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REVIEW

Eco-Compatible Synthesis of Metal Nanoparticles: Influencing Parameters, Characterization, Advancement and Applications

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The field of nanotechnology continues to offer profound implications across biomedical, environmental and materials science domains with metallic nanoparticles (MNPs) at the forefront due to their size-dependent physical and chemical attributes. This review provides a critical evaluation of the biosynthesis of MNPs particularly gold (AuNPs) and silver nanoparticles (AgNPs) employing plant-derived phytochemicals and microbial metabolites as reducing and stabilizing agents. The biosynthetic route is compared against conventional top-down and bottom-up methods, with specific attention to the influence of synthesis parameters (*e.g.* pH, temperature, extract concentration) on nanoparticle morphology, yield and surface chemistry. The unique optical and surface plasmon resonance properties of noble metals are discussed in the context of their biomedical applications, notably in antimicrobial coatings, cancer therapeutics, drug delivery vectors and diagnostic platforms. Moreover, functional nanoparticles of other metals (Pd, Cu, Fe, Fe_3O_4, α-Fe_2O_4, and nZVI) are examined for their roles in catalysis, pollutant degradation and water treatment. The review also delineates analytical techniques employed in nanoparticle characterization, encompassing structural, compositional, and surface profiling. Finally, the clinical relevance and translational potential of green-synthesized MNPs are contextualized within the broader framework of sustainable nanomaterials development.

Keywords: Synthesis, Mechanism, Factors affecting, Nanoscale metal.

INTRODUCTION

Nanoparticles are a specific subset of the vast domain of nanotechnology. These unaggregated particles are between 1 and 100 nm in size. Nonetheless, the bulk of materials used in drug delivery fall between 100 and 200 nm. Nanoparticles are becoming more and more important in modern day technology since of their uses in numerous domains, including drug delivery, health, information, energy, environmental technologies [1]. Moreover, nanoscale materials have improved the immobilization and activity of catalysts in the food industry, pharmaceuticals, chronic illness diagnostics, nanoengineering and nanochemistry [2].

To create nanoscale materials, the fabrication between nanoscience and medicinal plants has lately been investigated [3-5]. Medicinal plants offer a wealth of phytochemistry, which makes it possible to develop interesting nanomaterials with unique forms and characteristics. Different techniques (physical, chemical and biological) can be used to create the nanoparticles [6,7] by using various substrates (pure chemicals, microorganisms and plant extract). Using various synthesis conditions, the chemical approach is reliably scaled for the extensive manufacturing of the nanoparticle with customizable size and shape. However, the chemical approach is less suitable for biological applications due to the use of toxic and hazardous solvents [8]. The formation of nanoparticles by physical techniques is expensive and inappropriate for large-scale manufacturing [9,10]. Consequently, there is an increasing demand to develop high yield, low-cost, energy-efficient and environmentally viable synthesis methods. Nevertheless, over the past 10 years, the 'biosynthesis' or 'green synthesis' approaches (fungi, bacteria, plant/plant extract and yeasts) for synthesizing nanoparticles have increased to provide eco-friendly technologies for material synthesis [11,12]. The synthesis of metal and metal oxide nanoparticles greatly benefits from the use of plant extracts [13,14]. Both gold and silver nanoparticles have significant therapeutic applications. Researchers studying nanoparticles are interested in and demand gold nanoparticles (AuNPs) due to their distinct physico-chemical characteristics [15]. Gold nanoparticles find applications in optoelectronics [16], sensor devices, catalysis and medicine [17]. Silver nanoparticles (AgNPs) exhibit strong antibacterial properties, effectively targeting both Gram-positive and Gram-negative microorganisms including multi-drug-resistant strains. Silver nanoparticles (AgNPs) are recognized as effective antibacterial agents due to their ability to combat infectious pathogens both *in vitro* and *in vivo*. Globally, AgNPs are also utilized in the treatment of bacterial, viral and fungal infections [18]. This review highlights the current understanding of the potential for green sources, like fruit extract, plant extracts and microorganisms to be utilized in the biosynthesis of gold and also silver nanoparticles.

Properties of nanoparticles: Physical, chemical, optical, mechanical and magnetic characteristics are just a handful of many attributes that nanoparticles possess. The nanoscale size of nanoparticles imparts unique properties are essential to a wide range of applications and processes [19]. Nanoparticles are increasingly preferred in advanced biotechnological applications due to their tunable size, shape and unique physicochemical properties [20]. These characteristics enhance their effectiveness in electronics, drug delivery, sensing, catalysis, antimicrobial treatments and clinical diagnostics. Compared to bulk materials, nanoparticles offer greater stability, targeted functionality and improved electrical and surface properties, making them valuable across medicine, cosmetics, textiles, defense, agriculture and aerospace sectors [21]. Compare that to other bulk materials, nanoparticles have amazing size and shape properties, an array of uses and are employed for expansive implementations [22].

Synthesis of nanoparticles: While there exist multiple methods that might be utilized to synthesize nanoparticles, Fig. 1 illustrates that these practices can be roughly divided into two classes: (i) Bottom-up approach and (ii) Top-down approach [23]. Considering the methodology, reaction conditions and accepted synthetic protocols, all of these approaches have been splintered further into several subclasses.

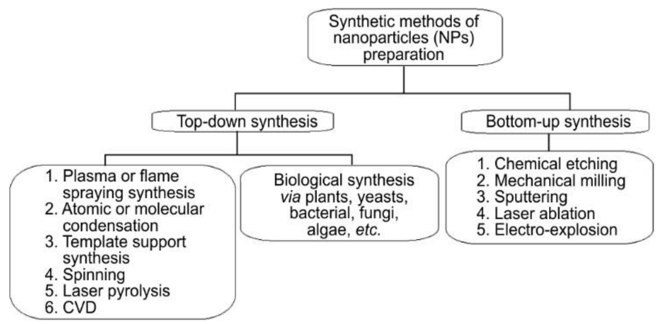

Fig. 1. A typical synthetic approach for nanoparticles for the (a) Top-down and (b) Bottom-up methods [23]

Possible mechanism for nanoparticles: In this context, AgNPs are synthesized without the need for external energy, whereas AuNPs require sunlight for their formation. This suggests that the oxidative cleavage occurs *via* a metal-catalyzed pathway for silver and through radiolysis for gold. In both cases, free electrons are generated, which reduce silver and gold ions to their metallic nanoparticle forms [24].

