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SHORT REVIEW

Green Nanotechnology: How Plants Can Help Synthesise Nanoparticles for Biomedical and Environmental Purposes

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Abstract

Nanoscale materials known as nanoparticles exhibit distinctive properties and functionalities owing to their minute size and expansive surface area. Employing plant extracts for nanoparticle synthesis represents an environmentally conscious and sustainable method that utilises natural resources as both reducing and capping agents. This comprehensive review presents the current state-of-the-art in the green synthesis of nanoparticles using plant extracts. It specifically explores the interplay between phytochemicals and metal ions, highlighting the impact of phytochemicals on various nanoparticle properties such as size, shape, morphology, crystal structure, elemental composition, surface charge and optical characteristics. The applications of these nanoparticles such as silver nanoparticles, gold nanoparticles, zinc oxide nanoparticles etc. span diverse fields, including biomedical, environmental, catalytic, optical, electrical and magnetic applications. The review also addresses challenges and future directions in this burgeoning field, emphasising the necessity for standardisation and optimisation of synthesis parameters, elucidation of the synthesis mechanism and kinetics and exploration of functionalisation and potential applications. In conclusion, the green synthesis of nanoparticles using plant extracts emerges as a promising and evolving field with considerable potential for future research and development.

Keywords: Gold Nanoparticles, Green Synthesis, Nanoparticles, Plant Extracts, Phytochemicals, Silver Nanoparticle

Abbreviations: AgNPs, Silver Nanoparticles; AuNPs, Gold Nanoparticles; CuNPs, Copper Nanoparticles; ZnONPs, Zinc Oxide Nanoparticles.

1. Introduction

Nanoparticles, characterised by their atomic or molecular scale and dimensions below 100 nm exhibit distinctive physical and chemical properties in contrast to bulk materials, influenced by factors like size, shape and morphology. Classification of nanoparticles encompasses various types based on these parameters including distinctions between organic (e.g., dendrimers, liposomes and polymeric nanoparticles) and inorganic (e.g., fullerenes, quantum dots and metal nanoparticles) categories. Metal nanoparticles, particularly, have garnered significant attention for their diverse applications in catalysis, imaging, medicine, energy and environmental contexts[1,2]. Conventional methods for synthesising metal nanoparticles such as chemical and physical approaches, often involve hazardous substances, high energy input and the generation of toxic waste, raising environmental and health concerns. Consequently, there is a growing inclination towards developing eco-friendly and sustainable synthesis methods, utilising biological agents like plants, microorganisms, enzymes and biomolecules as reducing and stabilising agents[3]. Among these alternatives, plants and their extracts stand out due to their widespread availability, cost-effectiveness and ease of handling. Recognized as nature's "chemical factories", plants produce an array of phytochemicals, including phenolic acids, flavonoids, terpenoids, alkaloids and proteins, which serve as effective reducing and capping agents for metal nanoparticle synthesis[4]. The green synthesis

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of metal nanoparticles using plant extracts offers a straightforward, cost-effective and environmentally benign method, yielding nanoparticles with diverse sizes, shapes and properties[5,6]. The outcome is contingent on factors such as plant species, extraction method, reaction parameters and precursor concentration. This approach boasts several advantages, including the elimination of toxic chemicals, reduced energy consumption, improved biocompatibility and bioactivity, and the potential for simultaneous synthesis and functionalisation[7]. However, challenges such as limited control over size and shape distribution, low yield and stability, variations in phytochemical composition and constraints in scalability and reproducibility should be acknowledged[8].

This review seeks to offer a thorough and evaluative examination of the present state of the art in the green synthesis of metal nanoparticles utilising plant extracts. Its primary objective is to shed light on both the opportunities and challenges associated with the advancement of innovative and efficacious herbal nanotechnology, particularly in diverse applications.

The review aims to accomplish: a) Present a comprehensive overview of recent strides in green synthesis, specifically focusing on the utilisation of herbal technology for nanoparticle synthesis. Herbal technology involves harnessing medicinal plants and their extracts to create nanoparticles imbued with therapeutic properties. b) Explore key aspects, such as the careful selection of plant species and extraction methods for green synthesis and the optimisation of synthesis parameters (temperature, pH, reaction time, precursor concentration and plant extract concentration) to govern the size, shape and morphology of nanoparticles. c) Scrutinise nanoparticle characterisation through varied techniques including UV-Vis spectroscopy, X-ray diffraction, scanning electron microscopy, transmission electron microscopy, Fourier transform infrared spectroscopy and dynamic light scattering. d) Explore the mechanisms governing green synthesis using plant extracts, explaining the role of phytochemicals in nanoparticle reduction, capping and stabilisation along with plausible pathways and models of nanoparticle formation within plants. e) Examine applications of green-synthesized metal nanoparticles derived from plant extracts, especially in biomedical and environmental contexts. This includes their role in antimicrobial, antioxidant, anti-inflammatory, anticancer, wound healing, drug delivery, biosensing, imaging, water treatment, catalysis and remediation. f) Discuss challenges and future perspectives associated with green synthesis using plant extracts, encompassing limitations and drawbacks of the method, comparisons with alternative biological methods, recommendations for enhancing efficiency, scalability and stability, and exploration of potential risks and ethical considerations.

