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Metal nanoparticles: Biosynthesis to applications (Review)

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Abstract. To attain sustainability, green nanotechnology uses nanomaterials in conjunction with the biosynthesis of nanomaterials from naturally occurring bioactive agents, such as plant extracts, microorganisms, agricultural wastes, eggshells, vegetable peels, fruit peels and other biowaste. The large number of applications of metal nanoparticles in biological sciences and their broad utilisations across different fields, has sparked a wide field of interest. In order to conjugate these materials with antibodies, ligands and drugs of interest, they can be fabricated and modified with different chemical functional groups. This indicates a large number of future uses in different fields, such as biotechnology, magnetic separation, the pre-concentration of target analytes, the targeted confinement of drugs, and vehicles for gene and drug delivery, although most importantly, diagnostic imaging. In the present review, applications of different metal nanoparticles, such as silver, gold, palladium, platinum, iron, selenium and copper synthesised using green methods are discussed. The present review also discusses the current challenges and future prospects of green synthesised metal nanoparticles. It is hoped that this information will prove to be helpful for promoting a sustainable environment. This will assist in the application of metal nanoparticles in different fields.

Contents

1. Introduction

The fascinating roots of nanotechnology can be connected with physicist, Richard Feynman, a great pioneer in the field. In his groundbreaking 1959 speech, *'There's Plenty of Room at the Bottom'*, Feynman introduced the noteworthy concept of regulating and influencing matter at the atomic and molecular scale (1). He envisioned the creation of miniaturised devices and materials at the nanoscale, setting the stage for remarkable advancements. The term nanotechnology was officially coined later, although its spirit was adopted by the Japanese scientist, Norio Taniguchi, in 1974, who examined the precise fabrication of nanoscale materials. The visionary work of Taniguchi focused on processes that could be finely tuned at the atomic level (2,3). Building on this foundation, the American engineer, Eric Drexler, further advanced the concept of molecular nanotechnology in the 1980s. The influential book of Drexler in 1986 entitled 'Engines of Creation' (4) explored the possibilities of constructing intricate structures at the atomic level using molecular machines, inspired by the pioneering theories of Feynman. Nanoparticles are tiny particles with dimensions between 1 and 100 nanometres, which possess distinctive characteristics due to their very small size and outstanding surface-to-volume ratio (5-7). These properties, which are often non-uniform compared with those of bulk materials, render nanoparticles highly valuable in various fields (8). For example, metal nanoparticles (MetNPs), such as gold and silver exhibit superior optical (9) and catalytic (10) behaviour due to surface plasmon resonance, while metal oxide nanoparticles (MONPs), such as titanium dioxide (TiO_2) and zinc oxide (ZnO) are widely used in photocatalysis (11) and environmental remediation (12). Carbon-based nanoparticles (CBNPs), including carbon nanotubes (CNTs) and graphene, exhibit marked electrical conductivity and mechanical

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strength, leading to their use in electronics and materials science. Nanoparticles are synthesised using top-down approaches, such as mechanical milling or bottom-up methods such as chemical vapour deposition (13,14). Their high reactivity and surface energy allow their advanced utilisation in fields, such as medicine, energy and environmental protection, where they play key roles in catalysis, drug delivery and pollutant removal. MetNPs such as gold, silver, selenium and iron synthesised through green methods have immense potential due to their ability to be modified with various chemical functional groups. This functionalisation permits their conjugation with antibodies, ligands and drugs, opening avenues for targeted drug delivery, gene therapy, and diagnostic imaging. Additionally, these nanoparticles play essential roles in biotechnology, particularly in magnetic separation, pre-concentration of target analytes, and the development of vehicles for drug and gene delivery (15,16). There are various properties of nanoparticles. To strengthen the conceptual organisation of the present review, a functionality-based classification of nanoparticles is introduced (Table I), categorising them according to their primary operational roles rather than composition alone. This framework classifies nanoparticles into catalytic, adsorptive, optical, magnetic, mechanical-reinforcement, electrochemical, antimicrobial, biocompatible and sensor-specific nanoparticles.

Size and surface area. The small size of nanoparticles leads to a large surface area relative to volume, which enhances reactivity and interaction with other substances. This makes nanoparticles highly effective in catalysis and adsorption processes (17,18).

Quantum effects. At the nanoscale, quantum mechanics begins to dominate material behaviour, leading to unique optical, electronic and magnetic properties that are not present in larger particles (19).

Surface energy. Nanoparticles possess higher surface energy, which can affect their stability and reactivity. As a result, they tend to agglomerate to reduce surface energy, but can be stabilised through surface treatments or coatings (20).

Mechanical strength. Some nanoparticles, such as CNTs, exhibit exceptional mechanical properties, such as high tensile strength and flexibility (21).

Optical properties. Nanoparticles can exhibit unique optical properties due to surface plasmon resonance, particularly in metals such as gold and silver, rendering them useful in imaging, sensing and photothermal applications (19).

Major developments in the field of MetNPs include a transition from early physical and chemical synthesis methods to modern green, biogenic methods that provide sustainable and eco-friendly production (Table II). Advances in nanoscale characterisation and mechanistic understanding have enabled greater control over particle size, shape and surface chemistry. These breakthroughs have led to rapid growth in applications such as biomedicine, catalysis, sensing, and environmental remediation, with recent advances focusing on the synthesis of hybrid nanocomposites and nanozymes.

2. Types of nanoparticles

MNPs. MetNPs are metallic particles ranging from 1 to 100 nanometres in size and exhibit unique physical, chemical and optical properties that differ significantly from their bulk counterparts. These properties arise from their high surface-area-to-volume ratio and quantum effects, making them highly versatile across various fields (22). The size, shape and surface characteristics of MetNPs can be tailored during synthesis, influencing reactivity, catalytic activity, and optical behaviour (23). Common types include gold nanoparticles, known for their biocompatibility and use in medical diagnostics and drug delivery; silver nanoparticles, widely used for antimicrobial properties; and iron nanoparticles, effective in environmental remediation. Platinum and copper nanoparticles are valued for their catalytic and electrical properties, respectively. The applications of MetNPs span diverse areas. In environmental remediation, they are used for heavy metal removal, the degradation of organic pollutants and the catalytic breakdown of contaminants (24). In medicine, they serve as drug delivery agents, imaging tools and antimicrobial agents. Their role in energy applications includes use in fuel cells and batteries, while in sensors and diagnostics they enhance disease detection and environmental monitoring (25). MetNPs are synthesised using chemical, physical and biological methods, including chemical reduction of metal salts, laser ablation and green synthesis using plant extracts or microorganisms. However, stability issues, potential toxicity and scalability concerns need to be addressed to fully harness their potential. Despite these challenges, MetNPs represent a promising avenue for innovation across multiple industries.

MONPs. MONPs are a class of nanomaterials consisting of metal cations bonded to oxygen anions. These nanoparticles exhibit exceptional properties, including high stability, catalytic activity, and tuneable electronic, magnetic and optical characteristics. Their unique properties are attributed to their small size, high surface-area-to-volume ratio, and quantum confinement effects, rendering them highly desirable in various scientific and industrial applications. MONPs are synthesised from a wide variety of metals, with some of the most common types being TiO_2, ZnO, iron oxide (Fe_2O_3/Fe_3O_4), cerium oxide (CeO_2) and aluminium oxide (Al_2O_3). TiO_2 is widely used for its photocatalytic activity in environmental remediation and self-cleaning surfaces (26). ZnO is prized for its antimicrobial properties and applications in sunscreens and sensors. Iron oxide nanoparticles, particularly magnetite (Fe_3O_4), are utilised in biomedical applications, such as magnetic resonance imaging (MRI) and targeted drug delivery. CeO_2 is known for its role as a redox catalyst, particularly in automotive catalytic converters and as an antioxidant in biological systems (27). The applications of MONPs span a range of fields. In environmental science, they are employed for water and air purification, as well as for the degradation of organic pollutants through photocatalytic processes (28,29). In the medical field, they play a role in drug delivery, imaging, and antimicrobial treatments (30). MONPs are also extensively used in energy storage and conversion devices, such as lithium-ion batteries, supercapacitors, and fuel cells (31). Their catalytic properties make them essential in industrial

Table I. Functionality-based classification of nanoparticles.