Biological synthesis of nanoparticles: Nanobiotechnology represents a rapidly advancing branch of nanotechnology that has gained global attention for its innovative and sustainable approaches. Among them, green nanotechnology offers a viable alternative by minimizing the environmental and health risks associated with conventional nanoparticle synthesis [25, 26]. The biological synthesis of nanoparticles, illustrated in Fig. 2, is influenced by parameters such as temperature and pH, which can significantly impact particle size and morphology

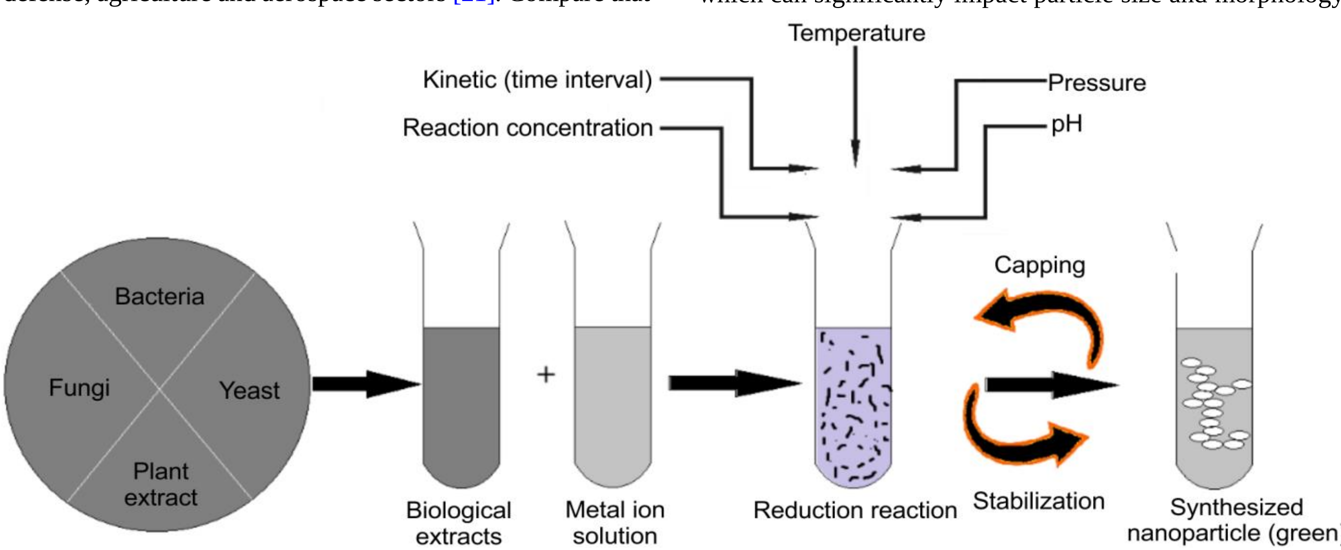

Fig. 2. General biological synthetic route of metal nanoparticle [27]

[27]. Nanotechnology leverages nanoparticles considerably smaller than their bulk counterparts with enhanced surface area, enabling unique physico-chemical properties and broader application potential [28-30].

The synthesis and stabilization of metallic nanoparticles typically require three key components *e.g.*, a reaction medium, a green reducing agent and a stabilizer. Eco-friendly alternatives to conventional chemical and physical synthesis methods have been anticipated including the use of plant extracts [31], enzymes [32] and microorganisms [33]. These biological systems offer sustainable and non-toxic routes for nanoparticle production, aligning with the principles of green chemistry (Fig. 3).

Factors impacting nanoparticle synthesis: Numerous aspects that are impacting the synthesis, characterization, practical implementation of nanoparticles. The nature of the synthesized nanoparticle is altered by the nature of adsorbent and the effectiveness of the catalyst utilized throughout the preparation process [34,35]. According to several studies, the dynamic nature of synthesized nanoparticles results in various responses and effects that evolve depending on environmental conditions and time [36]. The fabrication of nanoparticles is a critical process influenced by multiple environmental factors such as temperature, pressure and light intensity. Key parameters affecting synthesis include the pH and temperature of the solution, the concentration of plant extracts, the precursor salt concentration (*e.g*. $AgNO_3$ or $HAuCl_4$), the raw materials used, particle size and most importantly the specific protocols followed during the synthesis process [37]. For instance, according to Smitha *et al.* [38], the spherical particles predominated at higher extract concentrations, while gold nanoprisms dominated at lower extract concentrations of *Cinnamomum zeylanicum*.

The other key factors influencing nanoparticle formation are outlined as:

(A) Influence of reaction temperature: It is a crucial attribute for nearly every method of nanoparticle production. The chemical processes must have a low temperature (< 350 ºC) whereas a greater temperature is required for the physical technique (> 350 ºC). Green technology often requires temperatures below 100 ºC or room temperature to synthesize nanoparticles. Therefore, temperature plays a critical role in the synthesis of various types of nanoparticles, as it directly influences the reaction kinetics, nucleation rate and growth mechanism [39].

(B) Influence of reaction pH: The pH of the reaction medium is one of the crucial factors in nanoparticle synthesis. Adjusting the pH of the solution allows control over the size and shape of the resulting nanoparticles. Studies [40,41] have shown that changes in pH significantly influence the morphological characteristics of the nanoparticles. In particular, lower (acidic) pH levels tend to favour the formation of larger particles, whereas higher (alkaline) pH conditions typically yield smaller and more uniform nanoparticles. Soni & Prakash [42] demonstrated that the size and structure of synthesized silver nanoparticles were notably affected by variations in pH.