2. Materials and Methods

2.1 Selection of Plant Species and Extraction of Phytochemicals

The selection of plant species in the process of green nanoparticle synthesis is an important step. This step holds significance due to the variation in phytochemical composition among different plants, as these compounds serve as both reducing and capping agents during the nanoparticle synthesis process. The plant species should be chosen based on; a) the availability and abundance of the plant in the local area, b) the medicinal and therapeutic properties of the plant and its extracts, c) the diversity and richness of the phytochemicals in the plant, d) the compatibility and specificity of the phytochemicals with the metal precursors, e) the ease and simplicity of the extraction process, and f) the cost-effectiveness and eco-friendliness of the plant and its extracts[9].

Some of the commonly used plant species for the green synthesis of nanoparticles are listed in Table 1, along with their scientific names, families, parts used and types of nanoparticles synthesised.

The extraction of phytochemicals from plant materials is another crucial step, as it affects the quality and quantity of the nanoparticles (Figure 1). The extraction process involves the following steps; a) The plant materials are washed with distilled water to remove dust and impurities. b) The plant materials are cut into small pieces and dried in an oven or under sunlight. c) The dried plant materials are ground into a fine powder using a grinder or a mortar and pestle. d) The plant powder is mixed with a suitable solvent such as water, ethanol, methanol, acetone, etc., in a

Table 1. List of some nanoparticle formulations synthesised by the green synthesis method

Common Name	Scientific Name	Family	Part Used	Nanoparticles Type	References
Aloe vera	*Aloe barbadensis*	Asphodelaceae	Leaf gel	AgNPs, AuNPs, CuNPs	10
Basil	*Ocimum basilicum*	Lamiaceae	Leaf	AgNPs, AuNPs,	11
Cinnamon	*Cinnamomum verum*	Lauraceae	Bark	AgNPs, AuNPs,	12
Garlic	*Allium sativum*	Amaryllidaceae	Clove	AgNPs, AuNPs,	13
Ginger	*Zingiber officinale*	Zingiberaceae	Rhizome	AgNPs, AuNPs,	14
Lemon	*Citrus limon*	Rutaceae	Peel, Juice	AgNPs, AuNPs, CuNPs	15
Neem	*Azadirachta indica*	Meliaceae	Leaf, Bark, Seed	AgNPs, AuNPs, CuNPs, ZnONPs	16
Tea	*Camellia sinensis*	Theaceae	Leaf	AgNPs, AuNPs, CuNPs	17
Turmeric	*Curcuma longa*	Zingiberaceae	Rhizome	AgNPs, AuNPs, CuNPs	18

specific ratio and heated in a water bath or a microwave oven for a certain time. e) The plant extract is filtered using filter paper or a muslin cloth to remove the solid residues. f) The plant extract is stored in a refrigerator or a freezer until further use[19].

The choice of the solvent, the ratio of the plant powder to the solvent, the temperature and time of heating and the storage conditions of the plant extract may vary depending on the plant species, the type of phytochemicals and the desired nanoparticles. The plant extract should contain sufficient amounts of phytochemicals that can reduce the metal ions and cap the nanoparticles. Some of the common phytochemicals that are involved in nanoparticle synthesis are phenolic acids, flavonoids, terpenoids, alkaloids, proteins and polysaccharides[20].

2.2 Optimisation of Synthesis Parameters

The synthesis parameters, such as reaction time, precursor concentration, temperature, pH and plant extract concentration, play a vital role in determining the shape, size and stability of the nanoparticles[21]. Therefore, it is important to optimize these parameters to obtain the desired nanoparticles with high efficiency and quality. The optimisation of synthesis parameters can be done by using various experimental design methods such as response surface methodology, Taguchi method, factorial design, etc[22]. Some of the factors that influence the formulation parameters are discussed below.

2.2.1 Temperature

The temperature of the reaction affects the rate of reduction of metal ions, the nucleation and growth of nanoparticles, and the stability of the plant extract. Higher temperatures can increase the reaction rate and produce smaller and more uniform nanoparticles, but they can also degrade the phytochemicals and cause agglomeration of nanoparticles[23]. Therefore, an optimal temperature should be chosen to balance these effects. The optimal temperature may vary depending on the plant species, the metal precursor and the solvent used. For example, the optimal temperature for the green synthesis of nanoparticles using neem leaf extract was reported to be 60°C[24], while the optimal temperature for the green synthesis of silver nanoparticles using lemon peel extract was reported to be 80°C.

2.2.2 pH

The pH of the reaction affects the solubility of metal ions, the charge and stability of nanoparticles and the activity and availability of phytochemicals. Different pH values can produce different sizes and shapes of nanoparticles, as well as different surface charges and zeta potentials. Therefore, an optimal pH should be

