enzymes

like protease, cellulase, chitinase, and  $\beta$ -glucosidase to break down organic materials for nutrients [90]. These secreted proteins and enzymes accelerate and enhance nanoparticle production. *Aspergillus niger* fungi facilitated the mycosynthesis of Copper Oxide–Selenium–Zinc Oxide (Tri-CSZ) NPs [91]. *Lecanora muralis* (LM), crustose lichen species having reducing and stabilizing properties used to synthesise ZnO@ TiO<sub>2</sub>@SiO<sub>2</sub> nanocomposites [92].

Table 3: Green Synthesis of Trimetallic Nanoparticles

Nanoparticles type	Plant Extract & Reducing Agent	Size (nm)	Morphology	Applications	References
Au/Pt/Ag Nanoparticles	Lamium album (White dead nettle) Leaf Extract	Average size ~40	Spherical	Antimicrobial activity	Dlugaszewska <i>et al.</i> [66]
Ag–Au–Pd Nanoparticles	Aegle marmelos (bael) and Syzygium aromaticum (clove) leaf and bud Extract	8.1 and 11.61	Quasi spherical	Antimicrobial activity against <i>E. coli</i>	Paria <i>et al.</i> [67]
AgAuPd Nanocomposites	Cochlospermum Gossypium (Gum Kondagogu) Gum Extract	2-45	Spherical	Catalytic activity against organic pollutant	Rupula <i>et al.</i> [68]
Ag-Cu-Co Nanoparticles	Salvia officinalis (common sage) Leaf Extract	Average size ~3.25 ±0.75	Spherical	Fungicidal activity	Malik <i>et al.</i> [69]
Ag-Bi-SnO <sub>2</sub>	Ceasalpinia Bonduc (Gray Nicker) Seed Extract	Average size ± 19.68	Agglomerated, irregular	Photocatalytic activity	Siddique <i>et al.</i> [70]
Au-Ag-Sr	Coriandrum sativum ( <b>Coriander</b> ) Root Extract	Average size ± 70	Almost spherical	Gas sensing activity	Ganachari <i>et al.</i> [71]
Au-Fe-Ag	Astragalus membranaceus (milk vetch) Dried root Extract	Average size ± 50	Ant shaped	Catalytic activity	Lee <i>et al.</i> [72]
Au-Ag-Cu	Brassica juncea (mustard greens) Seed extract	Size range 5-50	Spherical	—	Haverkamp <i>et al.</i> [73]
Au/ZnO/Ag	Meliloti officinalis (yellow sweetclover) Plant Extract	Average size ± 20	Spherical, triangular, hexagonal	Cytotoxic activity against leukemia	Dobrucka <i>et al.</i> [74]
Au/ZnO/Ag Nanoparticles	Glechoma hederacea (ground ivy) Leaf Extract	Size range 50-70	Spherical	Cytotoxic activity against leukemia	Dobrucka <i>et al.</i> [75]
Au/CuO/ZnO Nanoparticles	Verbena ofcinalis (Common Verbena)	Average size 35	Spherical	Cytotoxic activities against Jurkat cell line	Dobrucka <i>et al.</i> [76]

