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Phytonanotechnology of *Moringa oleifera* Lam.: Green synthesis, characterization and multifunctional biomedical applications

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Abstract

Phytonanotechnology has emerged as a promising interdisciplinary approach that integrates green chemistry, nanotechnology and plant biotechnology for the sustainable synthesis of functional nanomaterials. Among medicinal plants, *Moringa oleifera* Lam. has gained considerable attention owing to its rich phytochemical composition, including polyphenols, flavonoids, glucosinolates, isothiocyanates, terpenoids, proteins, vitamins and polysaccharides, which serve as natural reducing, stabilizing and capping agents during nanoparticle biosynthesis. This review comprehensively summarizes recent advances in *M. oleifera*-mediated green synthesis of metallic and metal oxide nanoparticles, emphasizing the underlying molecular mechanisms, physicochemical characterization and multifunctional biomedical applications. The review discusses the preparation of plant extracts, phytochemical-mediated reduction pathways, nucleation, crystal growth, stabilization and the influence of reaction parameters on nanoparticle synthesis. Various *Moringa*-derived nanoparticles, including silver, gold, zinc oxide, copper oxide, iron oxide, selenium, titanium dioxide, magnesium oxide, silica and bimetallic nanoparticles are critically evaluated with respect to their synthesis, structural characteristics and biological activities. In addition, the roles of advanced characterization techniques such as UV-Visible spectroscopy, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning and transmission electron microscopy (SEM and TEM), dynamic light scattering (DLS), zeta potential analysis, Raman spectroscopy and inductively coupled plasma-mass spectrometry (ICP-MS) are highlighted. The biomedical potential of these nanoparticles in targeted drug delivery, cancer therapy, antimicrobial coatings, wound healing, tissue engineering, diagnostic imaging, gene delivery, vaccine development, dental applications and ophthalmic therapeutics is comprehensively discussed. Despite remarkable progress, challenges including synthesis standardization, large-scale production, reproducibility, long-term biosafety and regulatory approval remain significant barriers to clinical translation. Future integration of artificial intelligence, machine learning, advanced omics technologies and precision nanomedicine is expected to accelerate the development of M. oleifera-based nanoplatforms. Overall, Moringa-mediated phytonanotechnology represents a sustainable and versatile strategy for developing next-generation nanomaterials with broad biomedical applications and significant potential to advance environmentally responsible nanomedicine.

1. Introduction

Nanotechnology has emerged as one of the most transformative scientific disciplines of the twenty-first century, offering unprecedented opportunities for innovation in medicine, agriculture, environmental remediation, food technology and energy systems. Nanoparticles, typically ranging from 1 to 100 nm in size, possess unique physicochemical properties including high surface area-to-volume ratio, enhanced catalytic activity, tuneable optical characteristics and improved biological interactions that distinguish them from their bulk counterparts. These distinctive properties have facilitated the development of advanced drug delivery systems, biosensors, antimicrobial agents, diagnostic tools, tissue engineering scaffolds and multifunctional therapeutic platforms. The global nanotechnology market has experienced remarkable expansion, driven by increasing investments in biomedical research, personalized medicine and sustainable manufacturing technologies. However, conventional nanoparticle synthesis methods, which primarily rely on physical and chemical approaches, often require high energy consumption, expensive instrumentation, toxic reducing agents and hazardous solvents that pose significant environmental and health risks (Deshmukh *et al*., 2023; Ghosh *et al*., 2024). Consequently, there has been a paradigm shift toward environmentally benign and biologically sustainable alternatives, giving rise to the rapidly evolving field of green nanotechnology. Green nanotechnology integrates the principles of green chemistry and sustainable engineering with nanoscience to develop eco-friendly processes for

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nanoparticle synthesis while minimizing environmental impact throughout the production lifecycle. Unlike traditional methods that utilize hazardous chemicals such as sodium borohydride, hydrazine hydrate and organic solvents, green synthesis employs naturally occurring biomolecules from microorganisms, algae, fungi and higher plants as reducing, capping and stabilizing agents. Among these biological resources, plants have gained exceptional attention because they are readily available, inexpensive, renewable, biodegradable and rich in diverse phytochemicals capable of mediating nanoparticle formation under mild reaction conditions. Plant-mediated synthesis also eliminates the need for aseptic culture conditions required in microbial synthesis, making it highly suitable for large-scale industrial production. Moreover, green-synthesized nanoparticles often exhibit superior biocompatibility and enhanced biological activities due to the presence of phytochemical coatings on their surfaces, which improve stability, cellular interactions and therapeutic efficacy (Singh *et al*., 2023; Khan *et al*., 2024).

The growing demand for sustainable nanoparticle synthesis is driven not only by environmental concerns but also by the need to produce safer nanomaterials for biomedical applications. Conventional synthetic methods frequently generate toxic residues that may persist in biological systems and ecosystems, leading to cytotoxicity, genotoxicity, oxidative stress and environmental contamination. In contrast, plant-based synthesis aligns with several United Nations Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, good health and well-being, climate action and sustainable industrial innovation. Sustainable nanoparticle synthesis emphasizes the use of renewable raw materials, energy-efficient processes, waste minimization and the avoidance of toxic chemicals, thereby reducing production costs and environmental footprints. Additionally, advances in green nanotechnology have enabled the fabrication of multifunctional nanoparticles with enhanced antimicrobial, antioxidant, anticancer, anti-inflammatory and drug delivery capabilities while maintaining excellent biocompatibility (OECD, 2024; IPCC, 2023; Deshmukh *et al*., 2023). These advantages have accelerated research into plant-mediated nanomaterials for pharmaceutical, diagnostic, agricultural, cosmetic and environmental applications. Among the numerous medicinal plants investigated for nanoparticle biosynthesis, *M. oleifera* has emerged as one of the most promising biological resources owing to its extraordinary phytochemical richness and broad spectrum of pharmacological properties. Commonly referred to as the “miracle tree” or “tree of life,” *M. oleifera* belongs to the family Moringaceae and is extensively cultivated throughout tropical and subtropical regions of Asia, Africa, South America and parts of the Middle East. The plant is highly valued for its rapid growth, drought tolerance, adaptability to marginal soils and year-round availability, making it an economically viable resource for sustainable nanotechnology. Almost every part of the plant including leaves, seeds, bark, flowers, roots, pods and gum is utilized in traditional medicine, nutrition and industrial applications. These plant parts contain abundant bioactive compounds such as flavonoids (quercetin, kaempferol), phenolic acids (gallic acid, chlorogenic acid, caffeic acid), glucosinolates, isothiocyanates, tannins, alkaloids, terpenoids, saponins, proteins, polysaccharides, vitamins and amino acids. These phytochemicals function synergistically as natural reducing, capping and stabilizing agents during nanoparticle synthesis, enabling efficient conversion of metal ions into stable nanostructures without the need for hazardous chemicals (Leone *et al*., 2024; Vergara-Jimenez *et al*., 2023; Abd Rani *et al*., 2024).

The exceptional phytochemical diversity of *M. oleifera* also contributes to the enhanced biological functionality of biosynthesized nanoparticles. Polyphenols and flavonoids donate electrons to reduce metal ions such as Ag^{+}, Au^{3+}, Zn^{2+}, Cu^{2+} and Fe^{3+} into their corresponding nanoparticles, while proteins, polysaccharides and other macromolecules adsorb onto nanoparticle surfaces to prevent aggregation and improve colloidal stability. Furthermore, these phytochemical coatings often impart intrinsic antioxidant, antimicrobial, anti-inflammatory and anticancer properties to the synthesized nanomaterials, resulting in synergistic therapeutic effects that exceed those of chemically synthesized nanoparticles. Recent studies have demonstrated that *M. oleifera*-mediated silver, gold, zinc oxide, selenium, iron oxide and copper oxide nanoparticles exhibit potent activity against multidrug-resistant bacterial pathogens, fungal infections, oxidative stress, chronic inflammatory disorders, diabetes and several human cancers, highlighting their potential as multifunctional nanotherapeutic agents (El-Sheekh *et al*., 2024; Al-Hakkani, 2023; Ghosh *et al*., 2024). The convergence of phytochemistry and nanotechnology has led to the emergence of phytonanotechnology, an interdisciplinary field that explores the use of plant-derived biomolecules for the eco-friendly synthesis, functionalization and biomedical application of nanomaterials. Phytonanotechnology extends beyond the simple biosynthesis of nanoparticles by integrating plant metabolites with advanced nanoscience to create multifunctional nanoplatforms capable of targeted drug delivery, biosensing, tissue engineering, regenerative medicine, antimicrobial therapy, vaccine development and precision diagnostics. Plant-derived nanomaterials are increasingly recognized for their superior biocompatibility, lower toxicity, enhanced bioavailability and sustainable production compared with conventionally synthesized nanomaterials. Advances in molecular biology, metabolomics, computational chemistry, artificial intelligence and machine learning are further expanding the capabilities of phytonanotechnology by enabling precise optimization of nanoparticle synthesis, prediction of phytochemical interactions and rational design of next-generation nanotherapeutics (Khan *et al*., 2024; Singh *et al*., 2023).