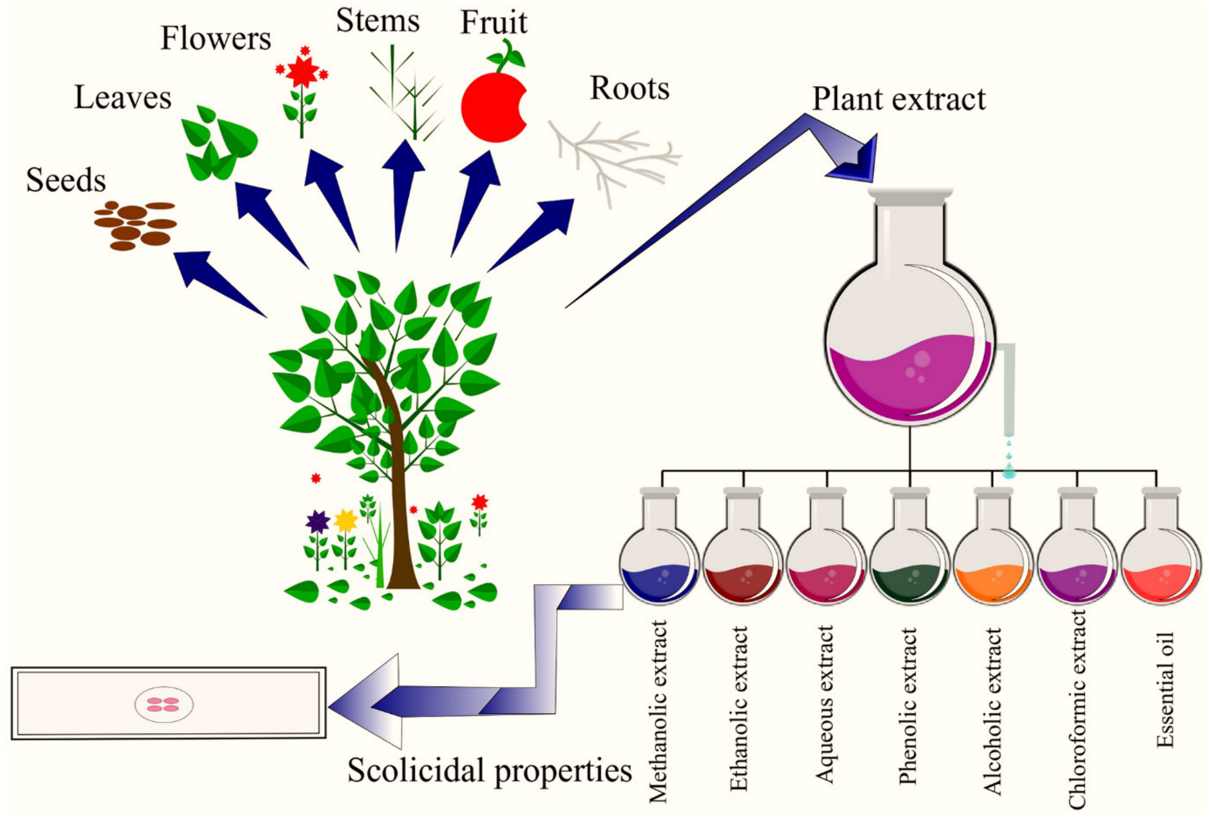

Figure 1. Schematic representation of medicinal parts of plants and their extracts. Reused from Ali *et al.,* 2020[21].

chosen to obtain the desired nanoparticles with high stability and functionality. The optimal pH may vary depending on the plant species, the metal precursor, and the solvent used. For example, the optimal pH for the synthesis of AgNPs using basil leaf extract was reported to be 9, while the optimal pH using ginger rhizome extract was reported to be 10[25].

2.2.3 Reaction Time

The reaction time affects the completion of the reduction of metal ions, the nucleation and growth of nanoparticles and the stability of the plant extract. Longer reaction times can increase the yield and size of nanoparticles but they can also cause aggregation and oxidation of nanoparticles. Therefore, an optimal reaction time should be chosen to obtain the desired nanoparticles with high purity and quality. The optimal reaction time may vary depending on the plant species, the metal precursor and the solvent used. For example, the optimal reaction time for the formulation of AgNPs by green synthesis using aloe vera gel was reported to be 15 minutes, while the optimal reaction time for the formulation of AgNPs using tea leaf extract was reported to be 30 minutes[26].

2.2.4 Precursor Concentration

The concentration of the precursor has a significant impact on the availability of metal ions, the nucleation and growth processes of nanoparticles and the stability of the plant extract. Higher precursor concentrations have the potential to enhance nanoparticle yield and size, yet they also pose risks of aggregation and toxicity. Therefore, an optimal precursor concentration should be chosen to obtain the desired nanoparticles with high efficiency and safety. The ideal precursor concentration can vary based on factors such as plant species, metal precursor and solvent employed. For instance, the green synthesis of silver nanoparticles using garlic clove extract exhibited an optimal precursor concentration of 1 mM while the green synthesis using cinnamon bark extract reported an optimal precursor concentration of 2mM[27].

2.3 Plant Extract Concentration

The plant extract concentration affects the availability of phytochemicals, the reduction and capping of nanoparticles and the stability of the plant extract. Higher plant extract concentrations can increase the rate and efficiency of nanoparticle synthesis but they can also cause saturation and interference of phytochemicals. Therefore, an optimal plant extract concentration should be chosen to obtain the desired nanoparticles with high quality and functionality. The optimal plant extract concentration may vary depending on the plant species, the metal precursor, and the solvent used. For example, the optimal plant extract concentration for the synthesis of nanoparticles using neem leaf extract was reported to be 10%[26], while using lemon peel extract, it was reported to be 20%[28].