(C) Influence of reaction time: The time duration of the green technology-assisted incubation of reaction medium significantly impacts the type in addition to quality of synthesized nanoparticles [43]. Storage conditions, light exposure, synthetic parameters and other environmental factors significantly influence the long-term stability and characteristics of nanoparticles [44,45]. Over time, changes may occur due to phenomena such as particle aggregation from extended storage, growth or shrinkage and limited shelf life. These time-dependent variations can alter the physical and chemical properties of the nanoparticles, potentially affecting their performance and application potential [46]. For instance, Dwivedi & Gopal [47] synthesized silver (Ag) and gold (Au) nanoparticles using *Chenopodium album* leaf extract as a bioreducing and stabilizing agent. The formation of nanoparticles began rapidly, with visible synthesis occurring within 15 min and the reaction continued for up to 2 h. However, after 2 h, the nanoparticle yield declined significantly, indicating that the bioactive compounds in the extract responsible for reduction and stabilization may have been consumed or degraded over time, thus limiting further nanoparticle formation [47].

(D) Influence of reaction pressure: Pressure plays a crucial role in nanoparticle synthesis, significantly influencing both the size and morphology of the resulting particles [48]. Pressure significantly influences several methods such

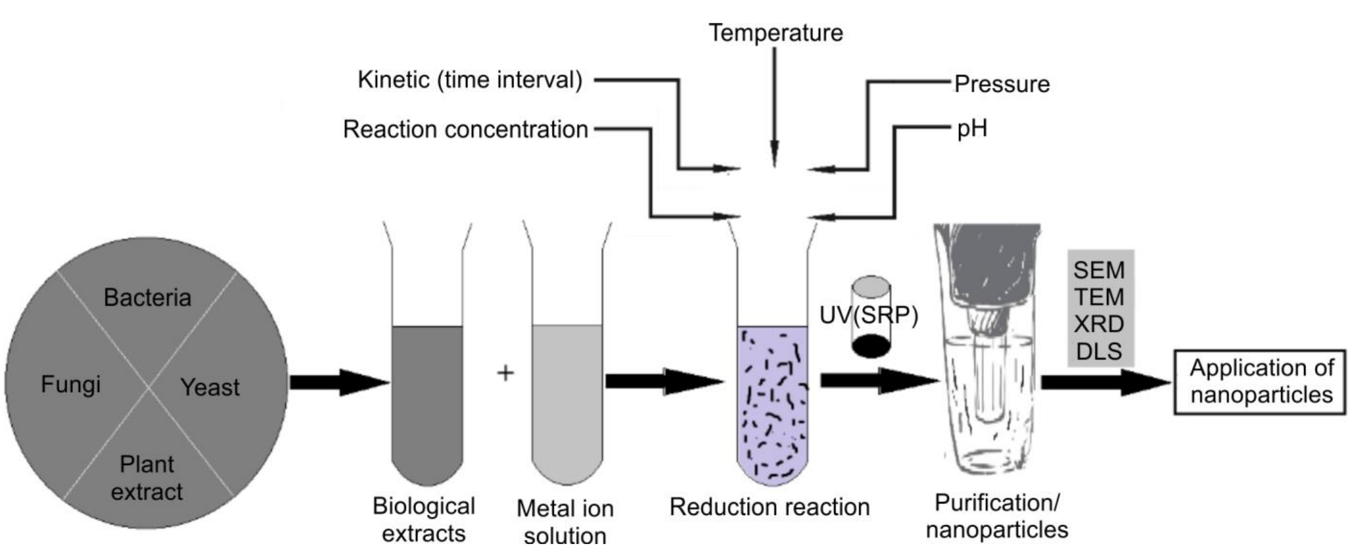

Fig. 3. Synthesis of method of nanoparticles [27,31-33]

as hydrothermal and solvothermal techniques, where it affects precursor solubility, reaction kinetics, and crystallinity, often enabling the formation of unique phases and morphologies unattainable at ambient pressure [49]. In contrast pressure has a minimal or negligible impact in common approaches like chemical reduction at atmospheric conditions or biological synthesis, where factors like temperature, pH and concentration are more crucial [50]. Research indicates that metal ion reduction by biological agents occurs more rapidly under ambient pressure conditions. This implies that lower pressure environments may enhance nucleation and growth efficiency, ultimately yielding smaller and more uniform nanoparticles [51].

(E) Particular methods or techniques: Nanoparticles can be synthesized through various methods including physical, chemical and biological approaches. Physical methods typically involve mechanical or energy-intensive processes, while chemical methods rely on a wide range of organic or inorganic precursors. In contrast, biological synthesis employs microorganisms, plant extracts or enzymes, offering a greener and more sustainable alternative. This eco-friendly approach integrates non-toxic reagents and mild reaction conditions, making it preferable over conventional techniques [52]. However, biological methods face challenges such as limited control over particle size and shape, lower production yields and slower synthesis rates due to the inherent biological growth cycles.

(F) Miscellaneous factors: The most prominent secondary metabolites in many living systems, including plants, serve as stabilizing and reducing agents throughout the nanoparticle formation process. However, the type of plant, the portion of the plant and the extraction method all affect the makeup of these metabolites [53]. Similarly, various microbes produce varied amounts of extracellular and intracellular enzymes that influence the creation of nanoparticles [54]. Moreover, the number and quality of the produced nanoparticles might be affected by the method chosen for purification. Depending on the force of gravity, centrifugation is sometimes used to disentangle the nanoparticles [55]. In other situations, nanoparticles are separated using chromatographic techniques considering the differences in the stationary phase and mobile phase coefficients [56]. The effective technique for separating synthesized nanoparticles involves exploiting their differential solubility in two miscible liquid phases typically water and an organic solvent followed by purification using chromatography or electrophoresis [57,58].