Functionality category	Types of nanoparticles	Properties	Typical synthesis methods	Applications	(Refs.)
Catalytic nanoparticles	Metal NPs (Pt, Pd, Au and Ag), metal oxides (TiO_2 and MnO_2), and MOF-derived NPs	High surface area, active sites, and redox activity	Chemical reduction, sol-gel, thermal decomposition, and MOF-templated synthesis	Photocatalysis, organic pollutant degradation, fuel cells, and hydrogen evolution	(119)
Adsorptive nanoparticles	Carbon nanotubes, graphene oxide, biochar NPs, zeolites and silica NPs	Large surface area, porosity, and surface functional groups	Hydrothermal, green synthesis, pyrolysis, and surface functionalisation	Heavy metal removal, dye adsorption, and water purification	(120)
Optical nanoparticles	Quantum dots, plasmonic Au/Ag NPs, and upconversion NPs	Fluorescence, plasmon resonance, and tuneable bandgap	Colloidal synthesis, solvothermal and microwave synthesis	Imaging, sensing, optical probes and biosensing	(51)
Magnetic nanoparticles	Fe_3O_4, $CoFe_2O_4$ and $MnFe_2O_4$	Superparamagnetism and magnetic separation capability	Co-precipitation, thermal decomposition, and solvothermal	MRI contrast agents, targeted drug delivery and magnetic separation of pollutants	(117)
Mechanical-reinforcement nanomaterials	Carbon nanotubes, nanofibers, nanoclays and graphene	High tensile strength, flexibility, and high modulus	Chemical vapor deposition, exfoliation, and electrospinning	Polymer nanocomposites, structural reinforcement, and coatings	(121,122)
Electrical/electro-chemical nanoparticles	Metal selenides ($NiSe_2$, $CoSe_2$), metal sulphides, conductive polymers, and carbon nanomaterials	High conductivity, fast electron transfer, and electrocatalytic activity	Electrodeposition, solvothermal, hydrothermal, and MOF-derived synthesis	Electrochemical sensors, super-capacitors and batteries	(123)
Antimicrobial nanoparticles	Ag NPs, ZnO NPs and CuO NPs	ROS generation, membrane disruption, and ion release	Green synthesis, chemical reduction, and precipitation	Antibacterial coatings, wound dressings and food preservation	(83, 124)
Biocompatible/drug-delivery nanoparticles	Liposomes, polymer NPs, silica NPs and gold nanoshells	Biocompatibility, controlled release, and surface modifiability	Self-assembly, emulsification, and nanoprecipitation	Drug delivery, gene delivery and targeted therapeutics	(125,126)
Sensor-specific nanoparticles	$NiSe_2$/MOF composites, AuNP-based probes and carbon dots	High selectivity, electrocatalysis, and signal amplification	MOF-derived synthesis, hydrothermal, and green synthesis	Pharmaceutical detection, environmental sensing and biosensors	(127)

NPs, nanoparticles; Pt, platinum; Pd, palladium; Au, gold; Ag, silver; TiO_2, titanium dioxide; MnO_2, manganese dioxide; MOF, metal organic framework; Fe_3O_4, iron (II,III) oxide; $CoFe_2O_4$, cobalt ferrite; $MnFe_2O_4$, manganese ferrite; $NiSe_2$, nickel disulphide; $CoSe_2$, cobalt diselenide; ZnO, zinc oxide; CuO, copper(II) oxide; ROS, reactive oxygen species; AuNP, gold nanoparticle.

Table II. Major developments in the field of metal nanoparticles.

Era/phase	Key developments	Description of advancement	Representative metals/examples	(Refs.)
Early phase (1980-2000)	Physical and chemical synthesis	Development of top-down and bottom-up methodssuch as chemical reduction, laser ablation, sol-gel and thermal decomposition	Au, Ag, Pt and Pd nanoparticles synthesised by citrate reduction (the Turkevich method)	(128,129)
Characterisation advancements	Introduction of TEM, SEM, XRD, UV-Vis and DLS enabling improved size/shape analysis	Enabled correlation between structure and optical properties	Au and Ag SPR studies	(9,130)
Green synthesis emergence (2000-2010)	Plant-based biosynthesis	Use of plant extracts (polyphenols, alkaloids, and proteins) for nanoparticle reduction	AgNPs from *Azadirachta indica* and AuNPs from *Camellia sinensis*	(101,103)
	Microbial synthesis	Bacteria, fungi, and algae used as bioreactors for metal ion reduction	AgNPs from *Bacillus subtilis* and AuNPs from *Fusarium oxysporum*	(82,131)
	Biomolecule-mediated synthesis	Amino acids, enzymes, and polysaccharides used as stabilising/capping agents	Chitosan-capped AgNPs and protein-stabilised AuNPs	(132)
Mechanistic understanding (2010-2018)	Mechanistic elucidation	Understanding of bioreduction pathways, enzyme involvement, and electron shuttle mechanisms	NADH-dependent enzymatic reduction for Au and AgNPs	(93,133)
	Controlled synthesis	Advancement in size/shape control: nanorods, nanoflowers, and nanocubes	Au nanorods, Ag nanocubes and Pt nanoflowers	(134)
	Surface functionalisation	Enhanced biocompatibility and targeting via PEGylation and ligand attachment	PEG-AuNPs and antibody-tagged AgNPs	(135)
Application expansion (2015-2022)	Biomedical applications	Use in drug delivery, imaging, hyperthermia, biosensors, and antimicrobial coatings	AuNPs for cancer therapy and AgNP wound dressings	(40)
	Environmental applications	Use in pollutant degradation, sensing, and heavy metal removal	Fe_3O_4 NPs for wastewater treatment and AgNP sensors for Hg_{2+}	(29)
	Catalytic applications	High catalytic activity due to surface area and active sites	PdNPs for hydrogenation and AuNPs for CO oxidation	(136)
Advanced Technologies (2020-present)	Hybrid nanocomposites	Integration with polymers, MOFs, graphene, and carbon nanotubes	$NiSe_2$/MOF hybrids and AgNP-graphene composites	(137)
	Nanozymes	Metal nanoparticles mimicking enzymatic activity (peroxidase and oxidase)	Fe_3O_4 NP peroxidase mimics and AuNP oxidase mimic	(138)
	Precision biosynthesis	Genome-engineered microbes and enzymatic pathways to tailor NP morphology	CRISPR-modified bacteria for AgNPs	(85)
	Clinical translation efforts	Toxicity reduction, pharmacokinetic studies, and regulatory focus	PEG-AuNPs in clinical imaging trials	(139)
Future directions (emerging)	AI-guided synthesis	Machine-learning models predicting shape, size, and stability	Computational design of Au, Ag and Pd NPs	(140)

Table II. Continued.

Era/phase	Key developments	Description of advancement	Representative metals/examples	(Refs.)
	Sustainable nanotechnology	Zero-waste synthesis and agro-waste-mediated nanoparticle production	Fruit peel-mediated AgNPs and biomass-derived AuNPs	(141)
	Multifunctional theranostics	Combining therapy + imaging in one nanoparticle platform	Au-Fe_3O_4 hybrid nanoplatforms	(142)

NPs, nanoparticles; Pt, platinum; Pd, palladium; Au, gold; Ag, silver; TEM, transmission electron microscopy; SEM, scanning electron microscopy; XRD, X-ray diffraction; UV-Vis, ultraviolet-visible spectroscopy; DLS, dynamic light scattering; SPR, surface plasmon resonance; AgNPs, silver nanoparticles; Fe_3O_4, iron (II,III) oxide.

chemical processes, including the production of fertilisers and the refinement of fuels. Several synthesis methods are used to produce MONPs, including sol-gel processes, hydrothermal methods, chemical vapor deposition, and green synthesis using biological agents (32). These methods allow control over the size, shape and surface characteristics of the nanoparticles, which are critical for optimising their performance in specific applications. Despite their advantages, MONPs pose challenges, such as potential toxicity, environmental persistence and the need for cost-effective and scalable production methods (33). Addressing these challenges is essential for their safe and sustainable use across various sectors, highlighting their potential to revolutionise industries ranging from healthcare to environmental management.

CBNPs. CBNPs are nanomaterials composed primarily of carbon atoms, engineered in various structures and dimensions. These nanoparticles exhibit notable mechanical, electrical, thermal and chemical properties, rendering them a cornerstone of nanotechnology research and applications. Their versatility stems from the unique bonding nature of carbon, which allows them to form various allotropes and hybrid structures (34). Key types of CBNPs include CNTs, fullerenes, graphene, graphene oxide, carbon dots (CDs) and nanodiamonds. CNTs are cylindrical structures with extraordinary tensile strength, electrical conductivity, and thermal stability, making them valuable in electronics, materials reinforcement, and energy storage (21). Fullerenes, spherical carbon molecules, are known for their electron-accepting capabilities and are used in drug delivery, solar cells and antioxidants. Graphene is a two-dimensional sheet of carbon atoms arranged in a hexagonal lattice, renowned for its high electrical and thermal conductivity, flexibility, and strength, leading to applications in flexible electronics, sensors and advanced composites (34). CDs are fluorescent nanoparticles with tuneable optical properties, commonly used in bioimaging and sensing. Nanodiamonds exhibit exceptional hardness and biocompatibility, making them ideal for polishing, drug delivery, and imaging (35). The applications of CBNPs span multiple disciplines. In medicine, they serve as drug delivery agents, bioimaging tools and antimicrobial materials. In electronics, they are employed in transistors, flexible displays and conductive coatings. Their thermal properties render them useful in heat management systems, while their mechanical strength is exploited in the development of advanced composites. Environmental applications include water purification, pollutant adsorption and catalysis for pollutant degradation. Additionally, their role in energy storage and conversion, such as in batteries, supercapacitors, and fuel cells, highlights their importance in renewable energy technologies. CBNPs are synthesised through various techniques, including chemical vapor deposition, laser ablation, arc discharge and green synthesis using biological agents. These methods allow control over their size, structure and functionalisation, which are critical for tailoring them to specific applications. However, challenges, such as production scalability, cost, potential toxicity and environmental impact need to be addressed. Despite these obstacles, CBNPs represent a transformative class of nanomaterials, with the potential to drive advancements in science, technology and industry (29,33-35).