3. Characterisation of Nanoparticles Using Various Techniques

The characterisation of nanoparticles is an essential step to evaluate the quality, purity and functionality of the nanoparticles. Different techniques can be used to characterise the size, shape, morphology, crystal structure, elemental composition, surface charge, optical properties and physical and chemical factors of the nanoparticles. Some of them are described below.

3.1 UV-Visible Spectroscopy

This technique measures the absorption of ultraviolet and visible light by the nanoparticles in a liquid medium. The absorption spectrum can confirm the presence, drug concentration and size of the nanoparticles as well as their optical properties such as Surface Plasmon Resonance (SPR)[29]. The SPR makes a strong peak in the absorption spectrum when the light frequency matches the vibration frequency of the nanoparticles (Figure 2)[30]. The position and intensity of the SPR peak changes depending upon the size, shape, material and medium of the nanoparticles (Figure 3)[31].

3.1 X-Ray Diffraction (XRD)

This technique measures the diffraction of X-rays by the nanoparticles in a solid state. The diffraction pattern can provide information about the crystal structure, phase and lattice parameters of the nanoparticles as

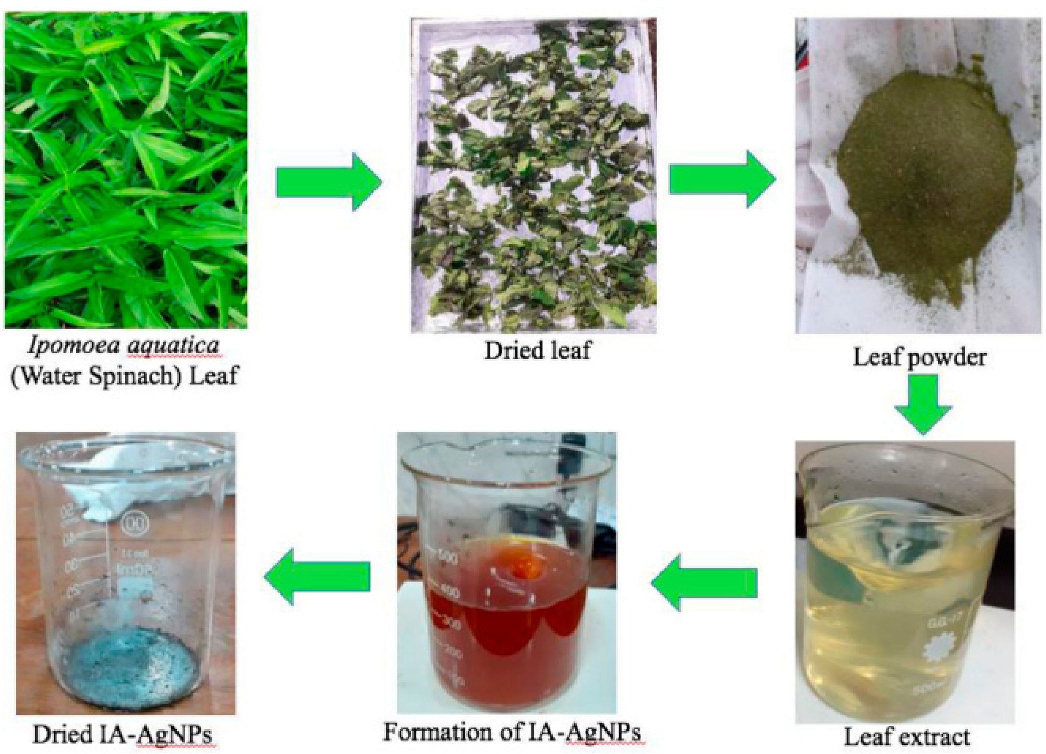

Figure 2. Plant extract from leaf *Ipomoea aquatica* and formulation of silver nanoparticles. Reused from Englebienne P *et al.,* 2003[30].