Green synthesis of metal nanoparticles: A wide range of techniques are available for the metal nanoparticle syntheses, including microemulsion methods, evaporation–condensation, laser ablation, arc discharge, photoinduced and UV-initiated photo-reduction, electrochemical synthesis, irradiation techniques and microwave-assisted synthesis. Furthermore, approaches utilizing polymers, polysaccharides, the Tollens method and various bio-based routes have also been employed for the controlled and eco-friendly nanoparticle production. In the subsequent section, we have discussed about each method with merits and limitations.

(i) Microemulsion method: Microemulsions, thermodynamically stable mixtures of oil, water and surfactants, serve as nanoreactors that enable controlled synthesis of nanoparticles by providing a uniform and confined reaction environment within their droplets. This technique offers precise control over particle size and shape, as demonstrated in the synthesis of highly monodisperse silver (Ag) and gold (Au) nanoparticles using reverse microemulsions. The approach benefits from excellent size control, low reaction temperatures and a tunable reaction environment; however, challenges remain due to the potential contamination from surfactants and organic solvents, as well as the limited scalability caused by complex purification processes [59,60].

(ii) Evaporation–condensation method: This physical vapour-phase approach, carried out under vacuum or an inert gas, involves vaporizing a metal (*e.g.* zinc) and condensing it (often with oxygen present) to form metal or metal-oxide nanoparticles such as ZnO. The resulting particles are very pure since no chemical reagents or solvents (beyond the inert gas or oxygen) are needed and hence there is minimal contamination. However, the technique requires very high energy input (to vaporize the metal), yields tend to be relatively low, and the process demands precise control of vapour pressure, temperature, carrier gas composition and condensation rates to achieve desired particle size and morphology [61-64].

(iii) Laser ablation: Pulsed laser ablation in liquid involves focusing a high-powered pulsed laser on a bulk target submerged in a liquid, ejecting material that condenses into nanoparticles such as Au, Pt and TiO_2. This technique yields high purity, ligand-free nanoparticles without the use of chemical reagents, making it eco-friendly [63,64]. However, it suffers from low throughput, high equipment costs and variable particle sizes if not precisely controlled.

(iv) Arc discharge: Arc discharge between graphite electrodes in an inert-gas atmosphere causes the electrodes to vapourize, generating carbon vapour that condenses to form carbon-based nanomaterials such as nanotubes and fullerenes. This method produces highly crystalline structures with unique graphitic order and few defects owing to the extremely high temperatures involved [65-67]. However, it also requires very high energy input and temperatures, is prone to contamination from electrode material (graphite and any catalysts used), and frequently yields a broad size and morphology distribution unless the discharge parameters and electrode setup are tightly controlled [67].

(v) Photoinduced and UV-initiated photo-reduction: This method relies on irradiating a solution of nobel metal ions (e.g. Ag^+, Au^{3+}) with UV or visible light in the presence of plant extracts or photosensitive biomolecules, which upon excitation generate radicals or excited states that reduce the metal ions to form nanoparticles [68,69]. This route is environmentally benign and operates at room temperature, yielding particles with clean surfaces free from chemical reducing agents, making it well suited for biological applications. However, the reaction kinetics tend to be slower and achieving reproducible particle size and uniformity requires precise control over light intensity, exposure time, extract composition and irradiation conditions [68,69].

(vi) Electrochemical synthesis: Electrochemical synthesis involves the reduction of metal ions (such as Cu^{2+}, Ag^+, Pt^{4+}, *etc.*) either on an electrode surface or in the bulk solution, by applying an electrical current or potential; by adjusting parameters such as current density, voltage, electrolyte composition, and electrode material, one can tune the nucleation and growth to control size, morphology and composition of the resulting nanoparticles. For example, in cyanide-free electrochemical co-deposition of Cu–Ag coatings, particle sizes around 4-6 nm with narrow distributions and high crystallinity have been achieved by varying current density [70]. Thus, electrochemical methods are highly tunable and allow relatively good control without needing harsh chemicals. However, they also require careful instrumentation; if parameters (current, potential, electrolyte pH or concentration) are not optimized, unwanted side products or phases may form, there may be poor uniformity in size or morphology and sometimes the process is limited by mass transport or electrode surface effects [71].

(vii) Irradiation techniques: Using γ-irradiation (or electron-beam irradiation) one can reduce metal ions in aqueous solution (*e.g*. Ag^+, Au^{3+}) to form nanoparticles without chemical reducing agents. Radiolysis of water produces reducing species ($H^•$ radicals) that convert the ions to zero-valent metal, resulting in high purity, uniform nanoparticle dispersions. For instance, γ-irradiation of $AgNO_3$ solutions yields more concentrated silver colloids with narrower size distributions compared to citrate reduction [72,73]. However, the method needs specialized radiation facilities, carries safety/regulatory concerns due to handling of ionizing radiation and achieving consistent control over size or morphology can be challenging if exposure, dose rate and solution conditions are not well optimized [74].

(viii) Microwave-assisted synthesis: Microwave heating enables rapid and uniform heating of reaction mixtures, drastically cutting down reaction times while improving crystallinity, which makes it well suited for producing metal-oxides like ZnO, TiO_2 and Fe_3O_4 nanoparticles. For example, microwave assisted combustion produces high-crystallinity ZnO particles (~20 nm) with good dispersion in a short time [75]. Similarly, microwave synthesis of $Fe_3O_4/SiO_2/TiO_2$ core-shell nanocomposites yields uniform particle size distributions and efficient phase formation [76]. Despite these advantages, fast, energy-efficient and uniform products, larger volumes lead to compromises due to non-uniform heating can develop; scaling up usually runs into issues with maintaining uniformity; and heat-sensitive precursors may decompose under intense microwave exposure [77].

(ix) Polymer- and polysaccharide-assisted methods: Polymer- and polysaccharide-assisted synthesis employs natural or synthetic polymers such as polyethylene glycol (PEG), starch or chitosan, which function both as stabilizers and reducing agents, enabling precise control over the size and shape of metal and metal oxide nanoparticles [78]. These polymers enhance biocompatibility and effectively stabilize nanoparticles, making the approach especially suitable for biomedical applications. However, residual organic matter from the polymers may persist, complicating purification processes and natural polymers can exhibit batch-to-batch variability that affects reproducibility [79-81].