Despite the rapid growth of research on *M. oleifera*-mediated nanoparticle synthesis, current knowledge remains fragmented across diverse scientific disciplines, with limited comprehensive reviews integrating phytochemistry, synthesis mechanisms, physicochemical characterization, biological functions, biomedical applications, toxicity assessment, regulatory considerations and future translational opportunities. Therefore, a holistic synthesis of the available evidence is essential to identify current advances, research gaps and future directions. Accordingly, this review aims to provide a comprehensive overview of the phytochemical basis of *M. oleifera*-mediated green nanoparticle synthesis, elucidate the underlying mechanisms responsible for nanoparticle formation and stabilization, summarize the major characterization techniques employed for structural and functional analysis, critically evaluate recent advances in antimicrobial, antioxidant, anticancer, anti-inflammatory, wound healing and drug delivery applications and discuss biosafety, toxicity, regulatory challenges, commercialization prospects and emerging future trends. By integrating recent scientific developments in phytonanotechnology and nanomedicine, this review seeks to establish *M. oleifera* as a versatile and sustainable platform for the development of multifunctional nanomaterials capable of addressing global healthcare challenges while promoting environmentally responsible nanotechnology.

2. Botanical overview of *M. oleifera*

M. oleifera commonly known as the drumstick tree, horseradish tree, miracle tree, or tree of life, belongs to the monogeneric family Moringaceae, which comprises 13 recognized species distributed mainly across tropical and subtropical regions. Among these, *M. oleifera* is the most extensively cultivated and economically significant species owing to its exceptional nutritional, medicinal and industrial value. The species is native to the sub-Himalayan tracts of northwestern India and has subsequently been introduced into Asia, Africa, South America, Central America and Oceania. Taxonomically, *M. oleifera* is classified under Kingdom Plantae, Division Magnoliophyta (Angiosperms), Class Magnoliopsida (Dicotyledons), Order Brassicales, Family Moringaceae, Genus *Moringa* and Species *M. oleifera* The close phylogenetic relationship of *Moringa* with members of the Brassicaceae explains its richness in glucosinolates and isothiocyanates, phytochemicals that contribute significantly to its medicinal properties and play a crucial role in plant-mediated nanoparticle synthesis (Fahey, 2023; Leone *et al*., 2024).

3. Phytochemical profile of *M. oleifera*

The remarkable ability of *M. oleifera* to mediate the green synthesis of nanoparticles is largely attributed to its diverse phytochemical composition. Plant extracts contain numerous secondary metabolites and biomacromolecules capable of reducing metal ions into nanoparticles while simultaneously acting as stabilizing and capping agents. These phytochemicals not only determine nanoparticle size, morphology, crystallinity and stability but also enhance their biological activities by forming bioactive surface coatings (Table 1). The synergistic interaction among polyphenols, flavonoids, glucosinolates, proteins, carbohydrates and vitamins enables the rapid production of highly stable metallic and metal oxide nanoparticles suitable for biomedical applications (Perumalsamy *et al*., 2024; Yadav *et al*., 2024).

3.1 Polyphenols

Polyphenols constitute one of the most abundant classes of bioactive compounds in *M. oleifera* and are considered the principal reducing agents during nanoparticle biosynthesis. Their multiple hydroxyl groups readily donate electrons to metal ions, promoting nucleation and nanoparticle formation while simultaneously preventing aggregation through surface adsorption. Quercetin is the predominant flavonol in *M. oleifera* leaves and exhibits potent antioxidant, anti-inflammatory, antimicrobial and anticancer activities. The catechol structure present in quercetin efficiently reduces Ag^{+} , Au^{3+} , Cu^{2+} and Fe^{3+} ions into nanoparticles while enhancing nanoparticle stability through chelation and hydrogen bonding. Quercetin-coated nanoparticles also display improved free radical scavenging and enhanced cytotoxicity against cancer cells (Perumalsamy *et al*., 2024). Kaempferol contributes significantly to nanoparticle biosynthesis due to its excellent metal-chelating capacity and antioxidant activity. It facilitates electron transfer reactions during metal ion reduction and forms stable complexes on nanoparticle surfaces, improving colloidal stability and biological functionality. Kaempferol-functionalized nanoparticles have demonstrated enhanced antimicrobial, cardioprotective and anti-inflammatory activities (Singh *et al*., 2023). Rutin, a glycosylated derivative of quercetin, possesses strong antioxidant and vascular protective properties. During phytonanoparticle synthesis, rutin acts as both a reducing and capping molecule, producing uniformly dispersed nanoparticles with improved stability, prolonged shelf life and enhanced biomedical efficacy (Yadav *et al*., 2024).

3.2 Flavonoids

M. oleifera contains numerous flavonoids, including myricetin, apigenin, luteolin, catechin, epicatechin and isoquercitrin. These compounds possess multiple hydroxyl groups capable of reducing metallic ions and stabilizing nanoparticle surfaces. Flavonoids also enhance the antimicrobial, antioxidant and anticancer properties of phytofabricated nanoparticles by modulating oxidative stress and inflammatory signaling pathways (Perumalsamy *et al*., 2024).

3.3 Phenolic acids

Major phenolic acids identified in *M. oleifera* include gallic acid, chlorogenic acid, caffeic acid, ferulic acid, p-coumaric acid, ellagic acid and sinapic acid. These compounds participate actively in nanoparticle nucleation through electron donation and stabilize synthesized nanoparticles by surface adsorption. Their antioxidant activity also contributes to enhanced biological performance of nanomaterials (Mahaveerchand and Abdul Salam, 2024).

3.4 Glucosinolates

Glucosinolates are sulfur-containing secondary metabolites characteristic of the order Brassicales. *M. oleifera* is particularly rich in glucomoringin and related glucosinolates, which contribute to antimicrobial and anticancer activities. During nanoparticle synthesis, glucosinolates participate indirectly through enzymatic conversion into biologically active compounds that enhance nanoparticle functionality (Fahey, 2023).

3.5 Isothiocyanates

Enzymatic hydrolysis of glucosinolates by myrosinase produces isothiocyanates, especially 4-(α-l-rhamnosyloxy) benzyl isothiocyanate (moringin). These compounds exhibit strong antioxidant, antimicrobial, anti-inflammatory and anticancer properties. Their presence on nanoparticle surfaces significantly enhances therapeutic efficacy and cellular interactions (Fahey, 2023).

3.6 Vitamins

M. oleifera is an excellent source of vitamins A, C, E, K and B-complex vitamins. Vitamin C functions as a natural reducing agent during nanoparticle formation, while vitamins A and E improve antioxidant stability and biological activity of biosynthesized nanoparticles (Leone *et al*., 2024).

3.7 Alkaloids

Alkaloids such as moringinine and related nitrogen-containing compounds contribute to nanoparticle stabilization through coordination with metal ions and surface adsorption. They also enhance antimicrobial and neuroprotective activities of phytofabricated nanoparticles (Mahaveerchand and Abdul Salam, 2024).

3.8 Terpenoids

Terpenoids including β-sitosterol, stigmasterol, lupeol and other triterpenes facilitate nanoparticle formation by acting as natural reducing molecules and hydrophobic stabilizers. They further contribute anti-inflammatory and anticancer properties to synthesized nanoparticles (Singh *et al*., 2023).

3.9 Proteins and peptides

Leaf and seed proteins, enzymes and antimicrobial peptides serve as efficient capping agents during nanoparticle synthesis. Functional groups such as amino, carboxyl and sulfhydryl residues bind strongly to nanoparticle surfaces, preventing aggregation and increasing colloidal stability. Protein-capped nanoparticles generally exhibit excellent biocompatibility and prolonged biological activity (Perumalsamy *et al*., 2024).