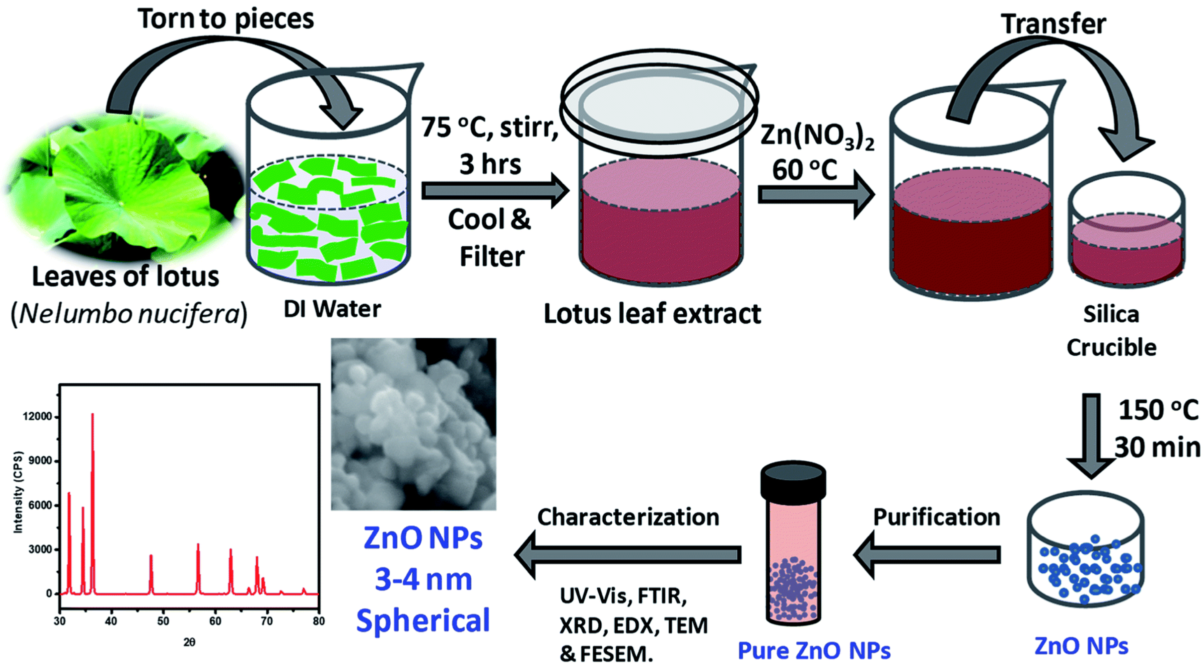

Figure 3. Representation of formulation of metal nanoparticles by green synthesis method. Reused from Begum R *et al.*, 2018[31].

well as their average size and strain[32]. The XRD pattern consists of several peaks, corresponding to the different planes of the crystal lattice, whose positions and intensities depend on the interplanar spacing and the atomic arrangement of the nanoparticles[33].

3.3 Scanning Electron Microscopy (SEM)

This technique uses a focused beam of electrons to scan the surface of the nanoparticles in a solid state. The electrons interact with the atoms of the nanoparticles, producing signals that can be detected and analysed. The SEM image can provide information about the morphology, size distribution and aggregation of the nanoparticles as well as their elemental composition using Energy Dispersive X-ray (EDX) Spectroscopy. The SEM image has a high resolution and magnification, allowing the observation of the individual nanoparticles and their features[34,35].

3.4 Transmission Electron Microscopy (TEM)

This technique uses a beam of electrons to transmit through a thin film of the nanoparticles in a solid state. The electrons interact with the atoms of the nanoparticles, producing signals that can be detected and analysed. The TEM image can provide information about the morphology, size, shape and crystal structure of the nanoparticles as well as their elemental composition, using EDX spectroscopy or Electron Energy Loss Spectroscopy (EELS). The TEM image has a higher resolution and magnification than the SEM image, allowing the observation of the internal structure and defects of the nanoparticles[36].

3.5 Atomic Force Microscopy (AFM)

This technique uses a sharp tip attached to a cantilever to scan the surface of the nanoparticles in a solid state. The tip interacts with the atoms of the nanoparticles, producing forces that can be measured and analysed. The AFM image can provide information about the morphology, size, shape and surface roughness of the nanoparticles as well as their mechanical and electrical properties such as elasticity, adhesion and conductivity. The AFM image has a high resolution and magnification, allowing the observation of the surface features and interactions of the nanoparticles[37].

4. Mechanisms of Formulation of Nanoparticles by Green Synthesis

The green synthesis of nanoparticles using plant extracts involves the reduction of metal ions by phytochemicals present in the plant extracts, followed by the capping and stabilisation of the nanoparticles by the same or different phytochemicals. The phytochemicals also influence the size, shape and morphology of the nanoparticles, as well as the possible pathways and models of nanoparticle formation in plants. These aspects are discussed below.

4.1 Role of Phytochemicals in the Reduction, Capping and Stabilisation of Nanoparticles

Phytochemicals are the bioactive compounds produced by plants that have various biological functions such as defence, signalling, growth and metabolism. Some of the common phytochemicals that are involved in the green synthesis of nanoparticles are phenolic acids, flavonoids, terpenoids, alkaloids, proteins and polysaccharides[19]. These phytochemicals can act as both reducing and capping agents for the nanoparticles or they can work in synergy with other phytochemicals or biomolecules to perform these roles[38].

The reduction of metal ions by phytochemicals is a redox reaction, where the phytochemicals donate electrons to the metal ions, resulting in the formation of metal atoms or clusters. The reduction can occur either extracellularly or intracellularly, depending on the location of the phytochemicals and the metal ions[39]. The reduction can also be influenced by various factors such as the type and concentration of the phytochemicals and the metal ions, the pH and temperature of the reaction medium and the presence of other substances[21].

The capping of nanoparticles by phytochemicals is a process where the phytochemicals bind to the surface of the nanoparticles, forming a protective layer that prevents further growth, aggregation and oxidation of the nanoparticles. The capping can also confer specific properties on the nanoparticles such as solubility, stability, biocompatibility and functionality[40]. The capping can be influenced by various factors such as the type and concentration of the phytochemicals and the nanoparticles, the size and shape of the nanoparticles and the interaction between the phytochemicals and the nanoparticles.