Polymeric nanoparticles (PNPs). PNPs are nano-sized particles composed of polymers, typically ranging in size from 1 to 1,000 nanometres. These nanoparticles are highly versatile and can be engineered for a wide range of applications due to their biocompatibility, chemical tunability, and ability to encapsulate and protect active agents. Their structure often includes a polymeric core and shell, which can be functionalised to enhance stability, target specificity and controlled-release properties. PNPs are categorised into different types based on their structure. Nanospheres are solid matrix-like particles in which the active compound is dispersed or adsorbed throughout the polymer matrix. Nanocapsules, on the other hand, are vesicular systems in which the active agent is enclosed within a polymeric shell (36,37). The polymers used in PNP synthesis can be natural (e.g., chitosan, gelatin and alginate) or synthetic [e.g., polylactic acid, polyglycolic acid and poly(lactic-co-glycolic acid)] and are selected based on the intended application and required properties (38). The applications of PNPs are vast, with their most prominent role in the biomedical field. They are widely used as drug delivery systems, enabling the encapsulation of therapeutic agents for enhanced solubility, stability and targeted delivery. Their ability to release drugs in a controlled manner reduces side-effects and improves therapeutic efficacy. In cancer therapy, PNPs can be designed to deliver chemotherapeutics directly to tumour cells, minimising damage to healthy tissues (36,39). They are also used in gene therapy, vaccine delivery and tissue engineering. Beyond medicine, PNPs are employed in the food industry for the controlled release of nutrients and additives, in agriculture for the delivery of pesticides and fertilisers, and in environmental applications for pollutant removal. Synthesis methods for PNPs include emulsion techniques (single or double emulsion), precipitation, solvent evaporation, and ionic gelation, among others. These methods allow the precise control over particle size, shape and surface properties. The functionalisation of the nanoparticle surface with ligands or coatings further enhances their ability to target specific cells or tissues, a feature particularly valuable in medical applications. Despite their advantages, challenges remain in the use of PNPs, such as scaling up production, ensuring uniformity, and addressing potential environmental and biological toxicity. Advances in polymer chemistry and nanoparticle engineering continue to overcome these hurdles, rendering PNPs a key player in modern nanotechnology and materials science. Their adaptability and functionality promise significant contributions across diverse industries, from healthcare to environmental sustainability (37,39-42).

Lipid-based nanoparticles (LNPs). LNPs are nanoscale structures composed of lipids, typically ranging in size from 10 to 1,000 nanometres. They have garnered significant attention due to their biocompatibility, ability to encapsulate hydrophilic and hydrophobic molecules and potential for targeted delivery. Their unique properties render them indispensable in drug delivery systems, particularly for delivering challenging therapeutic agents such as nucleic acids and poorly soluble drugs. The structure of LNPs generally includes a lipid bilayer or a core-shell configuration, in which a hydrophobic core is surrounded by a lipid shell (43-45). Common types of LNPs include liposomes, solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs). Liposomes are spherical vesicles with one or more lipid bilayers, capable of encapsulating hydrophilic drugs in their aqueous core and hydrophobic drugs within their lipid bilayer (46). SLNs are composed of a solid lipid core stabilised by surfactants, providing a highly stable system for drug encapsulation. NLCs are an advanced version of SLNs, incorporating both solid and liquid lipids to improve drug-loading and release characteristics. LNPs are widely used in the pharmaceutical and biomedical fields. They play a crucial role in the delivery of small molecules, peptides, proteins and nucleic acids, providing protection from enzymatic degradation and enhancing cellular uptake. LNPs have revolutionised the field of gene therapy and mRNA vaccines, as demonstrated by their use in COVID-19 mRNA vaccines (43,46-48). In cancer therapy, they enable targeted delivery of chemotherapeutics to tumour cells while minimising systemic toxicity. Beyond healthcare, LNPs are applied in cosmetics for enhanced skin delivery, in agriculture for the delivery of pesticides and fertilisers, and in food technology for encapsulating nutrients and bioactives. The synthesis of LNPs involves methods, such as thin-film hydration, microfluidics, high-pressure homogenisation and solvent evaporation (38). These techniques allow for the precise control over particle size, surface charge and encapsulation efficiency. Surface functionalisation with ligands, such as antibodies or peptides, enables targeted delivery to specific cells or tissues, enhancing therapeutic efficacy. While LNPs offer numerous advantages, challenges persist, including stability issues, scalability for industrial production and potential immunogenicity (49,50). Addressing these challenges through advances in lipid chemistry and nanotechnology will further enhance their efficacy and broaden their applications. LNPs continue to be a cornerstone of modern nanomedicine and materials science, with the potential to address unmet needs in healthcare, agriculture and beyond.

Semiconductor nanoparticles [quantum dots (QDs)]. Semiconductor nanoparticles, commonly known as QDs, are nanometre-scale crystals typically ranging from 2 to 10 nanometres in size. These nanoparticles exhibit unique quantum mechanical properties, particularly quantum confinement, which arises when the particle size is smaller than the exciton Bohr radius. This confinement results in discrete energy levels and size-dependent optical and electronic properties, rendering QDs highly versatile in various applications. QDs are composed of semiconductor materials such as cadmium selenide (CdSe), cadmium telluride (CdTe), indium phosphide (InP) and zinc sulfide (ZnS). Their most notable property is their size-tuneable fluorescence; by varying the particle size, QDs can emit light across the visible to infrared spectrum (9). This property, combined with their high photostability, broad absorption spectra, and narrow emission peaks, renders QDs invaluable for imaging and optoelectronic applications. The applications of QDs span multiple fields. In biomedicine, they are widely used as fluorescent probes for bioimaging and biosensing due to their brightness and resistance to photobleaching. QDs are instrumental in the development of advanced diagnostics, enabling high-resolution imaging of cellular and molecular processes. In optoelectronics, QDs are employed in QD light-emitting diodes (QD-LEDs), offering vibrant displays with superior colour accuracy and energy efficiency (9,35). They are also used in solar cells to improve light absorption and energy conversion efficiency, as well as in lasers and photodetectors. In environmental science, QDs are used in sensors for detecting pollutants and toxins, as well as in photocatalysis for water and air purification. QDs are typically synthesised using methods such as colloidal synthesis, chemical vapour deposition, molecular beam epitaxy, and microemulsion techniques. These methods allow precise control over particle size, composition, and surface properties, which are crucial for tuning their optical and electronic characteristics. Surface modification and functionalisation of QDs are often employed to improve their stability, biocompatibility, and specificity for targeted applications (51,52). Despite their advantages, the widespread use of QDs faces challenges. A number of QDs are made from heavy metals, such as cadmium, raising concerns about environmental toxicity and biocompatibility. Research is ongoing to develop eco-friendly and non-toxic alternatives, such as graphene and silicon QDs. Additionally, achieving cost-effective and scalable production remains a focus of current efforts. QDs represent a transformative class of materials with immense potential to impact science and technology. Their unique properties and adaptability make them a cornerstone of advancements in imaging, electronics, renewable energy and environmental applications (9,19).

Ceramic nanoparticles. Ceramic nanoparticles are nanoscale materials made from inorganic, non-metallic solids, such as oxides, carbides, nitrides, or silicates. Typically ranging in size from 1 to 100 nanometres, these particles are characterised by their high stability, hardness, chemical inertness, and resistance to heat and corrosion. Their properties can be finely tuned by controlling their size, composition and morphology, rendering them highly versatile in various scientific and industrial applications (53). Common types of ceramic nanoparticles include TiO_2, Al_2O_3, silicon dioxide (SiO_2), zirconium dioxide (ZrO_2) and magnesium oxide (MgO). These materials exhibit diverse properties, such as photocatalytic activity, thermal conductivity, and electrical insulation. For instance, TiO_2 is widely used for its photocatalytic and UV-blocking properties, while SiO_2 finds applications in reinforcement, electronics and drug delivery (54,55). Ceramic nanoparticles are utilised in a broad range of fields. In medicine, they serve as carriers for drug delivery, imaging agents in diagnostics, and materials for bone and dental tissue engineering. Their biocompatibility and ability to be functionalised make them suitable for these applications. In environmental science, they are employed for water purification, pollutant adsorption, and photocatalysis for the degradation of organic contaminants. In electronics, ceramic nanoparticles enhance the properties of devices such as capacitors, sensors, and thermal insulators. In industrial applications, they are used as additives to improve the mechanical strength, heat resistance, and durability of materials such as coatings, paints, and polymers (56,57). Furthermore, they are integral to the development of advanced ceramics for high-performance applications in the aerospace, automotive and energy industries. Synthesis methods for ceramic nanoparticles include sol-gel processes, hydrothermal synthesis, flame spray pyrolysis and mechanical milling. These methods enable precise control over particle size, morphology, and composition. Surface functionalisation techniques are often employed to enhance their dispersibility and compatibility with specific environments or applications. Despite their advantages, ceramic nanoparticles face challenges, such as aggregation, which can reduce their effectiveness, and concerns regarding their environmental and biological impacts. Addressing these challenges through improved synthesis techniques and comprehensive toxicity assessments is essential for their sustainable and safe use. Ceramic nanoparticles represent a critical class of materials with wide-ranging applications due to their unique physical and chemical properties. As research and technology advance, they continue to play a crucial role in addressing challenges across healthcare, environmental management, energy storage and materials engineering (53,58,59)

