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Green Synthesis of Nanoparticles for Biomedical Applications

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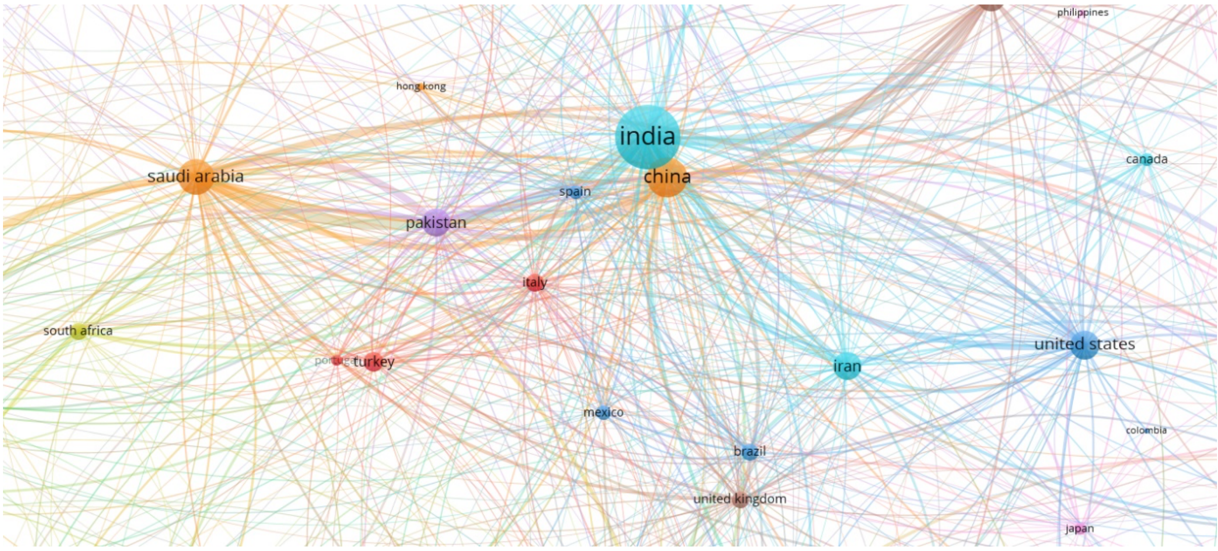

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Abstract: The development of eco-friendly and sustainable methods for nanoparticle synthesis has attained significant attention in recent years, particularly for biomedical applications. Green synthesis offers a promising alternative to conventional chemical and physical methods by utilizing biological systems such as plant extracts, bacteria, fungi, and algae as reducing and stabilizing agents. These biologically derived nanoparticles not only minimize environmental impact but also exhibit enhanced biocompatibility, making them ideal candidates for medical use. This review explores recent advancements in the green synthesis of metallic and metal oxide nanoparticles, focusing on their structural properties, synthesis mechanisms, and the role of various biological sources. Special emphasis is placed on their biomedical applications, including drug delivery, antimicrobial activity, and cancer therapy. The paper also discusses current challenges and future prospects in scaling up production and ensuring reproducibility while maintaining the green principles. Ultimately, green-synthesized nanoparticles represent a convergence of nanotechnology and sustainable science, holding great promise for safe and effective biomedical innovations.

1. Introduction

Nanotechnology is a rapidly growing field. It deals with materials at the nanoscale, usually between 1 and 100 nanometers. At this scale, matter shows unique physical, chemical, and biological properties. These properties make nanoparticles useful in medicine, electronics, energy, and environmental sciences (Salata, 2004). In medicine, nanoparticles are used for imaging, diagnostics, and therapy. Their small size and large surface area allow efficient interaction with biomolecules. Nanoparticles can be engineered to target specific cells or tissues. This feature makes them valuable in drug delivery and cancer therapy (Wang *et al.*, 2021).