(x) Tollens method: The Tollens method involves reducing diamminesilver(I) complex, $[Ag(NH_3)_2]^+$ (Tollens' reagent, typically ammonical $AgNO_3$), with an aldehyde (or other reducing sugar), to produce silver nanoparticles. This classic route is simple and yields high amounts of AgNPs as the mechanism is straightforward and has been well studied: particle size and morphology can be tuned by varying NH_3 concentration, pH and choice or structure of the reducing agent (monosaccharide *vs*. disaccharide) [82,83]. However, its drawbacks are that it is largely limited to AgNPs synthesis, uses ammonia (which is caustic and needs careful handling/ disposal) that control over size uniformity may require careful optimization of reagent concentrations, pH and reaction conditions to avoid large polydispersity or undesired side reactions [82].

(xi) Bio-based methods: Bio-based methods harness microorganisms, plant extracts, fungi or enzymes to enable green synthesis of several metallic nanoparticles exhibiting significant antimicrobial activity [84-86]. This eco-friendly and non-toxic approach is particularly suitable for biomedical applications due to the biocompatibility of the resulting nanoparticles. However, challenges include slower synthesis rates, limited control over particle size and shape, and variability stemming from the complex and heterogeneous nature of biological materials, which can affect reproducibility and scalability [87].

Analytical techniques for nanoparticle characterization: The comprehensive characterization of nanoparticles is vital for understanding their physico-chemical properties, stability and interactions, all of which directly impact their effectiveness in various applications. Due to their nanoscale dimensions and unique surface characteristics, nanoparticles present specific challenges that necessitate the use of multiple advanced analytical methods [88]. A variety of tools are available for characterizing parameters such as size, morphology, surface charge, crystallinity and chemical composition. These include nuclear magnetic resonance (NMR), atomic force microscopy (AFM), transmission electron microscopy (TEM), scanning electron microscopy (SEM), dynamic light scattering (DLS), Fourier-transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), powder X-ray diffraction (XRD) and others [89-91].

For instance, UV-Vis spectrophotometry is frequently used to confirm nanoparticle formation by monitoring surface plasmon resonance, which provides insights into particle size, structure and aggregation behaviour [92]. Crystallinity and phase identification are typically assessed using XRD, which helps determine elemental composition and crystalline structures [92,93]. Magnetic properties are examined using techniques like vibrating sample magnetometry (VSM) and superconducting quantum interference device (SQUID) magnetometry, offering high sensitivity for magnetic nanoparticle analysis [94]. Morphological details and particle sizing at the nanoscale are achieved through TEM, high-resolution TEM (HRTEM) and SEM [95-97], while AFM provides detailed surface topography and dimensional measurements [93]. DLS is used for analyzing the size distribution of nanoparticles in the colloidal suspensions [93,97].

Furthermore, the surface charge and chemical functionality are also key for assessing nanoparticle stability and interaction in biological or environmental systems. Zeta potential analysis helps determine colloidal stability, whereas FTIR and XPS provide molecular and elemental insights by identifying surface functional groups and bonding characteristics [94,96,98]. Thermogravimetric analysis (TGA) can confirm the presence and efficiency of surface coatings such as polymers or surfactants [94]. Moreover, techniques like chromatographic separation [99], energy-dispersive X-ray spectroscopy (EDX) [100], magnetic susceptibility separation [101], and size fractionation [102] offer further capabilities for isolating and characterizing nanoparticles. Fluorescence-based methods [103] and nanoparticle studies in aqueous environments [104] provide critical information about environmental interactions and transformations. Collectively, these methods support the development of safer, more effective nanomaterials for diverse scientific and industrial applications.

In the following section, this review primarily focuses on the recent advancements in the synthesis and application of metallic nanoparticles (MNPs), with a particular emphasis on silver (Ag) and gold (Au) nanoparticles due to their significant scientific and technological relevance. The unique properties of Ag and Au nanoparticles have driven extensive research, making them the central focus of this discussion.

Silver and gold nanoparticles: Amongst the different noble metal nanoparticles, silver and gold nanoparticles are especially popular in green synthesis due to their combination of superior optical/plasmonic properties, biocompatibility and functional advantages over other metals. Their localized surface plasmon resonance (LSPR) in the visible (and near-IR in some geometries) enables strong absorption and scattering of light, which is highly useful for sensing (including colorimetric sensors), surface-enhanced Raman spectroscopy (SERS), photothermal therapy and imaging as silver tends to offer sharper, stronger plasmonic peaks, while gold provides greater chemical stability. For example, silver and gold nanoparticles synthesized with plant extracts show narrow SPR bands and effective photocatalytic and sensing behaviour, confirming the importance of these optical effects [105,106].

Gold is chemically inert, resisting oxidation, corrosion and dissolution in many physiological or ambient environments, which reduces unwanted reactivity, metal ion release and degradation. This inertness contributes to excellent biocompatibility, lower toxicity in many applications and long-term behaviour *in vivo*, since green synthesized AuNPs are capped by biomolecules exhibit good stability and low cytotoxicity [107-109].

Silver nanoparticles, while less inert than gold, gain much of their usefulness from the Ag^+ ion release and reactive oxygen species (ROS) generation, which are toxic to bacteria and fungi. When AgNPs are produced *via* green synthesis, the biomolecules (from plants or microbes) often serve both as reducing agents and as capping/stabilizing agents, which moderates the rate of ion release and reduces cytotoxicity to no-target cells, improving safety. Green-synthesized AgNPs have repeatedly shown strong antimicrobial effects against both Gram-positive and Gram-negative bacteria [110-114].