3.10 Polysaccharides

Natural polysaccharides, including cellulose, hemicellulose, pectins, gums and water-soluble carbohydrates, act as biodegradable stabilizing matrices during nanoparticle biosynthesis. These polymers regulate nanoparticle growth, prevent agglomeration and improve dispersibility in aqueous media while enhancing biocompatibility and controlled drug release characteristics (Coelho *et al*., 2024).

Table 1: Major phytochemicals of *M. oleifera* involved in green nanoparticle synthesis

Phytochemical class	Major compounds	Primary role in nanoparticle synthesis	Biomedical significance
Polyphenols	Quercetin, Kaempferol, Rutin	Reduction and capping	Antioxidant, anticancer, antimicrobial
Flavonoids	Apigenin, Luteolin, Catechin	Electron donation and stabilization	Anti-inflammatory, antioxidant
Phenolic acids	Gallic, Chlorogenic, Caffeic, Ferulic acids	Metal ion reduction	Free radical scavenging
Glucosinolates	Glucomoringin	Precursor of bioactive isothiocyanates	Anticancer, antimicrobial
Isothiocyanates	Moringin	Surface functionalization	Anti-inflammatory, antimicrobial
Vitamins	Vitamins C, E, A	Reducing and antioxidant agents	Cytoprotection
Alkaloids	Moringinine	Surface stabilization	Neuroprotective, antimicrobial
Terpenoids	Lupeol, β-Sitosterol, Stigmasterol	Capping and stabilization	Anti-inflammatory
Proteins and peptides	Seed proteins, enzymes	Capping and colloidal stabilization	Enhanced biocompatibility
Polysaccharides	Cellulose, pectin, gums	Stabilization and controlled growth	Drug delivery and biocompatibility

4. Fundamentals of phytonanotechnology

Phytonanotechnology is an emerging interdisciplinary branch of nanoscience that integrates phytochemistry, nanotechnology, biotechnology, materials science and green chemistry to synthesize functional nanomaterials using plant-derived biomolecules. Unlike conventional nanoparticle fabrication, which often relies on hazardous chemicals and energy-intensive processes, phytonanotechnology exploits naturally occurring phytochemicals as reducing, stabilizing and capping agents during nanoparticle synthesis. Plant metabolites such as polyphenols, flavonoids, terpenoids, alkaloids, proteins, polysaccharides, enzymes and organic acids facilitate the conversion of metal ions into stable nanoparticles under environmentally benign conditions. These phytochemicals not only reduce metal ions but also functionalize nanoparticle surfaces, thereby enhancing their physicochemical stability, biocompatibility and biological activity. Consequently, phyto-mediated nanoparticles have attracted considerable attention for applications in medicine, agriculture, environmental remediation, biosensing, food preservation and regenerative medicine (Vanga and Satla, 2025; Lakhani *et al*., 2025).

The development of phytonanotechnology has evolved through successive advances in nanoscience, green chemistry and plant biotechnology. During the initial stages of nanotechnology in the late twentieth century, nanoparticle synthesis depended predominantly on physical methods such as laser ablation, evaporation-condensation, ball milling, sputtering and pyrolysis. Although, these techniques produced highly pure nanoparticles with controlled crystallinity, they required sophisticated instrumentation, elevated temperatures, vacuum systems and substantial energy inputs, limiting their sustainability and commercial feasibility (Vanga and Satla, 2025). The subsequent introduction of chemical synthesis enabled large-scale nanoparticle production through reducing agents such as sodium borohydride, hydrazine, citrate and ethylene glycol. Chemical methods provided excellent control over particle morphology, crystallinity and reaction kinetics but generated toxic residues that restricted biomedical applications and created environmental concerns. Growing awareness of sustainable manufacturing practices during the early 2000s stimulated interest in biological nanoparticle synthesis using bacteria, fungi, algae, yeast and higher plants (Ilavenil *et al*., 2025).

Green synthesis is based on the principles of green chemistry, emphasizing renewable resources, waste minimization, energy efficiency, non-toxic reagents and environmentally responsible manufacturing. Within phytonanotechnology, plant extracts function simultaneously as reducing agents, stabilizers, capping molecules and sometimes shape-directing agents. This multifunctionality greatly simplifies nanoparticle production while reducing production costs and environmental burdens (Vanga and Satla, 2025). The synthesis process generally begins with the extraction of phytochemicals from leaves, seeds, flowers, bark, roots, or fruits using water or environmentally friendly solvents. Following the addition of a metal precursor solution, phytochemicals containing hydroxyl, carbonyl, amino, sulfhydryl and carboxyl functional groups donate electrons that reduce metal ions into their elemental state. Once reduced atoms reach supersaturation, they aggregate into stable nuclei that subsequently grow into nanoparticles through crystal growth mechanisms. Simultaneously, surrounding phytochemicals adsorb onto nanoparticle surfaces, preventing aggregation and forming a protective phytochemical corona that improves colloidal stability and biological functionality (Gu *et al*., 2025; Lakhani *et al*., 2025).

5. Mechanism of green nanoparticle synthesis using *M. oleifera*

The green synthesis of nanoparticles using *M. oleifera* has emerged as one of the most promising approaches in phytonanotechnology owing to the plant's exceptional phytochemical diversity and its ability to act as a natural nanofactory. Unlike conventional physical and chemical synthesis methods, plant-mediated synthesis utilizes bioactive metabolites as reducing, stabilizing and capping agents, thereby eliminating the need for hazardous chemicals and high-energy processing. *M. oleifera* is particularly suitable for green nanoparticle synthesis because nearly every part of the plant including leaves, seeds, bark, roots, flowers and pods contains abundant polyphenols, flavonoids, glucosinolates, isothiocyanates, proteins, amino acids, carbohydrates, vitamins and terpenoids that participate directly in nanoparticle formation. During synthesis, these biomolecules convert dissolved metal ions into zero-valent metallic nanoparticles through oxidation–reduction reactions while simultaneously stabilizing the newly formed nanostructures against aggregation. Consequently, *M. oleifera*-mediated nanoparticles exhibit enhanced physicochemical stability, biocompatibility and biological activity, making them suitable for applications in antimicrobial therapy, cancer treatment, wound healing, drug delivery, biosensing, environmental remediation and catalysis (Perumalsamy *et al*., 2024; Yadav *et al*., 2024; Gu *et al*., 2025).

The biosynthesis process generally consists of three sequential stages: (i) preparation of phytochemical-rich plant extracts, (ii) phytochemical-mediated reduction and nucleation of metal ions and (iii) stabilization and capping of the synthesized nanoparticles. The efficiency of each stage depends on multiple physicochemical parameters, including the type of plant tissue used, extraction conditions, pH, temperature, precursor concentration, reaction time and storage conditions. Recent mechanistic investigations employing Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), transmission electron microscopy (TEM), dynamic light scattering (DLS), zeta potential analysis and molecular modelling have significantly improved our understanding of plant-mediated nanoparticle biosynthesis, enabling better control over nanoparticle size, morphology, crystallinity and biological functionality (Shahzadi *et al*., 2025; Vanga and Satla, 2025).

5.1 Preparation of plant extracts

The preparation of plant extracts is the initial and one of the most critical steps in the biosynthesis of nanoparticles because the concentration, composition and stability of phytochemicals directly influence nanoparticle formation. Freshly harvested plant materials are generally preferred because they contain higher concentrations of biologically active metabolites than dried materials. The selected tissues are thoroughly washed with running tap water followed by distilled water to remove soil particles, microorganisms, pesticides and other contaminants. The cleaned plant materials are either shade-dried under ambient conditions or processed immediately depending on the target phytochemicals. They are subsequently chopped into small pieces or pulverized to increase the extraction surface area before extraction using distilled water or environmentally friendly solvents such as ethanol, methanol, or hydroethanolic mixtures. Aqueous extraction remains the most widely adopted method because it preserves water-soluble phytochemicals, avoids solvent toxicity and complies with green chemistry principles. Following extraction, the solution is filtered through Whatman filter paper or centrifuged to remove particulate matter before being mixed with the desired metal precursor solution. The resulting extract serves simultaneously as a reducing medium, stabilizing matrix and capping agent throughout nanoparticle synthesis (Perumalsamy *et al*., 2024; Coelho *et al*., 2024).