Traditional methods of nanoparticle synthesis involve chemical and physical techniques. These include sol-gel, hydrothermal, chemical reduction, and laser ablation. Such methods often use toxic chemicals and require high energy. They can generate harmful by-products that may affect human health and the environment (Iravani, 2011; Aldwayyan *et al.,* 2013).

Green synthesis is emerging as a sustainable alternative. It uses biological sources such as plants, fungi, bacteria, and algae. These biological systems contain natural reducing agents. Examples are polyphenols, proteins, sugars, and alkaloids. These molecules help reduce metal ions into stable nanoparticles. They also act as capping agents that prevent aggregation (Mittal *et al.*, 2013). The green approach follows the principles of green chemistry. It aims to minimize hazardous substances, reduce energy consumption, and promote renewable resources. Green synthesis is low-cost and eco-friendly. It also produces biocompatible nanoparticles that are safer for biomedical use (Ahmed *et al.*, 2016). Nanoparticles synthesized by green methods show strong biomedical potential. Silver nanoparticles exhibit antimicrobial and antifungal activity. Gold nanoparticles are used in imaging and photothermal therapy. Zinc oxide nanoparticles are studied for wound healing and drug delivery. Plant-mediated synthesis of nanoparticles is especially attractive. It is simple, scalable, and does not require complex culture conditions as in microbes (Agarwal *et al.*, 2017). The biomedical relevance of green-synthesized nanoparticles is increasing. They have been tested in antimicrobial coatings, cancer therapeutics, and biosensors. Their stability and functional properties depend on the choice of biological source. Each plant or microbe provides different phytochemicals, leading to variations in particle size, shape, and activity (Iravani & Varma, 2019).

This review covers the field from basic concepts to advanced biomedical applications. It discusses conventional synthesis, the shift toward green methods, and the mechanisms involved. It also explores characterization, applications in medicine, toxicity issues, and future perspectives (Aaddouz *et al.*, 2024). The main aim of this review is to highlight how green synthesis can support sustainable nanomedicine.

Nanoparticles are materials with at least one dimension between 1 and 100 nanometers. At this scale, materials behave differently from their bulk forms. The high surface area to volume ratio is the main reason. It increases reactivity, surface energy, and binding capacity (Bhattacharyya *et al.*, 2012). Nanoparticles can be organic, inorganic, or hybrid. Organic nanoparticles include liposomes, micelles, and dendrimers. Inorganic nanoparticles include metals, metal oxides, and quantum dots. Hybrid nanoparticles combine features of both groups (Zhang *et al.*, 2016).

The unique features of nanoparticles make them attractive for biomedical use. They can cross biological barriers, such as cell membranes, and accumulate at specific sites. Their small size allows functionalization with ligands or drugs. Their optical, magnetic, and electrical properties are also useful in imaging and diagnostics (Gupta & Xie, 2018).

Bibliometric analysis for green synthesis of nanoparticles:

Bibliometrics is a way of using statistics to study research papers on a topic. It helps measure quality, spot important areas, and predicts future trends. Common indicators like publication numbers, citations, and h-index show how influential authors, institutions, or countries are. Databases like

Scopus collect most research articles and provide tools for tracking citations, collaborations, and affiliations. For deeper analysis, results can be used in software such as VOSviewer, CiteSpace, or Bibliometrix, which create maps and visualizations of research patterns, keywords, and trends. These tools make it easier to see how knowledge grows and changes over time (Bazzi *et al*., 2021; Byiringiro *et al*., 2025). The visualizations below highlight key countries involved in the green synthesis of nanoparticles, along with published documents and their types, subject areas, document sources, researchers, articles by country, author networks, and international collaboration networks (**Figures 1–9**). Detailed study indicated that over 40,000 articles were published on Scopus using "nanoparticles and biomedical", to be reduced at around 4750 articles when Green is associated to nanoparticles. At first glance, India is the profiled country with the most articles in this field (**Figure 1**). Number of articles over the years shows an exponential increase (**Figure 2**). **Figure 3** indicates that more than 98% of this production is research articles, reviews, book chapters and conference papers. The collected documents are distributed into Materials Sciences, Chemistry, Engineering, Chemical Engineering, Physics, Pharmacology and Medicine… (**Figure 4**).