Magnetic nanoparticles (MNPs). MNPs are nanoscale particles that exhibit magnetic properties due to their composition of magnetic materials such as iron oxide (magnetite Fe_3O_4 or maghemite γ-Fe_3O_4), cobalt, or nickel. These particles display unique characteristics, including superparamagnetism, whereby they exhibit strong magnetisation only in the presence of an external magnetic field and lose their magnetisation when the field is removed. This property, along with their high surface-area-to-volume ratio, makes them highly versatile for various applications. MNPs are often engineered with a core-shell structure, in which the core consists of a magnetic material and the shell is coated with substances such as silica, polymers, or carbon to enhance stability, biocompatibility, and dispersibility. These features render MNPs particularly suitable for biomedical, environmental and industrial applications (25). In the biomedical field, MNPs are widely used for drug delivery, where they function as carriers to transport drugs to specific sites in the body, guided by an external magnetic field. They are also employed in hyperthermia therapy, in which they generate localised heat under an alternating magnetic field to destroy tumour cells, and as contrast agents in MRI to improve imaging quality (60). Additionally, MNPs play a role in biosensing, aiding in the detection of biomolecules in diagnostic assays. In environmental science, MNPs are effective in water treatment, as they can remove heavy metals, organic pollutants and oil spills. They are also used as catalysts for pollutant degradation. In technology, MNPs are integral to high-density data storage and spintronics due to their exceptional magnetic properties. In industrial applications, they are used in magnetic fluids for seals, damping systems, and actuators, as well as in catalysis for chemical synthesis (61). MNPs are synthesised using various methods, such as co-precipitation, thermal decomposition, sol-gel synthesis and hydrothermal techniques, which allow precise control over their size, composition and surface properties. The functionalisation of their surface is often performed to attach specific ligands, polymers, or biomolecules, enabling targeted applications. Despite their advantages, challenges such as particle aggregation, long-term stability, scalability of production and potential toxicity remain. Addressing these challenges through advances in synthesis techniques, surface modifications and comprehensive safety assessments is crucial. Magnetic nanoparticles represent a transformative class of materials with diverse applications in medicine, environmental management, and technology, driven by their unique ability to respond to external magnetic fields (25,60,62).

Core-shell nanoparticles. Core-shell nanoparticles are a class of nanostructures comprising a core material surrounded by a shell of a different composition, typically designed to combine or enhance the properties of both the core and the shell materials. The core and shell can be made from various materials, such as metals, oxides, polymers, or carbon, providing versatility in tailoring their physical, chemical and optical properties for specific applications. The core-shell structure provides several advantages, including improved stability, enhanced functionality and controlled interaction with the surrounding environment. The core is typically selected for its unique intrinsic properties, such as magnetic, optical, or catalytic characteristics, while the shell is engineered to enhance biocompatibility, prevent core oxidation, or introduce new functionalities (63). For example, metallic cores such as gold or silver are often combined with silica or polymer shells to enhance stability and enable surface functionalisation. Similarly, magnetic cores, such as iron oxide, are coated with inert shells to reduce toxicity and improve dispersibility. Core-shell nanoparticles are widely utilised across various fields. In medicine, they are employed in drug delivery systems, imaging and diagnostics. For instance, nanoparticles with a magnetic core and a biocompatible polymer shell can deliver drugs to targeted sites under the influence of an external magnetic field while minimising off-target effects (64). In environmental applications, core-shell structures are used in pollutant adsorption, water purification and photocatalysis. In energy and electronics, they play a critical role in solar cells, fuel cells, and advanced sensors by enhancing efficiency and stability. Catalysis is another key area where core-shell nanoparticles are utilised, with the shell often serving to protect the catalytic core while allowing reactant access. Core-shell nanoparticles are synthesised using various techniques, such as co-precipitation, sol-gel processes, layer-by-layer assembly and chemical vapour deposition. These methods enable precise control over the size, morphology and composition of the particles (61,65). Surface functionalisation is often employed to introduce specific ligands or coatings that enhance compatibility with biological systems or improve stability in various environments. Despite their numerous advantages, challenges, such as scalability of production, potential environmental and biological impacts, and cost-effective synthesis need to be addressed (64,66,67). Ongoing research is focused on optimising fabrication techniques, exploring sustainable materials and ensuring safe use (68). Core-shell nanoparticles represent a versatile and innovative class of materials with significant potential to advance technology and address critical challenges in healthcare, energy and environmental sustainability.

Dendrimers. Dendrimers are highly branched, three-dimensional macromolecules with a well-defined, tree-like structure. These nanoscale materials, typically ranging from 1 to 10 nanometres in size, are synthesised in a controlled, stepwise manner to achieve uniformity in size, shape and surface functionality. The unique architecture of dendrimers consists of three main components: A central core, repetitive branching units, and peripheral functional groups. This structure endows dendrimers with a high degree of molecular precision, large surface area, and tuneable properties, making them highly versatile in a variety of applications (67). The interior of dendrimers features void spaces that can encapsulate guest molecules, while the terminal groups on their surface can be functionalised to interact with specific targets. The high density of functional groups on the surface allows for multivalency, which is particularly valuable in applications requiring targeted interactions, such as drug delivery, gene therapy and diagnostics. Dendrimers are classified by generations, with each successive generation adding more branching layers and increasing size and functionality (69). In biomedical applications, dendrimers have shown promise as drug delivery vehicles due to their ability to encapsulate drugs within their internal cavities or conjugate drugs to their surface functional groups. This dual functionality enables controlled drug release, improved solubility and targeted delivery to specific cells or tissues, reducing side-effects. They are also used in gene therapy as carriers for nucleic acids, enhancing stability and delivery efficiency. Additionally, dendrimers are employed in diagnostics as imaging agents and biosensors, benefiting from their multivalency and high surface reactivity (67,70). In environmental science, dendrimers are utilised for water purification, pollutant removal and as catalysts or photocatalysts for environmental remediation. Their functional groups can be tailored to bind specific contaminants, enabling selective and efficient removal. In materials science, dendrimers contribute to the development of advanced coatings, adhesives and nanocomposites, providing improved mechanical, thermal and optical properties. They are also employed in electronics and energy applications, such as in the fabrication of LEDs and fuel cells. Dendrimers are synthesised using two main approaches: Divergent synthesis, where branching units are added outward from the core, and convergent synthesis, where dendrons (branching segments) are built separately and then attached to the core. Both methods provide precise control over structure and functionality, although they differ in scalability and complexity (71). Despite their advantages, dendrimers face challenges such as high production costs, potential cytotoxicity, and complex synthesis processes. Advances in synthetic methodologies, the development of biocompatible dendrimers, and cost-effective production techniques are crucial for their broader adoption. Dendrimers represent a cutting-edge class of nanomaterials with immense potential to transform fields such as medicine, environmental science and materials engineering due to their unique architecture and versatile properties (36,67,43,44).

Despite the advantages of MetNPs, conventional methods of synthesis often pose significant environmental and health risks. Traditional chemical synthesis typically involves toxic reagents, hazardous solvents, and high energy inputs, leading to harmful by-products that can impact both human health and ecosystems. A number of nanoparticle synthesis methods (e.g., chemical reduction, pyrolysis and chemical vapour deposition) rely on toxic chemicals, high energy inputs and non-renewable resources. These processes can generate

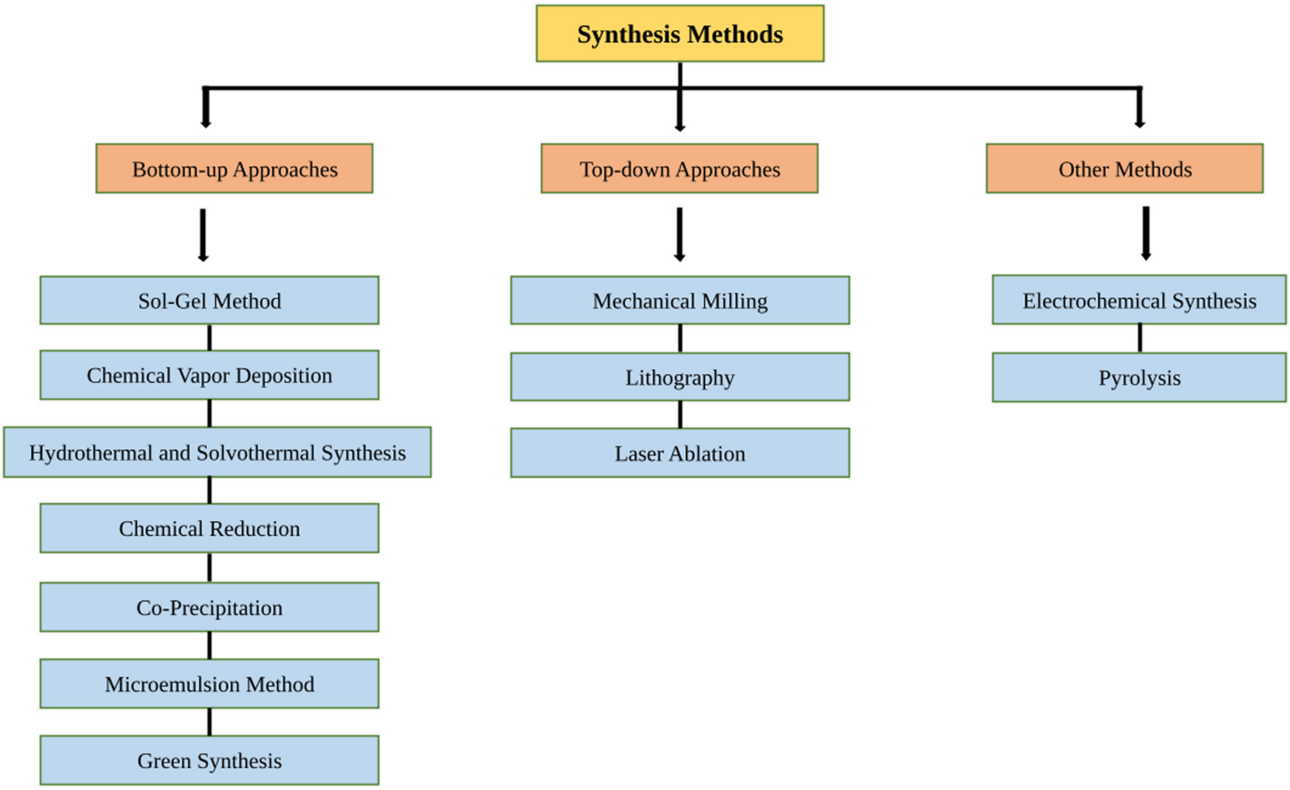

Figure 1. Methods used for the synthesis of nanoparticles.