Leaves represent the most extensively investigated plant organ for nanoparticle synthesis because they contain exceptionally high concentrations of flavonoids, phenolic acids, polyphenols, reducing sugars, proteins, vitamins, chlorophyll, carotenoids and organic acids. Major phytochemicals such as quercetin, kaempferol, rutin, chlorogenic acid, caffeic acid, gallic acid and ascorbic acid efficiently reduce metal ions into metallic nanoparticles while simultaneously stabilizing the resulting nanostructures. Leaf extracts have successfully synthesized silver, gold, zinc oxide, copper oxide, iron oxide, selenium, titanium dioxide and magnesium oxide nanoparticles with particle sizes generally ranging from 10 to 80 nm. Owing to their high antioxidant capacity, leaf-derived nanoparticles frequently exhibit enhanced antimicrobial, antioxidant, anti-inflammatory and anticancer activities. Furthermore, the abundance of proteins and polysaccharides contributes to the formation of a stable phytochemical corona that improves colloidal stability and prolongs nanoparticle shelf life (Perumalsamy *et al*., 2024; Singh *et al*., 2023).

Moringa seeds are another important source of reducing biomolecules because they contain proteins, peptides, glucosinolates, fatty acids, phytosterols, amino acids and cationic coagulant proteins. These constituents possess excellent metal-chelating properties and facilitate rapid nanoparticle nucleation. Seed extracts have been extensively used for synthesizing silver, gold, zinc oxide, iron oxide and titanium dioxide nanoparticles. The proteins adsorbed onto nanoparticle surfaces function as natural stabilizers by providing steric hindrance against aggregation, whereas glucosinolate-derived isothiocyanates impart additional antimicrobial and antioxidant properties. The high oleic acid content of seeds also contributes to nanoparticle stability through hydrophobic interactions at the nanoparticle interface (Coelho *et al*., 2024; Perumalsamy *et al*., 2024).

5.2 Phytochemical-mediated reduction

The conversion of dissolved metal ions into stable nanoparticles is a complex physicochemical process governed by the synergistic action of multiple phytochemicals present in *M. oleifera*. Unlike chemical synthesis, where individual reducing and stabilizing agents are added separately, plant extracts provide an integrated biochemical system capable of simultaneously reducing metal ions, initiating nucleation, directing crystal growth, stabilizing nanoparticle surfaces and forming a bioactive phytochemical corona. Polyphenols, flavonoids, proteins, reducing sugars, amino acids, vitamins, glucosinolates and terpenoids collectively contribute to these processes through oxidation-reduction reactions and intermolecular interactions. The resulting phytochemical-coated nanoparticles exhibit improved physicochemical stability and enhanced biological functionality, which explains their increasing application in nanomedicine and biotechnology (Perumalsamy *et al*., 2024; Gu *et al*., 2025; Vanga and Satla, 2025).

The initial stage of nanoparticle formation involves electron transfer from plant metabolites to metal precursor ions, initiating the reduction process that ultimately leads to nanoparticle nucleation and crystal growth. Polyphenols such as quercetin, kaempferol, rutin, chlorogenic acid and gallic acid are considered the principal reducing agents because their hydroxyl groups readily undergo oxidation, releasing electrons that reduce metallic ions into their elemental state. Simultaneously, proteins, amino acids and polysaccharides adsorb onto the nanoparticle surface, preventing aggregation and stabilizing the newly formed nanostructures. This coordinated mechanism forms the basis of the remarkable efficiency of *M. oleifera*-mediated green nanoparticle synthesis and will be discussed in detail in the following subsection.

Electron transfer is the fundamental biochemical process responsible for the initiation of nanoparticle biosynthesis. In *M. oleifera*, polyphenols and flavonoids containing hydroxyl (–OH) and carbonyl (C=O) functional groups undergo oxidation, releasing electrons that reduce dissolved metal ions (Ag^{+}, Au^{3+} , Zn^{2+}, Cu^{2+}, Fe^{3+} and SeO^{32-}) into their corresponding zero-valent metallic atoms. Quercetin, kaempferol, rutin, gallic acid, caffeic acid, chlorogenic acid and ascorbic acid are among the principal electron-donating molecules involved in this process. During oxidation, these compounds are converted into quinone or semiquinone intermediates while simultaneously reducing metal ions according to the generalized reaction:

$Mn^{+} + ne^{-} \longrightarrow M^{0}$ where Mn^{+} represents the dissolved metal ion and Mp represents the reduced metallic atom. Besides polyphenols, reducing sugars, amino acids, proteins and vitamins also contribute electrons during the reduction process, thereby accelerating nanoparticle formation. Spectroscopic investigations, particularly FTIR analyses, have consistently demonstrated shifts in hydroxyl, amino and carbonyl absorption bands before and after synthesis, confirming the active involvement of these functional groups in electron transfer (Perumalsamy *et al*., 2024; Gu *et al*., 2025; Shahzadi *et al*., 2025).

Freshly synthesized nanoparticles possess high surface energy and therefore have a strong tendency to aggregate. Natural stabilization is one of the major advantages of plant-mediated synthesis because *M. oleifera* extracts contain proteins, flavonoids, tannins, polysaccharides, amino acids and organic acids that spontaneously adsorb onto nanoparticle surfaces. These molecules provide both electrostatic and steric stabilization by generating repulsive forces between neighbouring particles. Zeta potential measurements frequently demonstrate that biosynthesized nanoparticles possess sufficient surface charge to maintain long-term colloidal stability. Stabilization also protects nanoparticles against oxidation, improves aqueous dispersibility and preserves biological activity during storage. Compared with chemically synthesized nanoparticles, phytochemically stabilized nanoparticles generally exhibit greater resistance to aggregation and enhanced compatibility with biological systems (Shahzadi *et al*., 2025; Gu *et al*., 2025).

5.3 Factors affecting nanoparticle synthesis

The physicochemical characteristics of *M. oleifera*-mediated nanoparticles are strongly influenced by reaction conditions. Careful optimization of synthesis parameters is essential for producing nanoparticles with reproducible size, morphology, crystallinity, surface charge and biological activity. The pH of the reaction medium is among the most influential factors because it regulates the ionization of phytochemicals, redox potential and metal ion availability. Alkaline conditions generally enhance the dissociation of hydroxyl groups, increasing electron donation and accelerating reduction reactions. Consequently, nanoparticles synthesized under mildly alkaline conditions are often smaller and more uniformly distributed than those synthesized under acidic conditions. Extremely acidic or highly alkaline environments, however, may denature proteins or degrade sensitive phytochemicals, thereby reducing synthesis efficiency (Vanga and Satla, 2025). Temperature directly influences reaction kinetics, diffusion rates and nucleation efficiency. Increasing temperature generally accelerates metal ion reduction and shortens synthesis time by increasing molecular collisions between phytochemicals and precursor ions. Moderate temperatures usually produce smaller nanoparticles because rapid nucleation creates numerous crystal nuclei. Excessively high temperatures, however, may degrade thermolabile metabolites and promote aggregation or irregular particle growth. Therefore, optimization of temperature is essential for balancing reaction speed with nanoparticle quality (Gu *et al*., 2025).

6. Types of nanoparticles synthesized using *M. oleifera*

The remarkable phytochemical diversity of *M. oleifera* has established this medicinal plant as one of the most efficient biological resources for the green synthesis of metallic and metal oxide nanoparticles. Various plant organs, including leaves, seeds, bark, roots, flowers, pods and gum, contain abundant bioactive compounds such as polyphenols, flavonoids, glucosinolates, proteins, terpenoids, vitamins, alkaloids and polysaccharides that act as reducing, stabilizing and capping agents during nanoparticle biosynthesis. These phytochemicals facilitate the reduction of metallic ions under mild reaction conditions while simultaneously improving nanoparticle stability and biological performance (Table 2). Depending on the precursor salt and synthesis parameters, *M. oleifera* extracts have been successfully employed to synthesize silver, gold, zinc oxide, copper, iron oxide, selenium, titanium dioxide, magnesium oxide, silica and bimetallic nanoparticles with diverse physicochemical properties and biomedical applications. Compared with chemically synthesized nanomaterials, *Moringa*-mediated nanoparticles generally exhibit superior biocompatibility, lower cytotoxicity, enhanced antioxidant activity and improved antimicrobial efficacy because of the bioactive phytochemical corona adsorbed onto their surfaces. Consequently, these nanoparticles have attracted considerable attention for applications in nanomedicine, targeted drug delivery, antimicrobial coatings, biosensing, environmental remediation, catalysis and tissue engineering (Perumalsamy *et al*., 2024; Gu *et al*., 2025; Vanga and Satla, 2025).