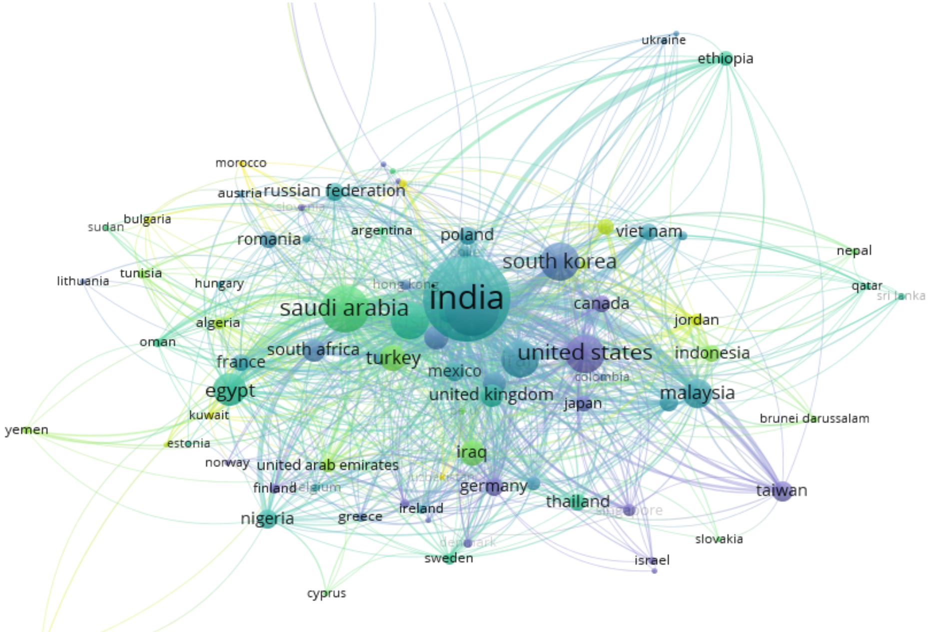

Figure 1: Bibliometric analysis coupling by country using VOS viewer

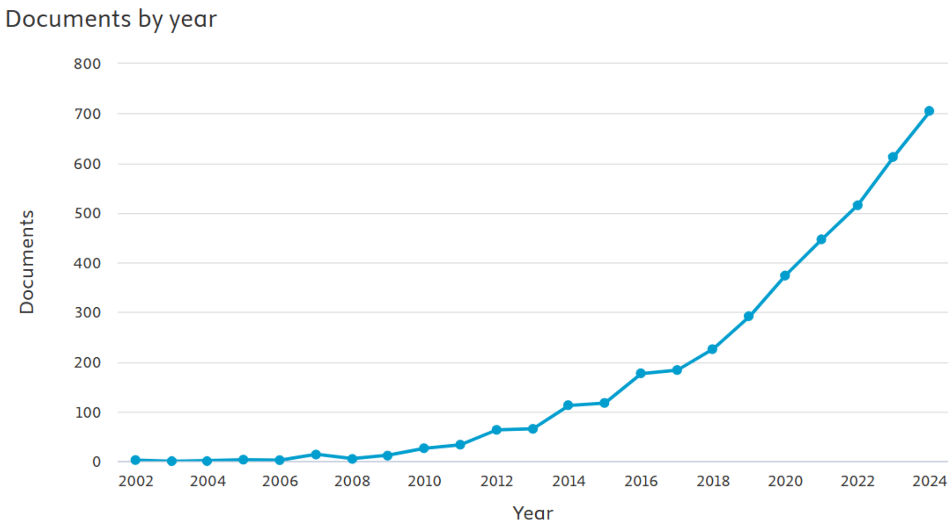

Figure 2: Number of published documents by the year

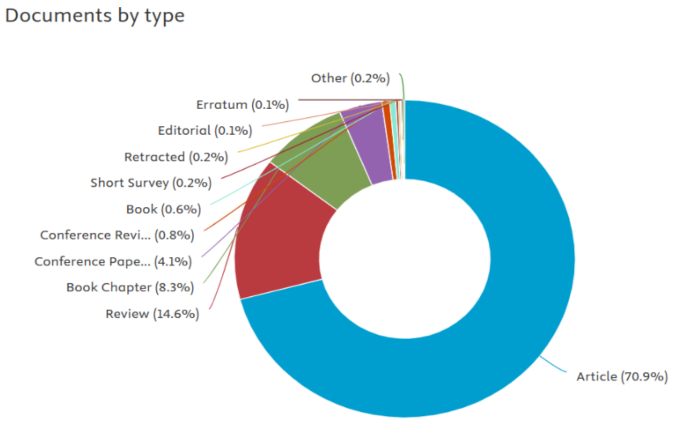

Figure 3: Summarized research documents by type from 2002-2024

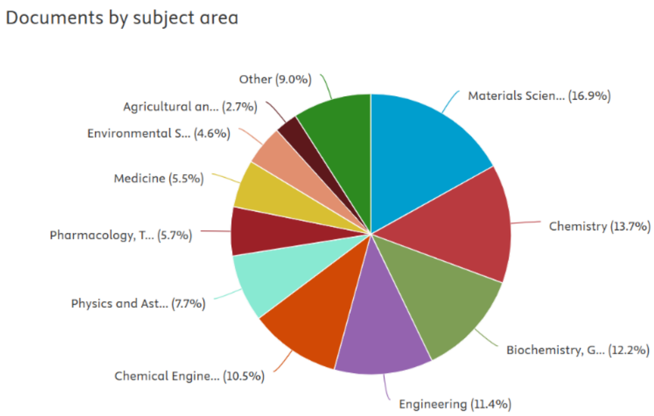

Figure 4: Summarized research documents by subject area around 2002-2024

In general, researchers prefer to publish their work in indexed journals having an important impact factor, as indicated in **Figure 5** (Hammouti *et al*., 2025). International Journal of Biological Macromolecules, an Elsevier journal reached an impact factor of 8.5 and Q1 at the first position followed by the International Journal of Nanomedicine published by Dove Medical Press (Q1, IF=6.5), the third one is Inorganic Chemistry Communications (Elsevier, Q1 and IF 5.4), Molecules, MDPI (Q1, IF=4.6) …