Another advantage is controllability of nanoparticle size and shape. The optical, catalytic, antimicrobial and biodistribution properties depend heavily on size (*e.g.* smaller to larger surface area, sharper LSPR; likewise, shape (spheres, rods, triangles, shells) can tune the LSPR position and intensity. Green synthesis methods using plant extracts or microbes often allow variation in these parameters (by altering pH, temperature, extract concentration, *etc*.) while avoiding toxic reducing/stabilizing chemicals [115-123].

Green synthesis of nanoparticles offers significant advantages in terms of sustainability, cost-effectiveness and environmental compatibility. Common metal precursors such as $AgNO_3$ and $HAuCl_4$ are readily available and the biomolecules present in plant or microbial extracts (*e.g.* polyphenols, proteins, flavonoids and enzymes) can function dually as reducing agents and stabilizing/capping agents. This dual functionality eliminates the need for separate, often toxic, chemical reductants (*e.g.* sodium borohydride) or surfactants (*e.g.* CTAB), thereby reducing the environmental impact and toxicity of the process. Furthermore, green synthesis typically proceeds under mild conditions, ambient temperature and pressure resulting in the lower energy consumption. These attributes collectively align green synthesis approaches with the principles of green chemistry, promoting safer, cleaner and more sustainable nanomaterial fabrication. This helps accelerate research and translation for applications in biomedical fields, diagnostics, sensing, antimicrobial coatings, *etc*. Several recent reviews (*e.g*. covering Ag, Cu, Au and metal oxides *via* plant extracts) highlight that Ag and Au tend to dominate in green synthesis studies due to their favourable combination of optical, biological and chemical stability properties.

Tables 1 and 2 provide a comprehensive overview of the physico-chemical properties such as particle shape and size distribution of silver and gold nanoparticles synthesized using various biological and plant-based materials. This comparative summary highlights the impact of different green synthesis approaches on the morphology and dimensional characteristics of the resulting nanoparticles.

Other nanoparticles: To synthesize targeted nanoscale metals, plant extracts are commonly used to reduce metal salts under specific conditions, followed by processes such as mixing, incubation, filtration, and purification. The nature of the plant extract, the type of metal salt, and the synthesis parameters (*e.g.*, temperature, pH, concentration) significantly influence the size, shape and stability of the resulting nanoparticles. Since, the synthesis conditions vary depending on both the metal and the plant species, future research should focus on optimizing and standardizing protocols for different metal-plant combinations. Moreover, each type of metal nanoparticle exhibits distinct physico-chemical and functional properties that are intrinsically linked to the unique activity and reactivity of the metal. Table-3 summarizes various metallic nanoparticles including Pd, Cu, CuO, Fe, Fe_3O_4, α-Fe_2O_3 and nanoscale zero-valent iron (nZVI) with diverse shapes and sizes ranging from 2 nm to over 300 nm. These nanoparticles exhibit broad applications such as antibacterial activity, dye degradation, cata-lysis (*e.g.* Suzuki-Miyaura coupling), wastewater treatment and heavy metal removal. The shape and size play a crucial role in determining their specific functional performance.

Application of nanomaterials: Nanotechnology has emerged as a transformative interdisciplinary field, integrating principles from chemistry, physics, biology and engineering. Its vast potential is driving significant advancements across

TABLE-1
LIST OF VARIOUS PLANT AND BIOLOGICAL SOURCES FOR THE GREEN SYNTHESIS OF SILVER NANOPARTICLES ALONG WITH SHAPE AND SIZE

Materials	Shape	Size (nm)	Ref.
Plants			
Daphne mucronata (leaf extract)	Spherical	40-60	[124]
Terminalia cuneata	Spherical	25-50	[125]
Trachyspermum ammi, fruit	Triangular	87	[126]
Capparis spinosa, leaf	Spherical	5-30	[127]
Alysicarpus monilifer, leaf	Spherical hexagonal	5-45	[128]
Nyctanthes arbor-tristis, seed	Spherical	50-80	[129]
Couroupita guianensis, fruit	Spherical	5-15	[130]
Couroupita guianensis, leaf	Spherical	10-45	[130]
Banana (*Musa paradisiaca*), peels	Spherical	23.7	[131]
Calliandra haemacephala, leaf	Spherical	70	[132]
Cymodocea serrulate, leaf	–	5-25	[133]
Acacia nilotica, bark	–	20-30	[134]
Aloe vera, leaf	Spherical, triangular	50-350	[135]
Camelia sinensis, leaf	Spherical, triangular, irregular	30-40	[136]
Citrullus colocynthis, stem, leaf	Spherical,	31	[137]
Eucalyptus macrocarpa, leaf	Spherical, cubes	10-100	[138]
Mangifera indica, leaf, peel, flower, kernel	Spherical, triangular, hexagonal	20	[139]
Rhododendron dauricum, flower	Spherical	25-40	[140]
Argyreia nervosa, seeds	Roughly spherical	20-50	[141]
Acorus calamus, rhizome	Spherical	31.83	[142]
Allium sativum, Sucrose and fructose	Spherical	4-22, 4 ± 1.5	[143]
Boerhaaviadiffusa, whole plant	Spherical	25	[144]
Citrus sinensis, peel	Spherical, triangular, hexagonal, rod-shaped	10-35	[145]
Cocos nucifera, Inflorescence	Spherical	22	[146]
Calotropis procera, plant	Spherical, cubic	19-45	[147]
Olea europaea extract, fruit	quasi-spherical	30	[148]
Passiflora foetida, leaf	spherical and hexagonal	14	[149]
Terminalia chebula, fruit	Spherical	100	[150]
Thevetia peruviana, latex	Spherical	10-60	[151]
Bacteria			
Bacillus licheniformis (bacteria)	Not specified	Not specified	[152,153]
Plectonema boryanum (cyanobacterium)	Not specified	Not specified	[154]
Oscillatoria willei NTDM01 (marine cyanobacterium)	Not specified	Not specified	[155]
Pseudomonas stutzeri, periplasmic space	Not specified	Not specified	[156]
Fungus			
Aspergillus fumigatus (fungus)	Not specified	Not specified	[157]
Penicillium brevicompactum WA2315 (fungus)	Not specified	Not specified	[157]
Fusarium semitectum (fungus)	Not specified	Not specified	[157]
Trichoderma asperellum (fungus)	Not specified	Not specified	[157]
Aspergillus niger (fungus)	Not specified	Not specified	[157]
Penicillium fellutanum (marine fungus)	Not specified	Not specified	[157]
Aspergillus flavus	Spherical	8-10	[158]
Volvariella volvacea	Spherical, hexagonal	20-150	[159]
Yeast			
Yeast strain MKY3	Hexagonal	2-5	[160]
Miscellaneous			
Hay grass (*Grass waste*)	Not specified	Not specified	[161]
Cocos nucifera (coir extract)	Not specified	Not specified	[162]