6.1 Silver nanoparticles (AgNPs)

Silver nanoparticles are the most extensively investigated nanomaterials synthesized using *M. oleifera*. Their popularity arises from their exceptional antimicrobial activity, relatively simple synthesis and broad applicability in medicine, agriculture, food preservation and environmental science. Leaves are the most commonly used plant material for AgNP biosynthesis owing to their high concentrations of quercetin, kaempferol, rutin, chlorogenic acid, caffeic acid, tannins, proteins and reducing sugars. These phytochemicals rapidly reduce Ag^+ ions from silver nitrate into elemental silver nanoparticles while simultaneously stabilizing the nanoparticle surface through adsorption of hydroxyl, amino and carbonyl-containing compounds (Perumalsamy *et al*., 2024). The biosynthesis of AgNPs is typically indicated by a colour change from pale yellow to dark brown due to surface plasmon resonance. UV-Visible spectroscopy generally reveals characteristic absorption peaks between 410 and 450 nm, confirming nanoparticle formation. Transmission electron microscopy (TEM) studies have demonstrated that *Moringa*-mediated AgNPs are predominantly spherical, although, triangular, hexagonal and rod-shaped particles have also been reported depending on reaction conditions. Particle sizes commonly range from 10 to 80 nm, with smaller nanoparticles exhibiting greater antimicrobial activity because of their larger surface area-to-volume ratio (Singh *et al*., 2023).

Silver nanoparticles synthesized using *M. oleifera* exhibit remarkable antibacterial activity against both Gram-positive and Gram-negative bacteria, including *Staphylococcus aureus*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae* and multidrug-resistant clinical isolates. Their antimicrobial mechanism involves disruption of bacterial membranes, generation of reactive oxygen species (ROS), leakage of intracellular components, inhibition of respiratory enzymes and DNA damage. In addition, AgNPs have demonstrated potent antifungal, antiviral, antioxidant, wound-healing, anti-inflammatory and anticancer activities, making them among the most promising phytofabricated nanomaterials for biomedical applications (Perumalsamy *et al*., 2024; Shahzadi *et al*., 2025).

6.2 Gold nanoparticles (AuNPs)

Gold nanoparticles synthesized using *M. oleifera* have attracted significant attention owing to their exceptional biocompatibility, chemical stability, optical properties and biomedical versatility. The biosynthesis process typically utilizes chloroauric acid ($HAuCl_2$) as the metal precursor, which is reduced by flavonoids, polyphenols, proteins and ascorbic acid present in *Moringa* extracts. During synthesis, the solution changes from light yellow to ruby red or purple due to localized surface plasmon resonance, with UV-Visible absorption maxima typically observed between 520 and 550 nm (Gu *et al*., 2025). *Moringa*-derived AuNPs are generally spherical with diameters ranging from 15 to 70 nm, although, triangular, hexagonal and star-shaped morphologies have also been reported. Gold nanoparticles possess unique optical properties that make them particularly suitable for biosensing, biomedical imaging, photothermal therapy and targeted drug delivery. Unlike silver nanoparticles, AuNPs exhibit comparatively lower intrinsic antimicrobial activity but significantly greater biocompatibility, making them ideal carriers for therapeutic molecules.

Recent studies have demonstrated that *Moringa*-mediated AuNPs effectively enhance the delivery of anticancer drugs through passive and active targeting mechanisms. Their surface can be readily functionalized with antibodies, peptides, nucleic acids, or phytochemicals, enabling selective accumulation within tumour tissues. Furthermore, exposure of AuNPs to near-infrared light produces localized heat that selectively destroys cancer cells during photothermal therapy while minimizing damage to surrounding healthy tissues. These multifunctional properties have positioned *Moringa*-derived AuNPs as promising candidates for precision nanomedicine (Yadav *et al*., 2024; Gu *et al*., 2025).

6.3 Zinc oxide nanoparticles (ZnO NPs)

Zinc oxide nanoparticles are among the most widely investigated metal oxide nanoparticles synthesized using *M. oleifera*. Zinc is an essential micronutrient with excellent biocompatibility and ZnO nanoparticles possess remarkable photocatalytic, antimicrobial, antioxidant, UV-blocking and anticancer properties. Biosynthesis typically employs zinc acetate or zinc nitrate as precursor salts, whereas flavonoids, proteins, amino acids and phenolic compounds within *Moringa* extracts mediate nanoparticle formation through controlled hydrolysis and reduction reactions (Perumalsamy *et al*., 2024). The resulting ZnO nanoparticles generally exhibit spherical or hexagonal morphologies with particle sizes ranging from approximately 20 to 100 nm. X-ray diffraction analyses consistently confirm the characteristic hexagonal wurtzite crystal structure of biosynthesized ZnO nanoparticles. Compared with chemically synthesized ZnO, plant-mediated nanoparticles frequently demonstrate improved dispersibility and enhanced biological activity owing to phytochemical surface functionalization.

The antimicrobial activity of ZnO nanoparticles primarily results from reactive oxygen species generation, membrane disruption, zinc ion release and oxidative stress induction within microbial cells. In addition, ZnO nanoparticles have demonstrated selective cytotoxicity toward cancer cells through mitochondrial dysfunction, DNA fragmentation and apoptosis induction. Their photocatalytic activity also enables degradation of organic pollutants and dyes under ultraviolet irradiation, highlighting their importance in environmental remediation. Furthermore, ZnO nanoparticles are increasingly incorporated into wound dressings, sunscreens, food packaging materials and agricultural formulations because of their antimicrobial and UV-protective properties (Vanga and Satla, 2025).

6.4 Copper nanoparticles (CuNPs/CuO NPs)

Copper and copper oxide nanoparticles synthesized using *M. oleifera* have gained increasing attention as economical alternatives to silver nanoparticles because copper is abundant, inexpensive and possesses broad-spectrum antimicrobial activity. Copper sulfate and copper acetate are the most frequently employed precursor salts, whereas polyphenols, proteins, flavonoids and reducing sugars present in *Moringa* extracts facilitate reduction and stabilization of Cu^{2+} ions (Shahzadi *et al*., 2025). Copper nanoparticles generally exhibit spherical or quasi-spherical morphologies with particle sizes ranging from 20 to 80 nm. However, because metallic copper is susceptible to oxidation, copper oxide nanoparticles (CuO NPs) are more commonly produced and display greater stability under ambient conditions. Biosynthesized CuO nanoparticles exhibit strong antibacterial, antifungal, antiviral, antioxidant and catalytic activities. Their antimicrobial mechanism involves membrane damage, intracellular reactive oxygen species generation, lipid peroxidation, protein denaturation and inhibition of essential metabolic enzymes.

Recent biomedical investigations have also demonstrated the anticancer potential of *Moringa*-derived CuO nanoparticles against breast, cervical, colon and liver cancer cell lines through apoptosis induction, mitochondrial dysfunction and oxidative stress-mediated cytotoxicity. In addition to biomedical applications, CuO nanoparticles are increasingly utilized in wastewater treatment, photocatalysis, electrochemical sensors and agricultural disease management because of their catalytic efficiency and relatively low production cost (Gu *et al*., 2025; Perumalsamy *et al*., 2024).

6.5 Iron oxide nanoparticles (Fe_3O_4/Fe_2O_3NPs)

Iron oxide nanoparticles represent another important class of nanomaterials synthesized using *M. oleifera*, particularly because of their magnetic properties, excellent biocompatibility and biomedical versatility. Ferric chloride, ferrous sulfate and ferric nitrate are commonly employed precursor salts, whereas flavonoids, polyphenols, proteins, carbohydrates and amino acids facilitate iron ion reduction and nanoparticle stabilization. Depending on synthesis conditions, magnetite (Fe_3O_4) or maghemite (γ-Fe, O_3) nanoparticles may be produced, typically exhibiting spherical morphologies with diameters ranging from 10 to 50 nm (Perumalsamy *et al*., 2024). One of the major advantages of iron oxide nanoparticles is their superparamagnetic behaviour, which enables external magnetic field-guided drug delivery and magnetic resonance imaging (MRI). *Moringa*-mediated Fe_3O_4 nanoparticles have demonstrated excellent colloidal stability owing to the adsorption of proteins, flavonoids and polysaccharides onto their surfaces. This phytochemical coating enhances biocompatibility while reducing aggregation and nonspecific interactions with biological tissues.