The stabilisation of nanoparticles by phytochemicals is a process where the phytochemicals maintain the size, shape and dispersion of the nanoparticles over time, avoiding their precipitation, degradation, or transformation. The stabilisation can be achieved by various mechanisms such as electrostatic repulsion, steric hindrance, hydrogen bonding or coordination bonding, depending on the nature and charge of the phytochemicals and the nanoparticles. The stabilisation can be influenced by various factors such as the type and concentration of the phytochemicals and the nanoparticles, the pH and ionic strength of the reaction medium and the presence of other substances.

4.2 Influence of Phytochemicals on the Size, Shape and Morphology of Nanoparticles

The influence of phytochemicals on the size, shape and morphology of nanoparticles for the mechanisms of green synthesis of nanoparticles using plant extracts can be summarised as follows:

The phytochemicals can affect the nucleation and growth of the nanoparticles by controlling the rate and extent of the reduction of metal ions as well as the capping and stabilisation of the nanoparticles[19]. The phytochemicals can affect the size and shape of the nanoparticles by influencing the solubility and diffusion of the metal atoms or clusters as well as the orientation and alignment of the nanoparticles[9]. The phytochemicals can affect the morphology and structure of the nanoparticles by affecting the growth rate and direction of the different facets of the crystal lattice as well as the fusion and aggregation of the nanoparticles[41]. The phytochemicals can produce various types of nanoparticles such as spheres, cubes, rods, wires, plates, stars and networks, depending on the type and concentration of the phytochemicals and the metal ions, the pH and temperature of the reaction medium and the reaction time and precursor concentration.

4.3 Possible Pathways and Models of Nanoparticle Formation in Plants

The possible pathways and models of nanoparticle formation in plants for the mechanisms of green synthesis of nanoparticles using plant extracts are as follows:

4.3.1 Direct Biosynthesis

This is the simplest and most common pathway, where the phytochemicals act as both reducing and capping agents for the nanoparticles, forming stable and uniform nanoparticles. Direct biosynthesis can occur either extracellularly or intracellularly, depending on the availability of the phytochemicals and the metal ions. Direct biosynthesis can produce various types of nanoparticles, such as silver, gold, copper, zinc oxide and titanium dioxide, using various plant species, such as neem, aloe vera, basil, garlic, ginger, lemon, tea and turmeric[19].

4.3.2 Indirect Biosynthesis

This is a more complex and less common pathway where the phytochemicals act as reducing agents and other biomolecules act as capping agents for the nanoparticles, forming stable and functional nanoparticles. The indirect biosynthesis can occur either extracellularly or intracellularly, depending on the availability of the phytochemicals, the metal ions and the capping biomolecules. The indirect biosynthesis can produce various types of nanoparticles such as silver, gold, copper, iron oxide and selenium, using various plant species such as neem, aloe vera, basil, garlic, ginger, lemon, tea and turmeric and various capping biomolecules, such as proteins, polysaccharides, lipids and DNA.

4.3.3 Biomineralisation

This is a more sophisticated and rarer pathway, where the phytochemicals act as templates or scaffolds for the nucleation and growth of the nanoparticles, forming complex and structured nanoparticles. The biomineralisation can occur only intracellularly, as it requires the involvement of the plant cell organelles and structures. The biomineralisation can produce various types of nanoparticles, such as silver, gold, copper, iron oxide and calcium carbonate, using various plant species, such as neem, aloe vera, basil, garlic, ginger, lemon, tea and turmeric and various templates or scaffolds such as cell wall, vacuole, chloroplast and mitochondria.

4.3.4 Biomimetic

This is a more advanced and novel pathway where the phytochemicals act as catalysts or modifiers for the synthesis of the nanoparticles forming novel and enhanced nanoparticles. The biomimetic can occur either extracellularly or intracellularly, depending on the availability of the phytochemicals and the metal ions. The biomimetic can produce various types of nanoparticles such as silver, gold, copper, iron oxide and magnesium oxide, using various plant species, such as neem, aloe vera, basil, garlic, ginger, lemon, tea and turmeric and various catalysts or modifiers such as enzymes, hormones and antioxidants[42].

5. Applications of Formulation of Nanoparticles Using Plant Extracts

One of the most promising applications of green synthesis of nanoparticles is in the field of antimicrobial research where the nanoparticles can act as effective agents against various pathogens such as bacteria, fungi, viruses and parasites. The nanoparticles can also enhance the activity of conventional antibiotics, overcoming the problem of antibiotic resistance. The applications of green synthesis of nanoparticles can be classified into two main categories, biomedical and environmental. These applications are based on the unique properties and functionalities of the nanoparticles such as size, shape, surface charge, and optical, electrical, magnetic, catalytic and biological properties. These aspects are discussed below.

5.1 Antimicrobial Activity of Nanoparticles Against Various Pathogens

The nanoparticles synthesised by plant extracts have shown remarkable antimicrobial activity against various pathogens, due to their small size, large surface area, high reactivity and ability to interact with the cell membrane and intracellular components of the microbes. The nanoparticles can cause various modes of action such as membrane disruption, oxidative stress, DNA damage, protein denaturation, enzyme inhibition and metabolic interference, leading to the death or growth inhibition of the microbes.

The nanoparticles can target different types of pathogens such as gram-positive and gram-negative bacteria, fungi, viruses and parasites. Some examples of the antimicrobial activity of nanoparticles synthesised by plant extracts are given below.