hazardous waste, consume large amounts of energy and can lead to the release of pollutants, including toxic solvents used in chemical reactions and by-products that are harmful to ecosystems. Energy consumption can also lead to increased carbon emissions. Some conventional synthesis methods use hazardous precursors and produce toxic by-products. Different synthesis methods of nanoparticles are illustrated in Fig. 1.

3. Biosynthesis of nanoparticles

Biosynthesis is critical for preventing the generation of unwanted or harmful by-products by establishing dependable, sustainable synthesis processes that are eco-friendly. This objective requires optimal solvent systems and natural resources. Some basic aspects of green synthesis may thus be described by numerous components, such as waste minimisation, pollution reduction, and the use of better (non-toxic) solvents. The green production of MNPs has been used to accommodate a variety of biological components, including bacteria, fungi and algae (3). Green synthesis involves the use of plant extracts, microorganisms, and enzymes as reducing and stabilising agents, thereby reducing the need for harmful chemicals and minimising environmental impact. MetNPs, including those made from silver, gold, copper and zinc oxide, have special properties such as high surface-to-volume ratios, quantum effects, and tuneable optical and catalytic properties, making them highly valuable in diverse fields such as catalysis, medicine, environmental remediation and electronics. However, conventional methods of nanoparticle synthesis often incorporate the use of toxic chemicals, high energy input and environmentally harmful by-products (8,3,72). The vast surface area of nanoparticles renders them ideal for a variety of applications, including medicine (73), cosmetics (74), food chemicals, drug delivery, biosensors, bioimaging and cancer treatment (75). Nanoparticles have gained popularity among scientists globally due to their potential applications in areas of research and technology and are gaining popularity in medical research due to their small size, vast surface area, solubility and potential applications. The mechanisms of the synthesis of nanoparticles using the green method is depicted in Fig. 2. The mechanisms of green synthesis for nanoparticles along with their size, characteristics, applications and synthesis methods are presented in Table III.

4. Principles of biosynthesis

The biosynthesis of MetNPs involves the reduction of metal ions to nanoparticles using naturally occurring biological entities. This method eliminates the need for harsh chemicals, toxic solvents and energy-intensive processes, which are often required in traditional chemical synthesis. The main principles guiding green synthesis are simplicity, sustainability and environmental safety. MetNPs derived from plant extracts are stable and readily monodispersed by adjusting pH values, temperature range, retention period and the ratio of mixing. MNPs formed using green methods are derived from diverse plant extracts, such as neem leaves (*Azadirachta indica*), basil leaves (*Ocimum tenuiflorum*), curry leaves (*Murraya koenigii*), guava leaves (*Psidium guajava*) and mango leaves (*Mangifera indica*) (72,76,77).

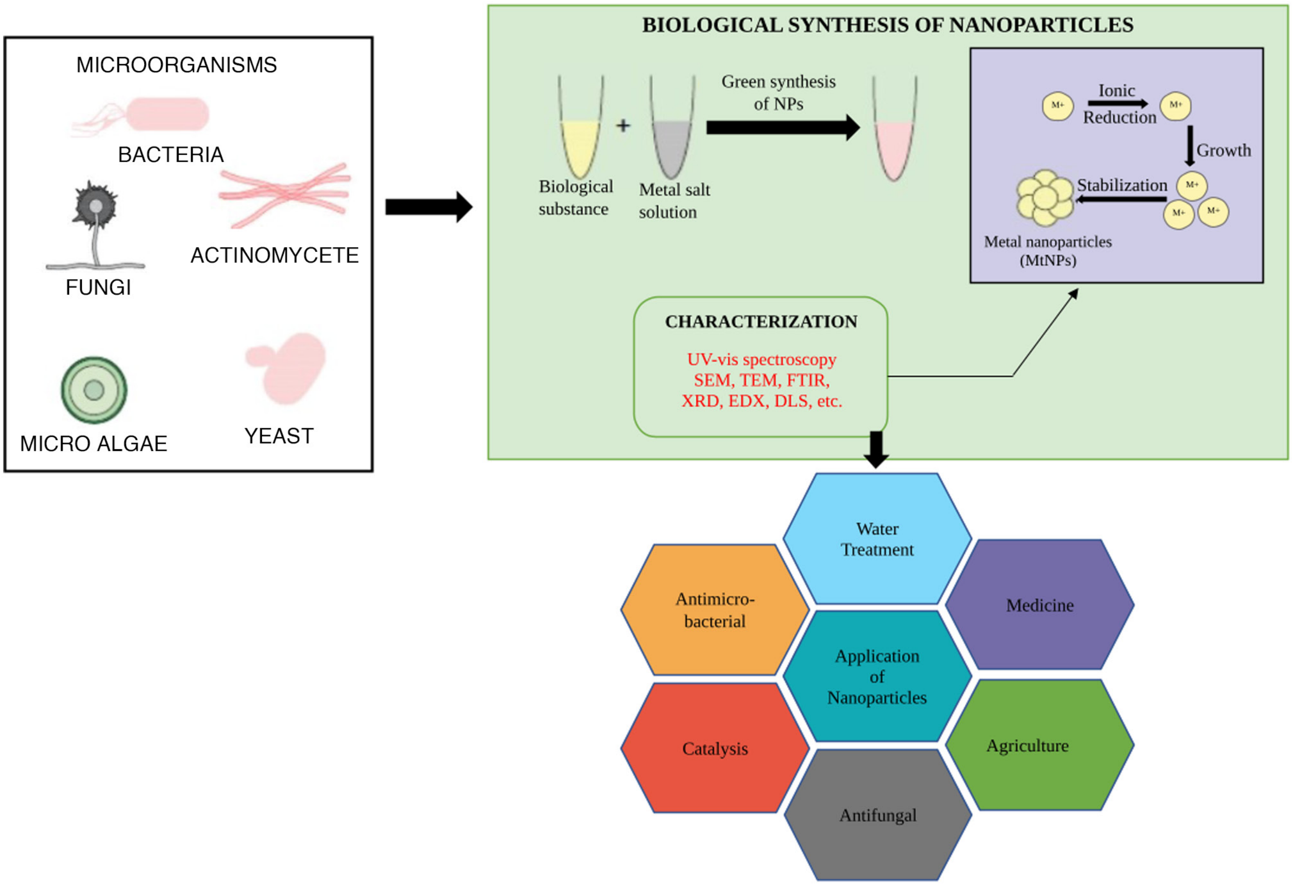

Figure 2. Mechanisms involved in the green synthesis of nanoparticles. SEM, as scanning electron microscopy; TEM, transmission electron microscopy; FTIR, Fourier transform infrared spectroscopy; XRD, X-ray diffraction; EDX, energy-dispersive X-ray spectroscopy; DLS, dynamic light scattering

5. Biological agents in green synthesis

Various biological agents have been explored for the synthesis of green nanoparticles. These include the following:

Plant extracts. The green synthesis of nanoparticles using plant extracts has emerged as an eco-friendly and sustainable approach to nanomaterial production. This method leverages the rich diversity of phytochemicals present in plants, such as flavonoids, alkaloids, terpenoids, phenols and enzymes, which act as natural reducing and stabilising agents. When plant extracts are exposed to metal ions, these biomolecules facilitate the reduction of the ions to their corresponding nanoparticles and stabilise them to prevent aggregation (3,72,77). This process is simple, cost-effective and scalable, making it an attractive alternative to conventional chemical methods that often involve toxic reagents and harsh conditions. Plant-mediated synthesis is versatile and has been successfully employed to produce a wide range of nanoparticles, including gold, silver, copper and zinc oxide, with controlled size and morphology. Extracts from plants such as *Azadirachta indica* (neem) (8), *Moringa oleifera*, *Aloe vera* (78) and *Ocimum sanctum* (holy basil) have been extensively studied for their efficacy in nanoparticle synthesis (79,80). The resulting nanoparticles often exhibit enhanced biocompatibility and bioactivity, rendering them suitable for applications in medicine, environmental remediation, and agriculture. For instance, silver nanoparticles synthesised using plant extracts have demonstrated potent antimicrobial activity, while gold nanoparticles have shown promise in drug delivery and cancer therapy (3,8). This green synthesis approach aligns with the principles of green chemistry by minimising waste, reducing energy consumption and avoiding hazardous chemicals. Despite its advantages, challenges such as achieving reproducibility, controlling particle size and shape, and scaling up the synthesis process remain (3,72,77,79,80).