Magnetic iron oxide nanoparticles have been extensively investigated for targeted chemotherapy, magnetic hyperthermia, biosensing, enzyme immobilization, wastewater purification and heavy metal adsorption. In cancer therapy, magnetic nanoparticles can be directed selectively toward tumour tissues using external magnetic fields, thereby minimizing systemic drug toxicity. Additionally, iron oxide nanoparticles synthesized using *Moringa* extracts exhibit significant antioxidant and antimicrobial activities while maintaining relatively low toxicity toward healthy mammalian cells. Their magnetic recoverability also makes them highly attractive catalysts for environmental remediation and industrial wastewater treatment (Yadav *et al*., 2024; Gu *et al*., 2025).

Table 2: Nanoparticles synthesized from different parts of *M. oleifera*

Nanoparticle	Plant part used	Major reducing phytochemicals	Typical size (nm)	Major biomedical applications
Silver (AgNPs)	Leaves, seeds, bark, flowers	Quercetin, kaempferol, rutin, proteins	10-80	Antimicrobial, wound healing, anticancer
Gold (AuNPs)	Leaves, flowers, seeds	Polyphenols, flavonoids, ascorbic acid	15-70	Drug delivery, biosensing, photothermal therapy
Zinc oxide (ZnO)	Leaves, seeds	Phenolics, flavonoids, proteins	20-100	Antimicrobial, photocatalysis, anticancer
Copper/CuO	Leaves, bark	Polyphenols, tannins, proteins	20-80	Antimicrobial, catalysis, cancer therapy
Iron oxide (Fe_3O_4 /Fe_2O_3)	Leaves, roots	Flavonoids, carbohydrates, proteins	10-50	MRI, targeted drug delivery, hyperthermia
Selenium (SeNPs)	Leaves, seeds	Polyphenols, proteins, amino acids	20-100	Antioxidant, anticancer, immunomodulation
Titanium dioxide (TiO_2)	Leaves, flowers	Flavonoids, carbohydrates	15-80	Photocatalysis, UV protection, antimicrobial
Magnesium oxide (MgO)	Leaves	Polyphenols, polysaccharides	20-70	Antimicrobial, agriculture, catalysis
Silica (SiO_2)	Leaves	Flavonoids, carbohydrates	30-150	Drug delivery, biosensing, tissue engineering
Bimetallic	Leaves, seeds	Mixed phytochemical complexes	15-100	Multifunctional nanomedicine, catalysis

6.6 Selenium nanoparticles (SeNPs)

Selenium nanoparticles (SeNPs) synthesized using *M. oleifera* have emerged as one of the most promising nanomaterials owing to their superior bioavailability, reduced toxicity and diverse pharmacological activities compared with inorganic selenium salts. Selenium is an essential trace element involved in antioxidant defense, immune regulation, thyroid hormone metabolism and cellular redox homeostasis. However, conventional selenium compounds often exhibit a narrow therapeutic window and dose-dependent toxicity.

Green synthesis using *M. oleifera* offers a sustainable strategy for producing biocompatible SeNPs by utilizing phytochemicals such as polyphenols, flavonoids, proteins, amino acids and reducing sugars as natural reducing and stabilizing agents (Perumalsamy *et al*., 2024). The synthesis generally employs sodium selenite (Na, SeO_3) as the precursor, which is reduced to elemental selenium by hydroxyl-rich phytochemicals. Formation of SeNPs is typically indicated by a colour change from colourless to orange-red due to nanoparticle formation. Biosynthesized SeNPs are predominantly spherical, with particle sizes ranging from 20 to 100 nm depending on synthesis conditions. FTIR studies have demonstrated that proteins and phenolic compounds remain adsorbed on nanoparticle surfaces, forming a stable phytochemical corona that improves colloidal stability and biological compatibility (Gu *et al*., 2025).

Moringa-derived SeNPs exhibit potent antioxidant activity by enhancing glutathione peroxidase and other antioxidant enzyme systems while scavenging reactive oxygen species (ROS). Furthermore, SeNPs demonstrate significant antibacterial, antifungal, antiviral, anti-inflammatory, antidiabetic and anticancer activities. Several investigations have reported selective cytotoxicity toward breast, colon, liver and cervical cancer cells through mitochondrial dysfunction, ROS-mediated apoptosis, DNA fragmentation and cell cycle arrest. Their excellent biocompatibility has also promoted applications in nutraceutical formulations, controlled drug delivery, vaccine adjuvants and tissue engineering (Yadav *et al*., 2024; Perumalsamy *et al*., 2024).

7. Pharmacological uses and biomedical applications of *M. oleifera* - mediated nanoparticles

M. oleifera has emerged as an important plant for phytonano-technology due to its rich content of bioactive compounds, including flavonoids, phenolic acids, proteins, alkaloids, terpenoids, and vitamins, which act as natural reducing and stabilizing agents during the green synthesis of nanoparticles. Plant extracts from its leaves, seeds, flowers, bark, and pods have been successfully employed to synthesize metallic nanoparticles such as silver, gold, zinc oxide, copper oxide, and iron oxide in an environmentally friendly and cost-effective manner. These nanoparticles are characterized using advanced analytical techniques including UV-Visible spectroscopy, fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), dynamic light scattering (DLS), zeta potential analysis, and energy dispersive X-ray spectroscopy (EDX) to determine their optical properties, crystalline structure, particle size, morphology, elemental composition, and stability. *M. oleifera* mediated nanoparticles exhibit diverse pharmacological activities owing to the synergistic effects of the phytochemicals and nanomaterials. They demonstrate potent antimicrobial activity against bacterial and fungal pathogens by disrupting microbial cell membranes and inhibiting biofilm formation. Their strong antioxidant properties help scavenge reactive oxygen species, thereby reducing oxidative stress and protecting cellular components from damage. In addition, *M. oleifera* derived nanoparticles have shown potential as targeted drug delivery systems, biosensors, bioimaging agents, tissue engineering materials, and controlled-release therapeutic formulations due to their enhanced biocompatibility, high surface area, and improved bioavailability. The integration of green nanotechnology with the medicinal properties of *M. oleifera* offers a sustainable and innovative platform for developing safe, effective, and multifunctional nanomedicines. Continued research on toxicity evaluation, pharmacokinetics, clinical validation, and large-scale production will further facilitate the translation of *M. oleifera* based phytonanotechnology into pharmaceutical, biomedical, and healthcare applications.

The integration of *M. oleifera* with phytonanotechnology has created a new generation of multifunctional nanomaterials possessing enhanced therapeutic efficacy, excellent biocompatibility and reduced toxicity. During green synthesis, phytochemicals such as polyphenols, flavonoids, proteins, glucosinolates, isothiocyanates, vitamins and polysaccharides remain adsorbed on nanoparticle surfaces, forming a bioactive phytochemical corona that significantly improves biological interactions. Compared with chemically synthesized nanoparticles, *Moringa*-mediated nanoparticles exhibit superior antioxidant, antimicrobial, anti-inflammatory, anticancer and immunomodulatory properties while minimizing cytotoxicity toward healthy tissues. Consequently, these nanoparticles have found increasing applications in drug delivery, cancer therapy, antimicrobial coatings, wound healing, tissue engineering, diagnostic imaging, vaccine development, gene delivery and regenerative medicine (Perumalsamy *et al*., 2024; Gu *et al*., 2025).