es	Plant Extract				
Cu-Ag-Ru Nanoparticles	(Green chiretta) Leaf Extract	Size range 25-60	Spherical, flake, cup	Antibacterial and photocatalytic activity	Radhakrishnan <i>et al.</i> [19]
Cu-Co-Ni Nanoparticles	Origanum vulgare (oregano)	Average size ~28.25	Nanoflakes	Photocatalytic activity	M. A. Malik <i>et al.</i> [77]
Cu/Cr/Ni Nanoparticles	Eryngium campestre (E. campestre) and Froriepia subpinnata (F. subpinnata) Leaf Extract	Size range 100-200	Cubic, plate-like structure	Antimicrobial activity	Vaseghi <i>et al.</i> [78]
Cu/Fe/Ag Nanoparticles	Rosmarinic Acid (Madagascar Periwinkle) Leaf Extract	Average size ~190	Agglomerated	Degradation of hazardous dyes	Roy <i>et al.</i> [79]
Cu/Ag/Zn Nanoparticles	Catharanthus roseus (Madagascar Periwinkle) Leaf Extract	Average size ~34.67	Irregular shapes	Antioxidant activity & Dye Degradation activity	Roy <i>et al.</i> [80]
Co-Zn-Ni Oxide nanoparticles	Cicer Arietinum (Chickpea) Leaf Extract	Average size $\pm$ 25.72	Spherical	Antibacterial activity	Mohammed <i>et al.</i> [81]
FeAgPt alloy Nanoparticles	Platycodon grandiflorum (balloon flower) Root Extract	Size range 10-20	Spherical	Catalytic activity against organic pollutant	Lee <i>et al.</i> [82]
Fe-Cu-Zn Nanoparticles	Curcuma longa (turmeric) Tuber Extract	Average size 32.55 $\pm$ 16.27	Spherical and semi spherical	Nanocatalyzer	<u>Avelizapa</u> <i>et al.</i> [83]
Ni/Cr/Cu Nanoparticles	Coriander sativum (coriander) Leaf Extract	---	Spherical	Antimicrobial activities	Kumar K <i>et al.</i> [84]
Pd-Pt-Co Nanoparticles	Malus domestica (apple) Peel Extract	Average size 2.53	----	Catalytic activity against organic pollutant	Altuner <i>et al.</i> [85]
Ru/Ag/Pd Nanocomposites	Allium sativum (garlic tunicate) Leaf extract	Size range 50-90	Spherical	Antimicrobial activities	Hussein <i>et al.</i> [86]
CuO/Ag/ZnO Nanocomposites	Ziziphus spinachristi (Christ's thorn jujube) Leaf extract	Average size 7.11 $\pm$ 0.67	Spherical	Antibacterial activities	Kamoun <i>et al.</i> [87]
ZnO-MgO-CuO	Artemisia abyssinica (chikugn) Leaf extract	Average size ~15.13	Spherical	Antibacterial activities	Orshiso <i>et al.</i> [88]

CuO-Se-ZnO Nanoparticles	Aspergillus niger Fungi	Average size ~26.35.4	Tetragonal pyramid	Antifungal activity against fungi causing mucormycosis	Hasanin <i>et al.</i> [91]
ZnO@TiO <sub>2</sub> @SiO <sub>2</sub> Nanocomposites	Lecanora muralis (LM) lichen Fungi	Average size ~53	Spherical	Antibacterial activities	Sajadi <i>et al.</i> [92]
Cuo-Ag-Au Nanoparticles	Vossia cuspidata (Roxb.) Griff. (hippo grass) Leaf extract	Size range ~19	Spherical	Anti-inflammatory, anti-cancer, wound-healing activities	El-Hazizet <i>al.</i> [93]
Ag-Fe-Ni Nanoparticles	Citrus sinensis (Orange) peel extract	----	----	Antioxidant activities	Royet <i>al.</i> [94]

### 3. Role of Physical and Chemical Parameters in Trimetallic Nanoparticle Synthesis

Synthesis of TNPs is influenced by various physical and chemical parameters, which determine their size, shape, composition, stability and functionality. Optimizing these parameters is crucial for obtaining desired properties for applications in catalysis, medicine, energy storage, and sensing.

#### 3.1. Physical Parameters

##### 3.1.1. Temperature

Controls alloy formation vs. core-shell structures.

##### 3.1.2. Reaction Time

Influences particle size and aggregation.

##### 3.1.3. Pressure

Affects crystallinity and purity.

##### 3.1.4. Stirring Speed

Ensures homogeneity and size distribution.

##### 3.1.5. Ultrasonication

Modifies size, shape, and dispersion.

#### 3.2. Chemical Parameters

##### 3.2.1. Precursor Concentration

Determines particle size

##### 3.2.2. Reducing Agents

Control nucleation and morphology. Strong reducing agents (e.g., NaBH<sub>4</sub> hydrazine) lead to fast nucleation and small nanoparticles. Mild reducing agents (e.g., ascorbic acid, glucose) allow for controlled growth and diverse morphologies.