Microorganisms. The green synthesis of nanoparticles using microorganisms is an innovative and eco-friendly approach that leverages the natural capabilities of bacteria, fungi and algae to produce nanoparticles. Microorganisms are particularly effective in nanoparticle synthesis because they possess enzymes and metabolites that can reduce metal ions to their nanoparticle forms, while also stabilising and shaping the nanoparticles during the process. This biogenic method of synthesis is beneficial for producing nanoparticles without the need for toxic chemicals, thus ensuring a more sustainable and environmentally friendly production process. Bacteria such as *Escherichia coli*, *Pseudomonas aeruginosa* and *Bacillus subtilis* are commonly used in the biosynthesis of MetNPs, including silver, gold, and copper. These bacteria can secrete enzymes, such as nitrate reductase and cytochrome, which play crucial roles in the reduction of metal ions. Fungi, particularly species such as *Aspergillus* and *Fusarium*, are also

Table III. Summary of the mechanisms of the green synthesis for nanoparticles along with their size, characteristics, applications and synthesis methods.

Metal	Synthesis mechanism	Size range	Characteristic	Application	Synthesis approach	(Refs.)
Silver (Ag)	Reduction of Ag^+ ions using plant extracts, microbes, or enzymes	5-100 nm	High antimicrobial activity, strong surface plasmon resonance, good electrical and thermal conductivity	Antimicrobial coatings, wound healing, drug delivery, water purification, biosensors	Plant extracts such as *Azadirachta indica*, *Moringa oleifera* and *Aloe vera*; microbial reduction by *Escherichia coli* and *Pseudomonas aeruginosa*; enzyme catalysis	(143-145)
Gold (Au)	Reduction of Au^{3+} ions with natural reducing agents (phytochemicals and enzymes)	10-100 nm	Biocompatible, non-toxic, and excellent optical properties, especially in drug delivery and diagnostics	Cancer therapy, drug delivery, biosensing, photothermal therapy, and diagnostics	Plant extracts such as *Coriandrum sativum*; fungal and bacterial reduction by *Fusarium* and *Bacillus subtilis*; and enzyme-assisted reduction by nitrate reductase	(146,147)
Palladium (Pd)	Reduction of Pd^{2+} ions by plant compounds or microbial metabolites	5-50 nm	Catalytic properties, biocompatible, can be functionalised for selective catalysis	Catalysis in organic reactions (hydrogenation, oxidation), electronics, ad hydrogen storage	Plant extracts such as *Jatropha curcas*; bacterial reduction by *Pseudomonas*; enzymatic reduction by laccase	(148)
Platinum (Pt)	Reduction of Pt^{4+} ions by enzymes, plant metabolites, or microbial activity	5-50 nm	High catalytic activity, biocompatibility, and stability under high temperature and pressure	Catalysis in fuel cells, sensors, drug delivery, and hydrogenation reactions	Plant extracts such as *Aloe vera*; microbial reduction by *Saccharomyces cerevisiae*; enzyme catalysis by nitrate reductase	(147)
Iron (Fe)	Reduction of Fe^{3+} or Fe^{2+} ions by biological agents (bacteria, fungi, and plant extracts)	10-100 nm	Magnetic properties, low toxicity, biocompatible, abundant and cost-effective	Water treatment, magnetic resonance imaging (MRI), drug delivery, and environmental remediation	Plant extracts such as *Moringa oleifera*; fungal reduction by *Aspergillus*; bacterial reduction by *Geobacter sulfurreducens*	(88,90)
Selenium (Se)	Reduction of SeO_3^{2-} ions to Se nanoparticles by plants or bacteria	10-200 nm	Antioxidant properties, biocompatible, and capable of enhancing immune responses	Antioxidant, cancer therapy, and environmental cleanup (removal of heavy metals)	Plant extracts such as *Coriandrum sativum*; bacterial reduction by *Bacillus subtilis*; enzymatic reduction by laccase	(118,149)
Copper (Cu)	Reduction of Cu^{2+} ions using plant polyphenols or bacterial enzymes	10-100 nm	High electrical and thermal conductivity, antimicrobial activity, and capable of oxidising organic compounds	Electrical applications, antimicrobial agents, catalysis, and environmental remediation	Plant extracts such as *Camellia sinensis*; microbial reduction by *Pseudomonas aeruginosa*; enzyme-assisted reduction by nitrate reductase and laccase	(116,150)

NPs, nanoparticles; Pt, platinum; Pd, palladium.

widely utilised for their ability to synthesise nanoparticles extracellularly. The metabolites and proteins produced by fungi not only reduce metal ions, but also function as stabilising agents, controlling the size and shape of the nanoparticles (81,82). Microalgae, such as *Chlorella* and *Spirulina*, are used to produce nanoparticles such as silver and selenium due to their high metal ion absorption capabilities. The microbial synthesis of nanoparticles provides numerous advantages, including the ability to precisely control the size, shape, and surface properties of nanoparticles, which are crucial for their functionality in various applications (83). These nanoparticles are often highly biocompatible, making them suitable for biomedical applications such as drug delivery, cancer therapy and biosensing, and find applications in environmental remediation, where they can be used for water purification, pollutant degradation, and heavy metal removal. Despite its advantages, microbial synthesis of nanoparticles does face challenges, such as scalability for industrial production, the variability of microbial strains, and the need for optimisation of culture conditions. Additionally, ensuring safety and minimising the toxicity of biogenic nanoparticles is an ongoing area of research. However, the use of microorganisms in green nanoparticle synthesis represents a promising, sustainable alternative to traditional chemical methods, offering both environmental and economic benefits in nanotechnology (32,83).

Algae and enzymes. The green synthesis of nanoparticles using algae and enzymes is an emerging and eco-friendly approach that combines the unique capabilities of biological systems to produce nanoparticles in a sustainable manner. Algae, both microalgae and macroalgae, are increasingly being explored for nanoparticle synthesis due to their high metal ion absorption capacity and ability to secrete biomolecules, including proteins, polysaccharides and secondary metabolites, which serve as reducing and stabilising agents. Enzymes, on the other hand, are natural catalysts that facilitate the reduction of metal ions to nanoparticles, providing precise control over the size and shape of the particles. This approach avoids the use of toxic chemicals, making it more environmentally friendly compared with conventional chemical synthesis methods. Algae such as *Chlorella*, *Spirulina*, *Dunaliella* and *Phaeodactylum* have been used for synthesising various MetNPs such as silver, gold and copper (61). These algae possess the ability to accumulate and reduce metal ions through their biochemical pathways, producing nanoparticles that are often biocompatible and environmentally safe. The synthesis process involves the exposure of algae to metal salt solutions, where enzymes and other cellular components facilitate the reduction of metal ions to their nanoparticle forms. The biogenic nanoparticles formed are stabilised by the natural biomolecules secreted by the algae, which also help control their size, shape and surface properties. Enzymes play a crucial role in the green synthesis of nanoparticles due to their high specificity and catalytic efficiency (84). Enzymes such as nitrate reductase, dehydrogenases and laccase are often used to reduce metal ions to their nanoparticle forms and are capable of selectively reducing metal ions, allowing for the controlled synthesis of nanoparticles with well-defined characteristics. In addition to their reducing ability, enzymes can stabilise the nanoparticles by coating them with functional groups that enhance their solubility and biocompatibility. The use of algae and enzymes in nanoparticle synthesis provides several advantages. This method is cost-effective, environmentally friendly and scalable, with algae being abundant and easy to culture. The nanoparticles produced are often highly biocompatible, making them ideal for applications in medicine, such as drug delivery, imaging and antimicrobial treatments. In environmental applications, algae-based nanoparticles are used for water purification, pollutant removal and the remediation of heavy metals (85). Additionally, enzyme-mediated nanoparticle synthesis is employed in catalysis and the development of advanced materials. Despite the benefits, challenges remain in optimising the synthesis process, such as improving the reproducibility of nanoparticle production, controlling particle size distribution and scaling up for industrial applications (86). Furthermore, research is ongoing to better understand the mechanisms involved in algae-mediated and enzyme-mediated synthesis to enhance efficiency and ensure the safety of the biogenic nanoparticles (87). Overall, the green synthesis of nanoparticles using algae and enzymes is a promising and sustainable method that holds great potential for applications in diverse fields, from environmental protection to biomedical engineering.