7.1 Drug delivery systems

Nanotechnology has transformed modern drug delivery by enabling precise transport of therapeutic molecules to target tissues while minimizing systemic toxicity. *M. oleifera*-mediated nanoparticles serve as efficient nanocarriers because their phytochemical-coated surfaces enhance drug loading, improve colloidal stability, prolong circulation time and facilitate cellular uptake. Gold, silver, iron oxide, silica and polymer-coated nanoparticles synthesized using *Moringa* extracts have demonstrated excellent compatibility with diverse therapeutic agents, including anticancer drugs, antibiotics, proteins, peptides and nucleic acids (Lakhani *et al*., 2025). Targeted drug delivery represents one of the most important advantages of nanoparticle-based therapeutics. Functionalized nanoparticles accumulate selectively within diseased tissues through passive targeting *via* the enhanced permeability and retention (EPR) effect or active targeting using ligands such as antibodies, peptides, folic acid, or aptamers. The phytochemical corona surrounding *Moringa*-derived nanoparticles enhances receptor-mediated cellular uptake while reducing nonspecific interactions with healthy tissues. Magnetic iron oxide nanoparticles additionally enable external magnetic field-guided delivery, whereas gold nanoparticles may be functionalized with tumour-specific ligands for selective accumulation within cancer cells (Gu *et al*., 2025; Vanga and Satla, 2025). Controlled drug release improves therapeutic efficacy by maintaining optimal drug concentrations over prolonged periods while reducing dosing frequency and adverse effects. Phytochemically stabilized nanoparticles gradually release encapsulated drugs in response to environmental stimuli such as pH, temperature, enzymatic activity, or redox conditions. For example, acidic tumour microenvironments accelerate the release of chemotherapeutic agents from nanoparticle carriers, thereby increasing local drug concentrations while minimizing systemic exposure. Such controlled release profiles significantly improve patient compliance and reduce toxicity associated with conventional drug administration (Perumalsamy *et al*., 2024).

7.2 Cancer therapy

Cancer remains one of the leading causes of mortality worldwide, creating an urgent need for safer and more effective therapeutic strategies. *M. oleifera*-derived nanoparticles combine the intrinsic pharmacological properties of *Moringa* phytochemicals with the unique physicochemical characteristics of nanomaterials, producing multifunctional nanotherapeutics capable of selectively targeting tumour tissues. These nanoparticles induce apoptosis, generate reactive oxygen species, disrupt mitochondrial membrane potential, inhibit angiogenesis, arrest cell-cycle progression and suppress tumour metastasis. Recent investigations have demonstrated significant anticancer activity against breast, cervical, liver, lung, prostate and colorectal cancer cell lines with comparatively low toxicity toward normal cells (Perumalsamy *et al*., 2024; Gu *et al*., 2025).

Photothermal therapy (PTT) utilizes nanoparticles capable of converting near-infrared (NIR) light into localized heat, producing selective destruction of tumour tissues while minimizing damage to surrounding healthy cells. *Moringa*-mediated gold nanoparticles exhibit excellent photothermal conversion efficiency because of their localized surface plasmon resonance properties. Following tumour accumulation, irradiation with NIR light generates temperatures exceeding 42°C, resulting in protein denaturation, membrane disruption, mitochondrial dysfunction and irreversible tumour cell death. The phytochemical coating further contributes antioxidant and anti-inflammatory effects that may reduce collateral tissue damage during therapy (Vanga and Satla, 2025). Photodynamic therapy (PDT) combines photosensitizing agents with visible or near-infrared light to generate highly reactive oxygen species that selectively destroy malignant cells. Nanoparticles synthesized using *Moringa* extracts improve photosensitizer stability, enhance tumour accumulation and increase intracellular reactive oxygen species production. Upon photoactivation, singlet oxygen and free radicals induce oxidative damage to cellular membranes, proteins, nucleic acids and mitochondria, ultimately triggering apoptosis or necrosis. Compared with conventional PDT, nanoparticle-assisted photodynamic therapy demonstrates improved selectivity and greater therapeutic efficacy (Gu *et al*., 2025).

7.3 Antimicrobial coatings

Healthcare-associated infections remain a major challenge in hospitals because microbial colonization of medical devices frequently leads to biofilm formation, chronic infections and antimicrobial resistance. *M. oleifera*-mediated nanoparticles possess broad-spectrum antibacterial, antifungal, antiviral and antibiofilm activities that make them highly attractive for antimicrobial surface engineering. Silver, copper oxide, zinc oxide, titanium dioxide and selenium nanoparticles synthesized using *Moringa* extracts effectively inhibit microbial adhesion, membrane integrity, respiratory metabolism and DNA replication while simultaneously generating reactive oxygen species that promote microbial cell death (Shahzadi *et al*., 2025). Nanoparticle-coated medical devices such as urinary catheters, vascular catheters, orthopedic prostheses, surgical instruments, contact lenses and cardiovascular implants exhibit significantly reduced microbial colonization compared with uncoated materials. The sustained release of antimicrobial metal ions from *Moringa*-derived nanoparticles provides long-term protection against bacterial biofilm formation while minimizing device-associated infections (Perumalsamy *et al*., 2024). Hospital environments frequently serve as reservoirs for multidrug-resistant pathogens. Incorporation of *Moringa*-mediated nanoparticles into paints, textiles, polymers, disinfectant coatings and touch surfaces provides continuous antimicrobial protection by preventing microbial attachment and biofilm development. Such self-disinfecting surfaces may significantly reduce nosocomial infections and improve infection control strategies in healthcare facilities (Gu *et al*., 2025).

7.4 Wound healing

M. oleifera-mediated nanoparticles have shown remarkable potential in accelerating wound healing because they combine antimicrobial activity with antioxidant, anti-inflammatory and regenerative properties. These nanoparticles reduce microbial contamination, modulate inflammatory responses, stimulate angiogenesis and promote fibroblast proliferation and collagen deposition. Silver, zinc oxide, selenium and gold nanoparticles incorporated into hydrogels, nanofibers, wound dressings and scaffolds provide sustained antimicrobial protection while maintaining a moist wound environment that supports tissue regeneration. Experimental studies have demonstrated accelerated re-epithelialization, improved granulation tissue formation and enhanced collagen synthesis in nanoparticle-treated wounds compared with conventional dressings (Perumalsamy *et al*., 2024; Gu *et al*., 2025).

7.5 Tissue engineering

Tissue engineering combines biomaterials, stem cells, growth factors and nanotechnology to restore damaged tissues and organs. *Moringa*-mediated nanoparticles enhance scaffold bioactivity by improving mechanical strength, cellular adhesion, proliferation, differentiation and extracellular matrix deposition. Their antioxidant and anti-inflammatory properties further promote tissue regeneration while minimizing oxidative stress at injury sites. Recent studies have investigated *Moringa*-derived nanoparticles for bone regeneration through enhanced osteoblast differentiation, skin regeneration *via* accelerated epithelialization and collagen remodeling and cartilage engineering by supporting chondrocyte proliferation and extracellular matrix synthesis. These multifunctional nanomaterials therefore represent promising components of next-generation regenerative medicine strategies (Lakhani *et al*., 2025; Vanga and Satla, 2025).

7.6 Diagnostic imaging

Nanotechnology has significantly advanced modern diagnostic imaging by improving image resolution, sensitivity and disease detection. *M. oleifera*-mediated nanoparticles have emerged as promising imaging probes because they combine excellent biocompatibility with unique optical, magnetic and electronic properties. The phytochemical coating surrounding biosynthesized nanoparticles enhances colloidal stability, minimizes nonspecific interactions with biological tissues and prolongs circulation time, thereby improving imaging efficiency. Gold nanoparticles, iron oxide nanoparticles, silica nanoparticles and quantum dot-based systems synthesized using *M. oleifera* extracts have demonstrated considerable potential as contrast agents for magnetic resonance imaging (MRI), computed tomography (CT), photoacoustic imaging, fluorescence imaging and multimodal diagnostic platforms (Perumalsamy *et al*., 2024; Gu *et al*., 2025).

Conventional contrast agents often suffer from rapid clearance, nephrotoxicity and limited tissue specificity. Green-synthesized nanoparticles provide safer alternatives owing to their improved biocompatibility and functional surface chemistry. Iron oxide nanoparticles exhibit superparamagnetic properties that enhance contrast in MRI, enabling accurate visualization of tumors, inflammatory lesions and vascular abnormalities. Similarly, gold nanoparticles possess high X-ray attenuation coefficients, making them effective CT contrast agents with superior image resolution. The phytochemical corona derived from *Moringa* extracts further enhances nanoparticle stability while reducing toxicity and facilitating selective accumulation in diseased tissues through passive or ligand-mediated targeting mechanisms (Vanga and Satla, 2025). *Moringa*-mediated nanoparticles have been widely investigated for biosensor development because of their large surface area, high electrical conductivity and catalytic activity. Functionalized nanoparticles improve the sensitivity and specificity of electrochemical, colorimetric and optical biosensors for detecting glucose, cholesterol, proteins, nucleic acids, pathogens, heavy metals, pesticides and environmental pollutants. Gold and silver nanoparticles synthesized using *M. oleifera* extracts exhibit localized surface plasmon resonance properties that facilitate rapid and highly sensitive detection of disease biomarkers. These biosensors have significant applications in point-of-care diagnostics, food safety, environmental monitoring and personalized medicine (Shahzadi *et al*., 2025).