diverse applications, as shown in Table-4. Significantly, several metal-based nanoparticles have progressed to clinical the evaluation stages, with some approved by regulatory agencies such as the FDA and EMA for cancer therapy. An overview of these clinically relevant nanomaterials is presented in Table-5.

Future scope: Nanomedicine will surely play a significant part in future personalized medicine, from monitoring to prediction. Nanoscale materials serve as the foundation for increasingly sensitive biomarkers and sensors that could accurately and concurrently identify more ailments in their early stages. With improved targeting and chemical sensitivity, nanomedicine can map illnesses extremely precisely. Once a disease has been identified, nanomedicine can be used more effectively to attack cells while reducing adverse effects and damage

TABLE-2
LIST OF VARIOUS PLANT SOURCES FOR THE GREEN SYNTHESIS OF GOLD NANOPARTICLES ALONG WITH SHAPE AND SIZE

Plants	Shape	Size (nm)	Ref.
Cinnamomum zeylanicum	Spherical	5-50	[163]
Pogostemon benghalensis, leaf	Spherical, triangular	10-50	[164]
Pelargonium	Spherical	10–100	[165]
Cassia auriculata, leaf	Triangular, spherical	15-25	[166]
Artocarpus heterophyllus Lam, leaf extract	Nanoflowers, nanospheres, nanoplates	131 ± 18, 64 ± 10, 347 ± 136	[167]
Coriandrum sativumr, leaf	Spherical	6.75-57.91	[168]
Artocarpus heterophyllus, leaf	Nanospheres, nanoflowers	64 ± 10, 131 ± 18	[169]
Gymnema sylvestra, leaf	Spherical	1-90	[170]
Terminalia catappa, leaf	Spherical	10-35	[171]
Sargassum myriocystum, leaf	Spherical	10-23	[172]
Phyllanthus amarus, leaf	Spherical	65-99	[173]
Coleus amboinicus, leaf	Triangle, spherical, hexagonal	4.6-55.1	[174]
Dalbergia sissoo, leaf	Triangular, spherical	5-55	[175]
Centella asiatica, leaf	Spherical	9.3-10.9	[176]
Achyranthes aspera, leaf	Spherical	50-80	[177]
Psidium guajava, leaf	Spherical	25-30	[178]
Ocimum sanctum, leaf	Hexagonal	30	[179]
Eucalyptus macrocarpa, leaf	Spherical, triangular, hexagonal	20-100	[180]
Citrus limon, fruit	Polyshaped	32.2	[181]
Citrus reticulate, fruit	Polyshaped	43.4	[181]
Citrus sinensis, fruit	Polyshaped	56.7	[181]
Pyrus pyrifolia, fruit extract	Triangular, hexagonal	200-500	[182]
Ananascomosus, fruit	Spherical	5-15	[183]
Saracaindica, bark	Polyshaped	15-23	[184]
Mirabilis jalapa, flower	Multishaped	60-70	[185]
Rosa hybrida, flower	Spherical, triangular, hexagonal	10	[186]
Nyctanthesarbor-tristis, flower	Spherical	14.8-24.8	[187]
Lantana camara, flower	Spherical	4–12	[188]

TABLE-3
A SUMMARY OF DIFFERENT METALLIC NANOPARTICLES WITH VARYING SHAPES, SIZES AND THEIR APPLICATIONS

Metal	Shape	Size (nm)	Application	Ref.
Pd	Rod	21.60	Hydrogen peroxide	[189]
	Spherical	2.5	Azo-dyes	[190]
	Spherical	2-22	Antibacterial activity	[191]
	Spherical	5-8	Suzuki-Miyaura coupling	[192]
	Spherical	5	Antibacterial activity	[193]
	Spherical	2.5-8.8	Antibacterial and antioxidant activities	[194]
	Spherical	10 ± 33	Suzuki-Miyaura coupling reactions	[195]
CuO	Monoclinic, spherical	5-10	Antibacterial activity	[196]
	Spherical, hexagonal	26.6	HeLa cells	[197]
	Monoclinic	5-30	Antibacterial activity	[198]
Cu	Spherical	23-94	Organic dyes CR MB	[199]
	Spherical	15-20	Huisgen (3 + 2) cycloaddition	[200]
	Flakes	15-30	Antibacterial activity	[201]
Fe_3O_4	Spherical	19.3-25.3	Catalytic effect for synthesis of 2-arylbenzimidazole	[202]
	Spherical	33	Eutrophic wastewater	[203]
α-Fe_2O_3	Rod-like, spherical	39	Cancer cells	[204]
Fe	Polydispersed	20-80	Removal of Cr(VI) and Cu(II)	[205]
	Spheroidal	20-80	Eutrophic wastewater	[206]
	Spherical	50-60	Removal of Cr(VI)	[207]
	Round	40-50	Removal of Ametryn	[208]
	Irregular	40-60	Removal of MB MO	[209]
	Crystalline	20-45	Removal of As(III) & As(V)	[100]
Nanoscale zero-valent iron	Spherical or elliptic	63-381	RBR, azo dye RB banthraquinone dye	[210]
	Spherical	40-70	Phosphorus	[211]
	Spherical	40-60	Remove of phosphorous	[212]
	Spherical	20-50	Removal of Cr(VI)	[213]
	Sphericalm cylindrical, irregular	3-300	Removal of Cr(VI)	[214]
	Spherical	20-80	Elimination of dyes	[215]
	Collar-type	61.1-100.6	Removal of arsenate	[216]