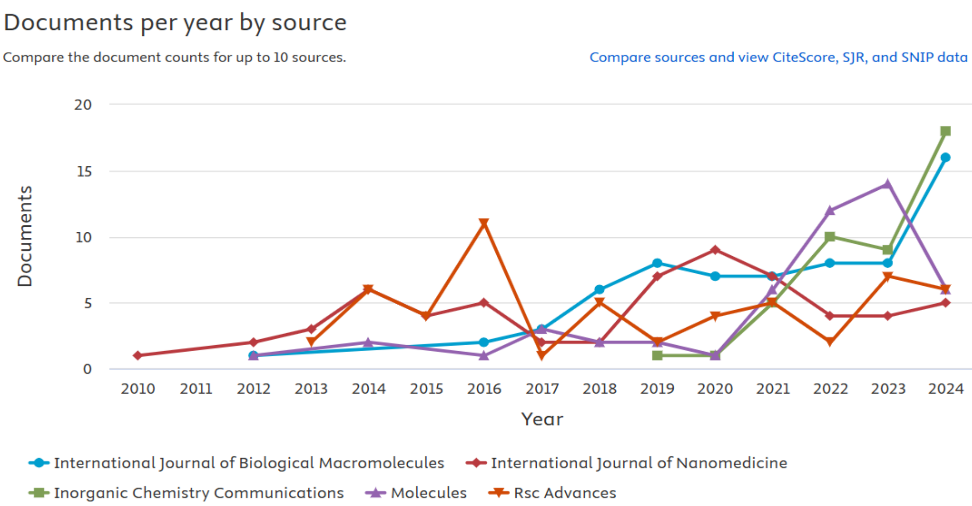

Figure 5: Documents per year (2010-2024) by source

The 4756 documents that were reviewed and authored by over 20,100 authors who are ranked by Scopus analysis (**Figure 6**) and visualized by VOS viewer (**Figure 7**). Rajeshkumar S. from India is the most published author followed by Patra J.K. VOS viewer also indicates the author's contribution by time **(**Aichouch *et al.*, 2025). Authors mentioned by yellow nodes have recent production, those with dark blue nodes around 2018 (**Figure 7**). The detailed productivity by country may be summarized in **Figure 8**. India reached more than 1500 papers, China 633 papers, Saudi Arabia 411 papers, … This finding is more visible at **Figure 9** showing India by the largest blue node, hiding that of China. Saudi Arabia by orange node and the US by dark blue node.