7.7 Gene delivery

Efficient delivery of nucleic acids remains one of the major challenges in gene therapy because naked DNA and RNA molecules are rapidly degraded by nucleases and exhibit poor cellular uptake. *M. oleifera*-mediated nanoparticles have emerged as promising non-viral gene delivery vectors owing to their low immunogenicity, excellent biocompatibility and versatile surface chemistry. Gold, silica, magnetic iron oxide and polymer-coated nanoparticles synthesized using *M. oleifera* extracts can bind plasmid DNA, messenger RNA (mRNA), small interfering RNA (siRNA) and CRISPR-Cas components through electrostatic interactions or covalent functionalization. Following cellular internalization *via* receptor-mediated endocytosis, nanoparticles protect nucleic acids from enzymatic degradation and facilitate intracellular release into the cytoplasm or nucleus. The phytochemical corona also contributes antioxidant and anti-inflammatory effects that reduce cellular stress associated with transfection. Recent studies have demonstrated successful gene silencing, enhanced transfection efficiency and reduced cytotoxicity using plant-mediated nanoparticles compared with conventional non-viral vectors. Such nanocarriers are being investigated for cancer gene therapy, treatment of inherited disorders, regenerative medicine and precision genome editing (Gu *et al*., 2025; Vanga and Satla, 2025).

7.8 Vaccine delivery

Nanoparticle-based vaccine delivery systems have gained enormous importance following recent advances in immunology and nanomedicine. *M. oleifera*-mediated nanoparticles provide biodegradable and biocompatible platforms capable of protecting vaccine antigens from degradation while promoting efficient uptake by antigen-presenting cells. Their nanoscale dimensions facilitate transport across biological barriers and controlled release of encapsulated antigens, thereby enhancing both humoral and cellular immune responses. Gold nanoparticles, selenium nanoparticles, silica nanoparticles and polymer-coated nanoparticles synthesized using *M. oleifera* have been explored as vaccine carriers and adjuvants. Surface functionalization with phytochemicals enhances antigen stability while simultaneously exerting antioxidant and immunomodulatory effects. Furthermore, nanoparticle-based vaccines permit co-delivery of antigens, immunostimulatory molecules and nucleic acid vaccines within a single platform, improving vaccine efficacy while reducing required antigen doses. These multifunctional systems show considerable promise for developing vaccines against infectious diseases, cancer and emerging viral pathogens (Lakhani *et al*., 2025; Perumalsamy *et al*., 2024).

7.9 Dental applications

Nanotechnology has transformed modern dentistry by improving antimicrobial protection, restorative materials, implant integration and regenerative therapies. *M. oleifera*-derived nanoparticles exhibit broad-spectrum antimicrobial activity against oral pathogens such as *Streptococcus mutans*, *Porphyromonas gingivalis*, *Candida albicans* and other microorganisms associated with dental caries, periodontal disease and oral candidiasis. Silver, zinc oxide, titanium dioxide and copper oxide nanoparticles synthesized using *M. oleifera* extracts have been incorporated into dental composites, adhesives, root canal sealers, implant coatings, orthodontic materials and mouthwashes. These nanoparticles inhibit bacterial adhesion, disrupt biofilm formation and reduce secondary infections without compromising the mechanical properties of dental materials. In implant dentistry, nanoparticle coatings improve osseointegration while simultaneously providing long-term antimicrobial protection. Their antioxidant and anti-inflammatory properties also promote gingival wound healing following oral surgical procedures. Consequently, *Moringa*-mediated nanoparticles are increasingly recognized as valuable biomaterials for restorative and preventive dentistry (Shahzadi *et al*., 2025; Gu *et al*., 2025).

7.10 Ophthalmic applications

Ocular drug delivery remains particularly challenging because of rapid tear turnover, blinking, corneal barriers and limited drug residence time. *M. oleifera*-mediated nanoparticles provide promising solutions by improving drug solubility, enhancing corneal penetration, prolonging ocular retention and enabling sustained drug release. Gold, silver, silica and polymer-coated nanoparticles synthesized using *M. oleifera* extracts have demonstrated excellent compatibility with ocular tissues while minimizing irritation and cytotoxicity. Nanoparticle-based ophthalmic formulations have been investigated for treating bacterial keratitis, conjunctivitis, glaucoma, cataracts, age-related macular degeneration, diabetic retinopathy and retinal degeneration. Their antimicrobial activity helps control ocular infections, whereas antioxidant phytochemicals protect retinal cells against oxidative damage. Furthermore, nanoparticle systems facilitate targeted delivery of anti-inflammatory drugs, corticosteroids, growth factors and gene therapies to specific ocular tissues, reducing dosing frequency and improving patient compliance. Future developments integrating smart nanocarriers with stimuli-responsive release systems may further enhance precision treatment of chronic eye diseases while minimizing systemic adverse effects (Perumalsamy *et al*., 2024; Vanga and Satla, 2025).

8. Future prospects

Phytonanotechnology based on *M. oleifera* is poised to become a transformative platform for developing sustainable and multifunctional nanomaterials with broad biomedical applications. Future research should focus on elucidating the molecular mechanisms governing phytochemical-mediated nanoparticle synthesis using advanced omics approaches, including metabolomics, proteomics and transcriptomics, to identify the key biomolecules responsible for nanoparticle nucleation, growth and stabilization. Standardization of extraction procedures, synthesis protocols and characterization methods is essential to ensure reproducibility, scalability and regulatory acceptance for clinical and industrial applications. The integration of artificial intelligence (AI), machine learning (ML) and computational modelling offers promising opportunities to optimize reaction parameters, predict nanoparticle properties and accelerate the design of customized nanoplatforms. Furthermore, the development of multifunctional hybrid nanoparticles capable of simultaneous drug delivery, imaging, biosensing and therapeutic functions will significantly expand the scope of precision medicine. Future investigations should also prioritize comprehensive in vivo toxicity studies, pharmacokinetic profiling, biodistribution analyses and long-term biosafety evaluations to facilitate successful clinical translation. In addition, exploring the use of *M. oleifera*-mediated nanoparticles in gene editing, mRNA therapeutics, vaccine delivery, tissue engineering, antimicrobial resistance management and smart diagnostic systems could open new avenues in nanomedicine. Collaborative efforts among plant scientists, nanotechnologists, clinicians and regulatory agencies will be crucial for translating laboratory-scale discoveries into safe, cost-effective and commercially viable healthcare technologies.

9. Conclusion

M. oleifera has emerged as an outstanding biological resource for green nanoparticle synthesis owing to its rich phytochemical composition and exceptional reducing, stabilizing and capping capabilities. Phytomediated nanoparticles exhibit enhanced biocompatibility, excellent physicochemical stability and diverse biomedical activities, including antimicrobial, antioxidant, anticancer, anti-inflammatory, wound-healing and drug-delivery applications. The integration of *Moringa*-based phytonanotechnology with advanced characterization techniques and multifunctional nanoplatforms offers significant potential for developing next-generation therapeutics and diagnostic tools. Nevertheless, challenges related to synthesis standardization, large-scale production, regulatory approval and comprehensive biosafety assessment must be addressed before widespread clinical implementation. Continued interdisciplinary research integrating green chemistry, nanotechnology, biotechnology and artificial intelligence will accelerate the translation of *Moringa*-mediated nanomaterials into sustainable biomedical innovations that contribute to improved global healthcare and precision medicine.

Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

M. Kabilan: Supervision, academic oversight and overall monitoring of the research work; **K. Sundharaiya:** Conceptualization, supervision, critical review and overall guidance of the manuscript; **T. Anitha:** Software handling, reference management, data organization and visualization of the review content; **M. Jayakumar:** Literature survey, data curation and critical analysis of published studies; **Adnan A. Khan:** Critical review, validation of scientific content and final approval of the manuscript.

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