6. Mechanisms of green synthesis

The green synthesis process typically follows three key steps:

Reduction of metal ions. The biological agents reduce the metal ions (e.g., Ag^+, Au^{3+}, Cu^{2+}) to their corresponding nanoparticles. The reduction of metal ions is a central mechanism in the green synthesis of nanoparticles, where metal ions are reduced to their elemental or nanoparticulate state with the aid of biological agents, such as plant extracts, microorganisms and enzymes. In this process, metal ions, often in their higher oxidation states (e.g., Ag^+, Au^{3+}, Cu^{2+}), are converted into their zero-oxidation state (e.g., Ag^0, Au^0, Cu^0) through electron transfer facilitated by natural reducing agents (18). Phytochemicals in plant extracts, such as polyphenols, flavonoids and terpenoids, function as electron donors, reducing metal ions while being oxidised themselves. Similarly, microorganisms, including bacteria and fungi, produce enzymes such as nitrate reductase and laccase that catalyse the reduction of metal ions. These enzymes typically transfer electrons from biological substrates to metal ions, promoting nanoparticle formation. The reduction of metal ions can also be accelerated by light in certain cases, a process known as photoreduction, where light energy induces the production of reactive oxygen species that aid in the reduction. This reduction results in the formation of nanoparticles that are stabilised by the biomolecules present in the biological agents. These biogenic nanoparticles often exhibit enhanced biocompatibility and tuneable properties, making them ideal for applications in medicine, environmental science, and materials engineering (18,88).

Stabilisation of nanoparticles. Biomolecules from the biological agents stabilise the synthesised nanoparticles, preventing agglomeration and controlling size and shape. In the green synthesis of nanoparticles, stabilisation is a crucial mechanism that ensures the nanoparticles retain their size, shape, and functionality without agglomerating or degrading over time. Once metal ions are reduced to form nanoparticles, the biological agents involved in the synthesis, such as plant extracts, microorganisms, or enzymes, play an essential role in stabilising the nanoparticles (89). This stabilisation is typically achieved through the adsorption of biomolecules onto the surface of the nanoparticles. Phytochemicals such as polyphenols, flavonoids and proteins, which are naturally present in plants, provide functional groups such as hydroxyl, carboxyl and amino groups that form a protective layer around the nanoparticles. This surface coating prevents the nanoparticles from aggregating by hindering interactions between particles through electrostatic repulsion or steric hindrance (90). In microbial systems, proteins, enzymes and polysaccharides secreted by bacteria, fungi and algae can serve as capping agents that not only stabilise the nanoparticles but also impart specific properties, such as increased biocompatibility or targeted functionality. These biomolecules function by binding to the surface of the nanoparticles, reducing surface energy and preventing the particles from clumping together. Furthermore, the size and shape of the nanoparticles can be controlled by adjusting the concentration and type of stabilising agents used, which is essential for tailoring the properties of the nanoparticles for specific applications. This stabilisation mechanism also helps in maintaining the dispersion of nanoparticles in solution, preventing agglomeration and enhancing their stability under varying environmental conditions. The biocompatible nature of the stabilising agents makes these nanoparticles suitable for applications in fields such as medicine, environmental remediation and sensor technology, where prolonged stability and safe interaction with biological systems are paramount (3,72,80,91).

Purification and characterisation. The synthesised nanoparticles are purified and characterised using techniques, such as scanning electron microscopy (SEM), UV-visible spectroscopy, X-ray diffraction (XRD) and transmission electron microscopy (TEM). In the green synthesis of nanoparticles, purification and characterisation are essential steps that ensure the quality, size, shape and functionality of the synthesised nanoparticles. After the nanoparticles are formed through the reduction of metal ions by biological agents (such as plant extracts, microorganisms, or enzymes), they must be purified to remove any residual reactants, by-products, or unreacted metal ions. This purification is typically achieved through methods, such as centrifugation, filtration, dialysis, or gel electrophoresis, which help separate the nanoparticles from unwanted materials. These methods rely on differences in particle size, charge, or solubility to isolate the nanoparticles in their purest form, ensuring that they are free from contaminants that could affect their properties or hinder their intended applications (6,80,92,93).

Once purified, the nanoparticles are characterised to determine their physical, chemical and structural properties. Characterisation techniques provide insight into the size, shape, morphology, surface charge and composition of the nanoparticles, which are critical for assessing their suitability for specific applications. Common techniques used in the characterisation of green-synthesised nanoparticles include the following:

i) TEM and SEM. These techniques provide detailed images of the size, shape and surface morphology of the nanoparticles, enabling researchers to assess their uniformity and dispersion (6).

ii) XRD. XRD aids in the determination of the crystalline structure of the nanoparticles and can provide information about their phase composition (80).

iii) UV-Vis spectroscopy. UV-Vis spectroscopy is used to monitor the optical properties of nanoparticles, such as their absorption spectra, which are influenced by particle size and shape. It can also confirm the formation of nanoparticles by detecting the characteristic plasmon resonance peaks (92).

iv) Dynamic light scattering (DLS). DLS measures the size distribution and zeta potential of nanoparticles, providing information on their stability and surface charge (93).

v) Fourier transform infrared spectroscopy (FTIR). FTIR is used to analyse the functional groups present on the surface of the nanoparticles, which helps identify the biomolecules responsible for stabilisation and capping (94).

vi) Energy-dispersive X-ray spectroscopy (EDX). EDX, often coupled with SEM or TEM, provides elemental analysis of the nanoparticles, confirming their composition and verifying the successful incorporation of metal ions (95).

Through purification and characterisation, researchers can ensure that the green-synthesised nanoparticles possess the desired properties, are free of contaminants, and are suitable for various applications in medicine, environmental remediation, catalysis and materials science. These steps are crucial in ensuring that the nanoparticles meet the necessary quality standards for their intended uses.

7. MetNPs synthesised using the green method

Various types of nanoparticles can be synthesised using biological sources, including plants, fungi and bacteria, which serve as reducing and stabilising agents. Silver nanoparticles may be readily synthesised using a silver metal ion solution and a reducing biological agent. Silver nanoparticles have been reported to be synthesised from a variety of medicinal plants, including *Cinnamomum camphora* (96), *Oryza sativa* and *Zea mays*. Silver ion reduction is one of the simplest and most cost-effective processes for producing silver nanoparticles. Kumar *et al* (97) synthesised silver nanoparticles by reducing an $AgNO_3$ solution with *Nelumbo nucifera* plant extract. Philip (98) produced silver nanoparticles from the leaf extract of *Hibiscus rosa-sinensis*. In 2009, Bar *et al* synthesised silver nanoparticles using *Jatropha curcas* seed extract after heating an aqueous solution at 80°C; the appearance of a crimson colour suggested the formation of silver nanoparticles (99).

Gold nanoparticles have a variety of uses in biomedical research, including the rapid detection and identification of heart disorders, cancer and infectious pathogens (100). Shankar *et al* (101) also stated that the synthesised nanoparticles were of different forms, including spherical, decahedral, triangular and icosahedral structures. The same group produced gold nanoparticles from neem extract (102). According to Song *et al* (103), temperature plays an essential role in the development of specific shapes and sizes of synthesised gold nanoparticles. Gold nanoparticles were also synthesised using a variety of biological sources, including *Bacillus marisflavi*, *Coffea arabica* (104), *Aeromonas hydrophila* (105,106) and *Croton sparsiflorus* leaf extract (107). Both palladium and platinum are highly valuable metals that appear silvery white. Several plant species, including *Cinnamomum zeylanicum*, *Anogeissus latifolia*, *Curcuma longa*, *Diospyros kaki*, *Gardenia jasminoides*, *Cinnamomum camphora*, *Glycine max* and *Musa paradisiaca*, have been used to prepare palladium and platinum nanoparticles (91). Ahmed *et al* (8) discovered that proteins were responsible for converting chloroplatinic ions into platinum nanoparticles. Ascorbic acid, terpenoids, amino acids, specific proteins and gallic acid found in basil leaf extract all played major roles in reducing platinum ions. The green synthesis method for the development of zero-valent iron nanoparticles has been a major approach for the treatment of brominated organic compounds, pesticides, azo dyes, alkaline-earth metals, malachite green, nitrate, monochlorobenzene, antibiotics, and for converting metals such as chromium, cobalt, and copper (89,108,109). Green-synthesised iron nanoparticles have been produced from several plants, including common lantana (*Lantana camara*), water hyacinth (*Eichhornia crassipes*), and sensitive plants (*Mimosa pudica*) (110). The green synthesis of selenium nanoparticles using plants is an environmentally friendly, cost-effective and non-toxic technology. Garlic (*Allium sativum*) bud extract, for example, has been utilised to produce selenium nanoparticles with high antioxidant activity, as validated using ferric reducing antioxidant power (FRAP), 2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid and 2,2-diphenyl-1-picrylhydrazyl assays (111). Tea extract (*Camellia sinensis*) has also been used to produce selenium nanoparticles with antioxidant properties. Furthermore, horseshoe geranium (*Pelargonium zonale*) leaf extract has produced selenium nanoparticles with substantial antibacterial and antifungal activity against pathogens (112). These nanoparticles also assist in the removal of heavy metals from the environment. Copper nanoparticles exhibit therapeutic potential, including antimicrobial, antifungal and antiviral activities, and have been synthesised using plant-mediated methods from a variety of plants, including fire lily (*Gloriosa superba L.*), common grape (*Vitis vinifera*), oleander (*Nerium oleander*), Ceylon caper (*Capparis zeylanica*), and jackfruit champa (*Artabotrys odoratissimus*) (113). Copper nanoparticles synthesised from fire lily (*Gloriosa* superba *L.*) leaf extract and pomegranate (*Punica granatum*) bark extract have been shown to exhibit enhanced reduction and capping properties (114,115). Copper nanoparticles have also been synthesised using various plant extracts, with sizes ranging from 4 to 100 nm, including Japanese magnolia (*Magnolia kobus*) and angel's trumpet (*Datura innoxia*) (113).