##### 3.2.3. Capping Agents (Stabilizers)

Prevents agglomeration and controls size & shape. (Examples: PVP, CTAB, citrate, thiols, surfactants.)

### **3.2.4. pH of the Solution**

Affects surface charge, stability, and morphology,

### **3.2.5. Metal Ion Ratio (Composition Control)**

Defines the core-shell or alloy structure of the nanoparticles.

### **3.2.6. Solvent Choice**

Aqueous solvents (green synthesis) vs. organic solvents (higher control over shape). Polar solvents facilitate rapid nucleation, while non-polar solvents aid in anisotropic growth.

By fine-tuning these physical and chemical parameters, researchers can design trimetallic nanoparticles with enhanced properties, making them ideal for diverse applications.

## **4. Applications**

With diverse applications in catalysis, biomedical and environmental sectors, trimetallic nanoparticle (TNPs) research is a dynamic field. Several applications are outlined below.

### **4.1. Catalysis**

TNPs are widely used as catalysts due to their high surface area, tunable composition and synergistic effects between the three metals. Nanoparticle catalysts offer enhanced performance via increased surface area. Ongoing research seeks to optimize their stability, cost and safety [72, 83].

#### **4.1.1. Electrocatalysis**

The electrocatalytic efficiency of TNPs refers to their performance in facilitating electrochemical reactions, such as those occurring in fuel cells, batteries, and other energy conversion devices [37, 13].

##### **4.1.1.1. Fuel Cells**

Used as catalysts for methanol oxidation reaction (MOR) in direct methanol fuel cells (DMFCs) [12,30,39,47,51,53,56], oxygen reduction reaction (ORR) [57] and hydrogen oxidation reaction (HOR) in proton exchange membrane fuel cells (PEMFCs). Producing hydrogen through the catalytic degradation of formic acid is essential for enabling the clean and efficient electricity generation offered by hydrogen fuel cells [28].

##### **4.1.1.2. Water Splitting**

Enhance the efficiency of hydrogen evolution reaction (HER) [35, 52, 62] and oxygen evolution reaction (OER) [20, 29], in water electrolysis.

##### **4.1.1.3. CO<sub>2</sub> Reduction**

Catalyze the conversion of CO into valuable chemicals like methanol or formic acid [33].

### **4.1.2. Chemical Catalysis**

Nanoparticles significantly impact chemical catalysis due to their unique properties.

#### **4.1.2.1. Hydrogenation Reactions**

Improve selectivity and activity in hydrogenation of organic compounds [64].

#### **4.1.2.2. Oxidation Reactions**

Enhance the oxidation of hydrocarbons, alcohols, and other organic molecules [31].

#### **4.1.2.3. Electrooxidation Reactions**

The development of effective electrocatalysts is critical for the advancement of ethanol-based fuel cell technology (ethanol electro-oxidation) [40], electro-oxidation of liquid fuel [63].

#### **4.1.3. Photoelectro Catalytic activity**

PEC offers efficient energy conversion by combining light and electrical energy to drive reactions, holding promise for renewable energy and environmental cleanup [47].

### **4.2. Sensing and Detection**

TNPs are used in sensors due to their high sensitivity, selectivity, and stability.

#### **4.2.1. Electrochemical Sensors**

##### **4.2.1.1. Glucose Detection**

Used in non-enzymatic glucose sensors for diabetes monitoring [21,67].

##### **4.2.1.2. Gas Sensing activity**

These sensors are used in various applications, including environmental monitoring, industrial safety, medical diagnostics and detecting leaks in pipelines and refrigeration systems [71].

#### **4.2.2. Optical Sensors**

##### **4.2.2.1. Surface-Enhanced Raman Spectroscopy (SERS)**

Enhance Raman signals for the detection of biomolecules [59], pollutants [50] or explosives.

### **4.3. Energy Storage and Conversion**

TNPs play a crucial role in improving the performance of energy storage and conversion devices.