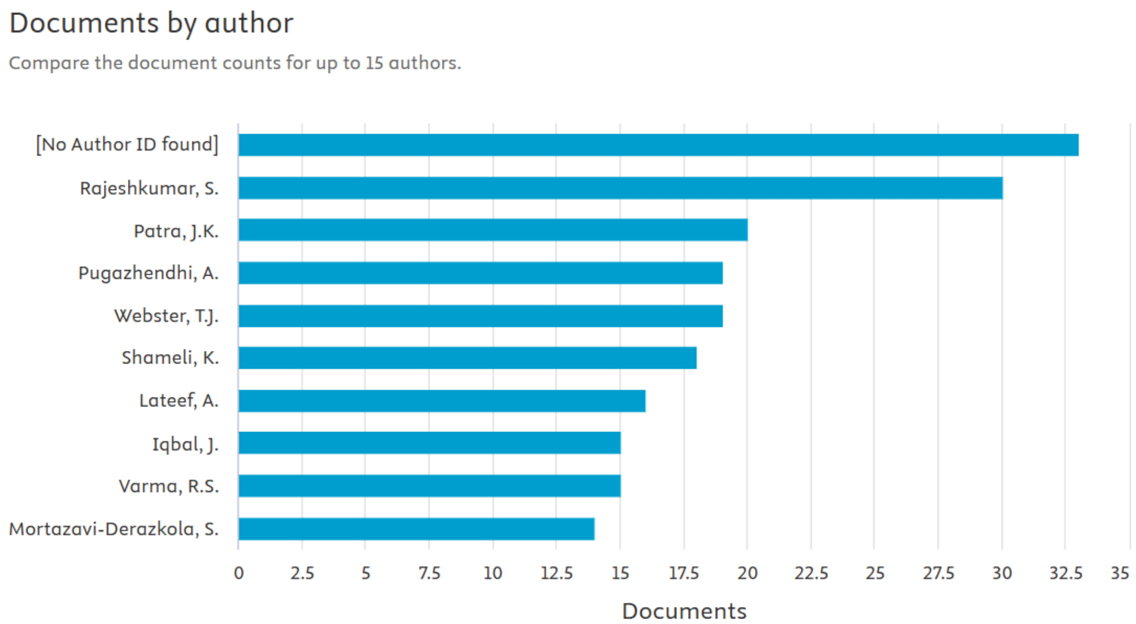

Figure 6: Top 10 researcher in green synthesis of nanoparticles

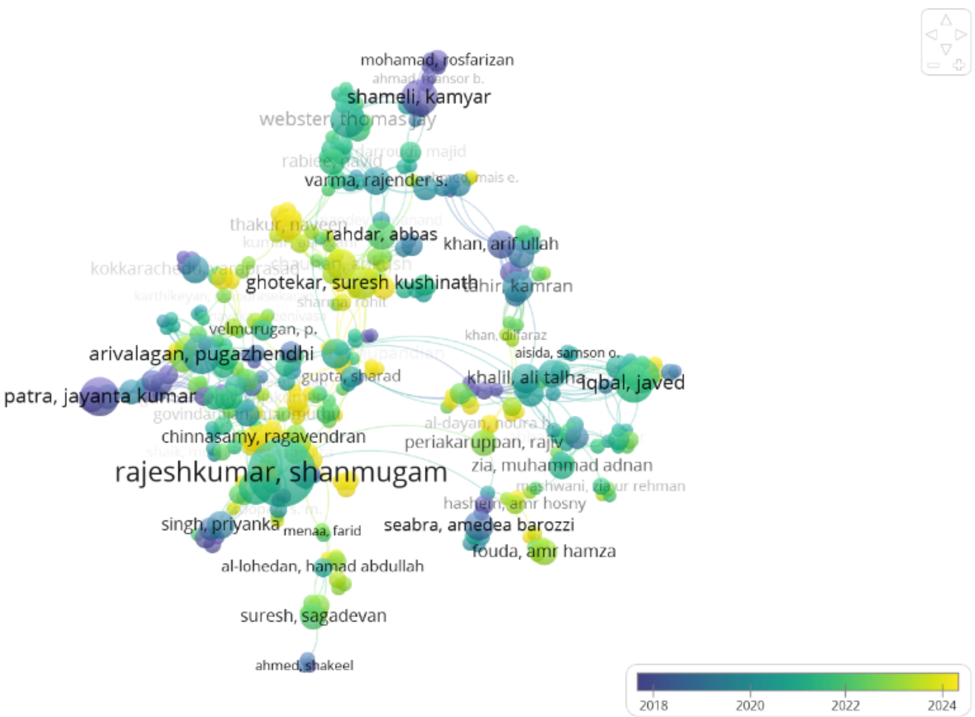

Figure 7: Network visualization on VOS