8. Characterisation techniques

Characterisation approaches are critical for understanding the characteristics, structure and behaviour of nanoparticles, and aid in determining shape, particle size, surface charge, chemical composition, crystallinity and other essential properties. The various characterisation techniques used for nanoparticles, as well as a description of each, is presented in Table IV.

9. Applications of biosynthesised MetNPs

Green-synthesised MetNPs derived from environmentally friendly biological agents, such as plants, bacteria, fungi, or algae have a wide range of applications due to their unique properties, biocompatibility and a low environmental impact (75). In biomedicine, silver and gold nanoparticles exhibit potent antibacterial properties, rendering them useful in wound dressings, medical device coatings and disinfectants (97). They also serve as effective drug delivery systems, enhancing treatment outcomes, while minimising adverse effects. Additionally, these nanoparticles are being investigated for cancer therapy and antioxidant applications, such as reducing oxidative stress-related disorders (75,105). In environmental remediation, nanoparticles such as iron, silver and selenium remove heavy metals and degrade contaminants from polluted water and soil. They are also utilised in air purification systems to break down hazardous substances (66). In agriculture, green-synthesised nanoparticles act as nanopesticides and fertilisers, stimulating plant growth and enhancing crop yield. Silver nanoparticles are used to extend the shelf life of food through antimicrobial packaging, whereas selenium nanoparticles are employed as nutritional supplements due to their increased bioavailability (11,78,111). These nanoparticles also provide benefits in skincare products, sunscreens, and antimicrobial fabrics. Furthermore, they play crucial roles in catalysis, biosensing and imaging for medical diagnostics and environmental monitoring, demonstrating their adaptability across multiple sectors (69).

10. Current challenges and future prospects

Despite recent advancements, green-synthesised MetNPs face challenges related to scalability and consistency during the transition from laboratory-scale to industrial-scale production. The diversity of biological agents, such as plants and bacteria, can lead to variations in nanoparticle characteristics. Furthermore, the mechanisms underlying nanoparticle formation remain insufficiently understood, limiting optimisation. Concerns regarding toxicity and long-term environmental effects require further investigation (68,87).

While biosynthesised MetNPs demonstrate substantial promise for biomedical, environmental and industrial applications, several critical obstacles remain for their practical translation, with toxicity being one of the most significant challenges. Biological molecules involved in synthesis (proteins, polysaccharides, secondary metabolites, etc.) can unpredictably alter nanoparticle surface chemistry, affecting cellular uptake and potentially leading to variable genotoxicity and long-term environmental effects (116). Additionally, variations in size, shape and capping agents can result in markedly different biological responses, complicating risk assessment. Scalability represents another major bottleneck. A number of biosynthetic processes are limited by slow reaction rates, poor metal-ion conversion efficiency and strong dependence on biological sources (plant extracts, microbial cultures, etc.), making it difficult to achieve reproducible industrial-scale production. The lack of standardised purification processes can introduce impurities or residual biomolecules, contributing to inconsistencies in stability and performance. Furthermore, regulatory challenges continue to hinder commercialisation due to the absence of harmonised global guidelines for assessing safety, environmental impact, and long-term biodegradation of biosynthesised nanomaterials. Regulatory agencies also require extensive datasets to differentiate laboratory-based findings from real-world exposure scenarios, which are currently limited (105,117,118).

Table IV. Types of characterisation techniques for nanoparticles.

Techniques	Characteristics	Typical output	(Refs.)
Transmission electron microscopy:	Provides accurate images for determining nanoparticle size, shape, and structure. A beam of electrons passes through the nanoparticle sample, and the interaction of electrons with the atoms in the sample produces a highly detailed image. Used to study morphology, particle size distribution, and structural details down to the atomic level.	High-resolution images	(151)
Scanning electron microscopy;	Provides surface images and information about the morphology and topography of nanoparticles. Electrons are focused on the surface of the nanoparticles, and secondary electrons emitted from the surface create a detailed image. Used to analyse surface texture and particle shapes with a slightly lower resolution than TEM.	Surface images	(152)
Dynamic light scattering;	Measures the hydrodynamic size and size distribution of nanoparticles in suspension. Measures the scattering of light caused by the Brownian motion of nanoparticles in a liquid medium, providing size distribution. Commonly used for determining particle size in colloidal suspensions and solutions.	Size distribution graph	(153)
X-ray diffraction;	Determines the crystalline structure and phase composition of nanoparticles. X-rays are directed at the sample, and the diffraction pattern of the rays reveals the crystal structure. Used to identify crystallinity, lattice structure, and particle size (through the Debye-Scherrer equation).	Diffraction patterns	(130)
Fourier-transform infrared spectroscopy;	Identifies chemical bonds and functional groups on the surface of nanoparticles. Infrared radiation is passed through the sample, and the absorption spectra are analysed to determine chemical bonds. Used to identify surface modifications, coatings, and interactions between nanoparticles and other molecules.	IR spectra (functional groups)	(154)
Ultraviolet-visible spectroscopy;	Measures the optical properties, such as absorption and scattering, of nanoparticles. Light in the ultraviolet and visible range is passed through the sample, and the absorbance is measured. Commonly used to confirm the formation of nanoparticles (e.g., for metal nanoparticles like gold and silver) and study their optical properties.	Absorption peak (SPR band)	(9)
Atomic force microscopy:	Provides 3D topographical information and surface details at the nanoscale. A cantilever with a sharp tip scans the surface of the nanoparticles, and the interaction between the tip and sample generates a 3D surface map. Used to examine surface roughness, particle height, and nanoscale surface interactions.	2D/3D surface images	(155)
Energy dispersive X-ray spectroscopy;	Determines the elemental composition of nanoparticles. Attached to an SEM or TEM, EDX detects X-rays emitted from the sample when bombarded by electrons, identifying the elements present. Used for elemental analysis and mapping, useful for confirming the composition of nanoparticles.	Elemental spectra	(152)
Thermo-gravimetric analysis;	Measures changes in the physical and chemical properties of nanoparticles as a function of temperature. A sample is heated, and changes in weight are monitored to study thermal stability and decomposition. Used to determine thermal stability, degradation temperatures, and the presence of organic or inorganic components on the nanoparticle surface.	Weight-loss curves	(156)
Zeta potential analysis;	Determines the surface charge and stability of nanoparticles in suspension. Measures the electrophoretic mobility of particles in an applied electric field, providing information about surface charge and dispersion stability. Used to evaluate colloidal stability and predict nanoparticle aggregation behaviour.	Zeta potential values (mV)	(157)

Looking ahead, addressing these challenges will require a multi-pronged strategy. Advances in the mechanistic understanding of biosynthesis, using omics tools, real-time spectroscopy and molecular-level modelling, may allow improved control over nanoparticle morphology and stability. The development of high-throughput, reactor-based green synthesis systems could overcome yield limitations and enable consistent large-scale production. Establishing standardised international protocols for toxicity testing, quality control and environmental risk assessment will be essential for regulatory approval (94). Finally, future research should emphasise application-specific surface functionalisation, hybrid biochemical synthesis approaches and life-cycle assessment to ensure that biosynthesised MNPs are deployed safely, sustainably and at a commercial scale.

Future advances in nanotechnology and biotechnology may further enhance scalability and precision. Standardised methodologies and comprehensive safety evaluations will be critical for widespread adoption. Future research is likely to focus on improving sustainability and expanding applications in industries such as energy, agriculture and medicine.

11. Conclusion

The purpose of this review aligns with the growing emphasis on sustainable nanotechnology, mechanistic insight and translational potential. MetNPs, particularly those synthesised through biogenic and green routes, are a rapidly evolving class of functional materials with major implications for healthcare, catalysis, sensing and environmental remediation. However, the existing literature is fragmented across individual studies, lacking an integrated approach that connects biosynthesis mechanisms with application-driven performance and safety considerations. The present review aimed to address this gap by providing a comprehensive, critically evaluated overview of recent advances, highlighting sustainable synthesis innovations, structure-property relationships, challenges in toxicity and scalability and future research directions.

The journey of nanotechnology, begun by visionaries such, as Richard Feynman and Norio Taniguchi, has resulted in the revolutionary invention of MetNPs. These small entities, having unique features arising from their nanoscale size, have several uses in health, environmental remediation, and electronics. The green synthesis of MetNPs provides a viable alternative to traditional approaches, since it employs biological agents that reduce environmental effects while promoting sustainability. Despite the potential benefits, issues such as scalability, consistency and safety persist. Addressing these difficulties is critical for moving green nanotechnology beyond laboratory research and into practical applications. Future studies are thus warranted to focus on optimising synthesis procedures, understanding the mechanisms underlying nanoparticle creation and conducting safety studies for wider deployment. As the discipline advances, incorporating nanotechnology into common applications holds immense promise for improving human health, safeguarding the environment and driving technological innovation.

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Authors' contributions

RV designed the scope of the study, AK edited the manuscript, and RBA was involved in the literature review and writing of the manuscript. RS designed the structure of the review. NG, BSR and IR guided the direction of the review. RV and RS supervised the overall preparation of the review. All the authors have read and approved the final version of the manuscript. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

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Competing interests

The authors declare that they have no competing interests.

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