TABLE-4
A SUMMARY OF EFFECTIVENESS OF VARIOUS METALLIC NANOMATERIALS: APPLICATIONS AND ITS KEY FUNCTIONS

Application field	Key function	Nanomaterials used	Ref.
Biomedical research	Facilitates gene transfer and delivery	Carbon nanotubes	[217]
COVID-19 Diagnostics & prevention	Enables virus tagging and supports mRNA vaccine formulation	Lipids, gold nanoparticles	[218-221]
Targeted drug delivery & cancer therapy	Enhances precision and therapeutic efficiency in treatments	Au, Si, CNTs, nano-graphene	[222,223]
Cancer detection	Utilized in biomedical imaging for tumor identification	Au, Fe	[222-224]
Monkeypox treatment	Binds circulating viruses and prevents cell entry	Fe_2O_3, Au	[221,225]
Medical applications	Reacts selectively with biomolecules and exhibits antiviral effects	Fullerenes	[226]
Antibacterial properties	Effective against bacterial infections	Au, Ag, Cu, Ti, Fe	[222]
Vaccine development	Enhances immune response as an adjuvant	Aluminum hydroxide, Au	[222]
Kidney disease treatment	Targets mesangial cells in kidney glomeruli for therapeutic intervention	Au	[227]
Cosmetics & skincare	Incorporated into sunscreens and beauty products	TiO_2, ZnO	[228]
Food safety & quality	Detects volatile organic compounds despite concerns about toxicity	TiO_2, Ag	[224]
Agricultural advances	Improves nutrient absorption in fertilizers	SiO_2, ZnO, CuO, Fe, Mg	[224]
Environmental applications	Enhances plant growth and development	CNTs	[224,229]

TABLE-5
A SUMMARY OF DIFFERENT METAL NANOPARTICLES APPROVED
FOR CANCER THERAPY BY FDA OR EMA AND CLINICAL TRIALS

Nanomaterial	Developer/Institution	Application & clinical trial identifier
Iron oxide (Fe_2O_3) nanoparticles	University College London (Magnablate I)	Investigated for prostate cancer treatment. Clinical Trial: NCT02033447 (Phase 0)
Hafnium oxide (HfO_2) nanoparticles	Nanobiotix	Evaluated for prostate adenocarcinoma therapy. Clinical Trial: NCT02805894
Silver-calcium hydroxide ($Ag/Ca(OH)_2$) composite	Cairo University	Used for post-surgical pain management. Clinical Trials: NCT03692286 (Phase IV), NCT04213716 (Phase II)
Magnetic iron oxide (Fe_2O_3) nanoparticles	University of New Mexico (MagProbe™)	Utilized in leukemia detection. Clinical Trial: NCT01411904
Gold-coated iron oxide with silica shell	Ural Medical University (NANOM)	Investigated for plasmonic photothermal therapy and stem cell treatment of atherosclerosis. Clinical Trials: NCT01270139 (Not Applicable), NCT01436123 (Phase I)
Spherical gold nanoparticles	Northwestern University (NU-0129)	Examined for treating recurrent glioblastoma or gliosarcoma in surgical patients. Clinical Trial: NCT03020017 (Phase 0)
Silver gel-based formulation	Madigan Army Medical Center (SilvaSorb)	Applied for antibacterial therapy. Clinical Trial: NCT00659204 (Phase III)
Nanocrystalline silver	Acticoat	Evaluated for conditions like pemphigus and pemphigoid. Clinical Trial: NCT02365675 (Not Applicable)
Zinc oxide nanoparticles	Multiple research institutions	Studied for applications in foot dermatoses and dental caries. Clinical Trials: NCT04000386 (Not Applicable), NCT03478150 (Not Applicable)

to healthy cells. Numerous products, such as the nanoencapsulated doxorubicin [230], are already in use. Essentially, future challenges include improving medication loading and release as well as expanding the possibilities for metallic nanoparticle diagnosis and treatment. Like any cutting-edge technology, nanomedicine must weigh its alluring potential against potential risks. Before treating patients to the fullest extent possible, nanomedicine must be carefully regulated and assessed, as is the case with other medical devices and treatments. Multistage clinical trials and toxicity assessments must be completed. Nanotechnology may one day be able to detect issues on the ground instead of relying on a mix of inputs from third-party sensors, medical expertise and probabilistic diagnostic algorithms.

Conclusion

Eco-synthesis of metallic nanoparticles has emerged as a compelling strategy that aligns with environmental safety, biocompatibility and the principles of green chemistry. Unlike traditional physical and chemical methods, biosynthetic approaches utilizing plant extracts, microbes and other bioresources offer a low-energy, non-toxic route to nanoparticle production. The review highlights the supremacy of gold and silver nanoparticles in this domain, owing to their highly tunable physico-chemical properties, excellent stability and wide-ranging applications from catalysis and antimicrobial coatings to diagnostics and cancer therapeutics. The performance and functionality of these nanoparticles are profoundly influenced by synthesis conditions such as pH, temperature, precursor concentration and the nature of biological agents used. Beyond noble metals, green synthesis has also enabled the generation of other functional nanomaterials such as Fe_3O_4, CuO and Pd nanoparticles, expanding the application landscape to include environmental remediation and chemical transformations. However, challenges related to large-scale production, consistency in particle characteristics, and mechanistic clarity remain unresolved. Advancing this field will require interdisciplinary collaboration focused on optimizing synthesis protocols, elucidating reaction pathways, and deploying robust characterization tools. As nanotechnology continues to intersect with sustainability goals, green-synthesized nanoparticles stand as viable candidates for next-generation materials across multiple sectors.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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