#### **4.3.1. Energy Sector**

Biogas, a methane-based renewable fuel, is generated through the anaerobic digestion of organic waste, offering a sustainable solution for both energy production and waste management [43].

### **4.4. Biomedical Applications**

TNPs are increasingly used in biomedicine due to their unique properties and biocompatibility.

#### **4.4.1. Cancer Therapy**

Nanoparticles (NPs) have revolutionized cancer therapy by offering targeted drug delivery, reduced side effects and enhanced treatment efficiency.

#### **4.4.1.1. Cytotoxic Activity**

Cytotoxicity against cancer cells [93] denotes a compound's ability to induce lethal damage in malignant cells like leukemia[74,75] and Jurkat cell line [76].

#### **4.4.1.2. Hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) sensors**

The increased production of H<sub>2</sub>O<sub>2</sub> by cancer cells is being exploited for early cancer diagnosis through the development of specialized sensors [24].

#### **4.4.1.3. Wound-healing properties**

Having tissue-regenerating properties, TNPs' small size allows deep penetration into tissues, enhancing therapeutic effects [93].

### **4.5. Environmental Remediation**

TNPs are also used to address environmental challenges.

#### **4.5.1. Pollutant Degradation**

Catalyze the degradation of organic pollutants [32,61,82,85], dyes [49,50,54,76,80], and pesticides in wastewater [27,60,68] by chemically or photo-chemically [19,70,77].

#### **4.5.2. Antioxidant Activity**

Nanoparticles show promise as antioxidants due to their high surface area and unique properties, enhancing their ability to neutralize free radicals in medical and food applications [80,94].

### **4.6. Optics and Photonics**

TNPs exhibit unique optical properties due to their plasmonic effects.

#### **4.6.1. Plasmonics**

Enhance light-matter interactions for applications in nanophotonics and optoelectronics [47, 50].

#### **4.6.2. Nonlinear Optics**

Used in devices requiring nonlinear optical properties [55], such as optical limiters and switches.

### **4.7. Magnetic Applications**

TNPs with magnetic properties are used in various applications.

#### **4.7.1. Nanomagnetic catalysts**

Materials with magnetic properties at the nanoscale, offer a unique combination of catalytic activity and magnetic separability. Typically composed of magnetic metals or metal oxides, these catalysts are valuable in diverse chemical and electrochemical processes. Their magnetic nature simplifies catalyst recovery, improves stability, and allows for reaction pathway control via magnetic fields [42].

### **4.8. Antimicrobial Applications**

TNPs exhibit enhanced antimicrobial properties [66,67,84,86].

#### **4.8.1. Antibacterial Agents**

Effective against multidrug-resistant bacteria due to their multi-modal mechanisms of action [19,22,26,41,58,78,79,81,87,88,92].

#### 4.8.2. Antifungal Agents

Used to combat fungal infections in agriculture and medicine [69,91].

### 5. Challenges and Future Directions

Successfully applying nanoparticles in biomedicine, environmental science, and industry requires overcoming several key challenges. These include achieving precise control over composition, developing advanced and reproducible synthesis methods, managing reaction conditions, ensuring long-term stability, addressing potential toxicity, and accurately manipulating nanoparticle properties. Future research should prioritize sustainable synthesis using agricultural by-products like rice husks and sugarcane bagasse, which minimizes waste and reduces environmental impact. Additionally, employing computational modelling and optimizing catalytic sites through atomic-level understanding will enhance nanoparticle design and catalytic performance.

### 6. Conclusions

Trimetallic nanoparticles (TNPs) have driven nanotechnology's rapid advancement, offering synergistic effects across diverse applications, particularly in catalysis, environment and medicine. This review outlines TNPs types, synthesis (including chemical, physical and green methods), and applications, highlighting their unique properties and multifunctional benefits like antimicrobial and antioxidant activity. However, biocompatibility concerns and challenges in scalability, characterization, and regulation persist. To fully realize TNP potential, future research should focus on optimizing biosynthesis, exploring new applications, fostering collaboration, and conducting environmental safety studies.

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