Silver nanoparticles synthesised by neem leaf extract could inhibit the growth of bacteria such as *Escherichia coli, Staphylococcus aureus, Pseudomonas aeruginosa* and *Bacillus subtilis* and fungi such as *Candida albicans*, *Aspergillus niger* and *Fusarium oxysporum*[43]. Gold nanoparticles synthesised by aloe vera gel could prevent the infection of *E. coli, S. aureus*, and *P. aeruginous* and against herpes simplex virus type 1 and type 2.

Copper nanoparticles synthesised by basil leaf extract showed antibacterial activity against *E. coli, S. aureus* and *Salmonella typhi* and antifungal activity against *C. albicans* and *A. niger*. Zinc oxide nanoparticles synthesised by garlic clove extract showed antibacterial activity against *E. coli, S. aureus* and *P. aeruginosa* and antiparasitic activity against *Leishmania* major. Titanium dioxide nanoparticles synthesised by tea leaf extract showed antibacterial activity against *E. coli, S. aureus*, and *P. aeruginosa* and antiviral activity against hepatitis B virus[44-46].

5.2 Synergistic Effect of Nanoparticles with Conventional Antibiotics

The nanoparticles synthesised by plant extracts can also enhance the activity of conventional antibiotics, overcoming the problem of antibiotic resistance which is a major threat to public health. The nanoparticles can act as synergists, potentiators or carriers for the antibiotics, improving their efficacy, stability and delivery. The nanoparticles can enhance the activity of antibiotics by various mechanisms such as increasing the permeability of the cell membrane, facilitating the penetration of the antibiotics, inhibiting the efflux pumps, reducing the biofilm formation and preventing the degradation of the antibiotics.

The nanoparticles can synergise with different types of antibiotics such as beta-lactams, aminoglycosides, quinolones, macrolides and tetracyclines. Some examples of the synergistic effect of nanoparticles with antibiotics are given below.

Silver nanoparticles synthesised from neem leaves enhanced the effectiveness of ampicillin, gentamicin, ciprofloxacin, and erythromycin against *E. coli, S. aureus*, and *P. aeruginosa*, enlarging the zone of inhibition and lowering the minimum inhibitory concentration. Gold nanoparticles from *Aloe vera* extract had a similar effect with amoxicillin, ceftriaxone, and vancomycin against the same bacteria. Similarly, Copper nanoparticles from basil leaves also showed this effect against *E. coli, S. aureus*, and *S. typhi*. Zinc oxide nanoparticles from garlic cloves and titanium dioxide nanoparticles from tea leaves demonstrated similar synergistic effects against the same bacterial strains[47,48].

5.3 Biomedical Applications of Nanoparticles

Nanoparticles produced through plant extracts find diverse applications in the biomedical field, particularly in drug delivery, wound healing, biosensing and imaging. These applications hinge on the nanoparticles' biocompatibility, stability, solubility and functionality as well as their capacity to interact with biological systems and molecules.

5.4 Drug Delivery

Nanoparticles serve as effective carriers for drugs, including anticancer, anti-inflammatory, antidiabetic and antibacterial agents. They deliver these drugs to specific target sites like tumours, wounds or infections with heightened efficiency and specificity. These nanoparticles enhance drug solubility, stability, bioavailability and permeability while safeguarding them from degradation and elimination. Additionally, they enable controlled drug release, modulating pharmacokinetics and pharmacodynamics. Examples include silver nanoparticles synthesised from neem leaf extract, exhibiting enhanced anticancer activity when loaded with paclitaxel for human breast cancer cells (MCF-7). Nanoparticles play a crucial role in wound healing by promoting skin tissue regeneration, improving blood clotting, reducing inflammation and preventing infections. They also enhance the mechanical strength, elasticity and biodegradability of wound dressings. For instance, silver nanoparticles from aloe vera gel accelerate wound healing in rats by increasing collagen synthesis and reducing bacterial load and inflammation. Moreover, nanoparticles function as sensors or probes for detecting and quantifying biomolecules and pathogens. They enhance biosensor sensitivity, selectivity, stability and reproducibility, providing various signal transduction mechanisms. Examples include silver nanoparticles synthesised from neem leaf extract, showing optical sensing of glucose through a colour change in the UV-Vis spectrum. Furthermore, nanoparticles also act as contrast agents or tracers in imaging biological structures and processes. They enhance imaging modalities' contrast, resolution, specificity and stability. Examples include gold nanoparticles synthesised from aloe vera gel, facilitating computed tomography imaging of the brain and kidney in rats with high contrast enhancement and low accumulation[49-51].

Thus, nanoparticles derived from plant extracts exhibit immense potential in revolutionising biomedical applications, offering innovative solutions in drug delivery, wound healing, biosensing and imaging.

5.5 Environmental Applications of Nanoparticles

Nanoparticles synthesised from plant extracts offer versatile environmental applications, particularly in water treatment, catalysis and remediation. In water treatment, these nanoparticles demonstrate effective removal of pollutants like heavy metals, organic dyes, pesticides and pathogens through various mechanisms such as absorption, coagulation, flocculation, precipitation, oxidation, reduction or degradation. For instance, silver nanoparticles from neem leaf extract adsorb lead ions, while gold nanoparticles from aloe vera gel coagulate turbidity in river water. Similarly, copper nanoparticles from basil leaf extract facilitate the flocculation of suspended solids in wastewater, showcasing their potential for diverse water treatment applications. In catalysis, nanoparticles serve as catalysts or catalyst supports, enhancing activity, selectivity, stability and reusability in chemical reactions like hydrogenation, oxidation, reduction, hydrolysis, esterification and polymerisation. For example, silver nanoparticles from neem leaf extract exhibit high efficiency in hydrogenating nitrobenzene to aniline, while gold nanoparticles from aloe vera gel efficiently oxidize benzyl alcohol to benzaldehyde. These plant-extract-synthesised nanoparticles contribute to sustainable catalytic processes, reducing energy consumption and waste generation. For remediation purposes, nanoparticles synthesised by plant extracts address environmental media contamination, including soil, air and sediments, by removing pollutants such as heavy metals, organic compounds, radionuclides and pathogens. Notably, silver nanoparticles from neem leaf extract remediate cadmium-contaminated soil through high adsorption capacity while gold nanoparticles from aloe vera gel efficiently oxidise carbon monoxide in polluted air. Copper nanoparticles from basil leaf extract effectively remediate sediments contaminated with mercury showcasing the broad applicability of plant-extract-synthesised nanoparticles in environmental remediation[52].

6. Challenges and Future Perspectives of Green Synthesis of Nanoparticles

The green synthesis of nanoparticles using plant extracts is a promising and eco-friendly approach that has many advantages over conventional chemical and physical methods, such as low cost, high yield, easy scalability, biocompatibility and biodegradability. However, there are also some challenges and limitations that need to be addressed and overcome to make this approach more efficient, reliable and applicable. Some of the challenges and future perspectives of green synthesis of nanoparticles using plant extracts are discussed below.

Standardisation and optimisation: One of the major challenges of green synthesis of nanoparticles using plant extracts is the lack of standardisation and optimisation of the synthesis parameters, such as the type and concentration of the plant extract and the metal precursor, the pH and temperature of the reaction medium, the reaction time and precursor concentration and the purification and characterisation methods. These parameters can affect the quality, quantity and functionality of the nanoparticles, as well as their reproducibility and stability. Therefore, there is a need to develop and establish standardised and optimised protocols for the green synthesis of nanoparticles using plant extracts, using various experimental design methods, such as response surface methodology, Taguchi method, factorial design, etc[53].

Mechanism and kinetics: Another challenge of green synthesis of nanoparticles using plant extracts is the lack of understanding and elucidation of the mechanism and kinetics of the synthesis process such as the role and interaction of the phytochemicals and the metal ions, the nucleation and growth of the nanoparticles and the capping and stabilisation of the nanoparticles. These aspects can provide insights into the factors that influence the size, shape, morphology, crystal structure, elemental composition, surface charge, optical properties and other physical and chemical properties of the nanoparticles, as well as their biological and environmental activities. Therefore, there is a need to investigate and elucidate the mechanism and kinetics of the green synthesis of nanoparticles using plant extracts, using various analytical and spectroscopic techniques such as UV-visible spectroscopy, X-ray diffraction, scanning electron microscopy, transmission electron microscopy, atomic force microscopy, energy-dispersive X-ray spectroscopy, electron energy loss spectroscopy, Fourier transform infrared spectroscopy, nuclear magnetic resonance spectroscopy, etc[54].

Functionalisation and application: A further challenge of green synthesis of nanoparticles using plant extracts is the lack of functionalisation and application of the nanoparticles such as the modification and enhancement of their properties and functionalities, the integration and incorporation of them into various devices and systems and the evaluation and validation of their performance and efficiency. These aspects can expand the scope and potential of the nanoparticles for various applications in various fields such as biomedical, environmental, catalytic, optical, electrical, magnetic and others. Therefore, there is a need to functionalise and apply the nanoparticles synthesised by plant extracts, using various methods and techniques such as surface modification, doping, coating, hybridisation, conjugation, immobilisation, encapsulation, etc[53,54].

7. Conclusion

The green synthesis of nanoparticles using plant extracts is a promising and eco-friendly approach that has many advantages over conventional chemical and physical methods such as low cost, high yield, easy scalability, biocompatibility and biodegradability. The plant extracts provide various phytochemicals that act as both reducing and capping agents for the nanoparticles as well as influence their size, shape, morphology, crystal structure, elemental composition, surface charge, optical properties and other physical and chemical properties. The nanoparticles synthesised by plant extracts have various applications in various fields, such as biomedical, environmental, catalytic, optical, electrical, magnetic and others. However, there are also some challenges and limitations that need to be addressed and overcome to make this approach more efficient, reliable and applicable such as the lack of standardisation and optimisation of the synthesis parameters, the lack of understanding and elucidation of the mechanism and kinetics of the synthesis process and the lack of functionalisation and application of the nanoparticles. Therefore, there is a need to develop and establish standardised and optimised protocols, investigate and elucidate the mechanism and kinetics and functionalised and apply the nanoparticles synthesised by plant extracts, using various experimental design methods, analytical and spectroscopic techniques and methods and techniques for surface modification, doping, coating, hybridisation, conjugation, immobilisation, encapsulation, etc. The green synthesis of nanoparticles using plant extracts is a novel and emerging field that has great potential for future research and development.

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