viewer of nanoparticles green synthesis authors

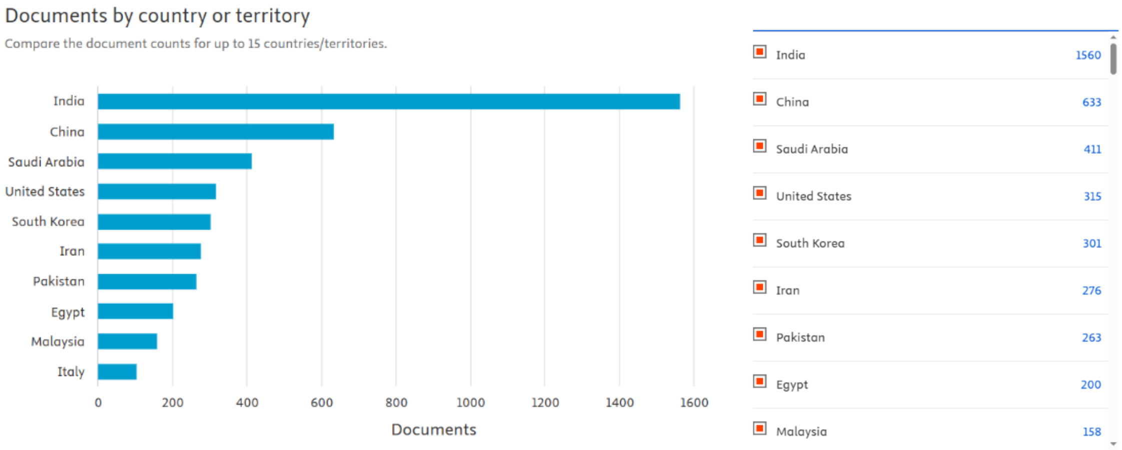

Figure 8: Distribution of published articles by countries on green synthesis of nanoparticles

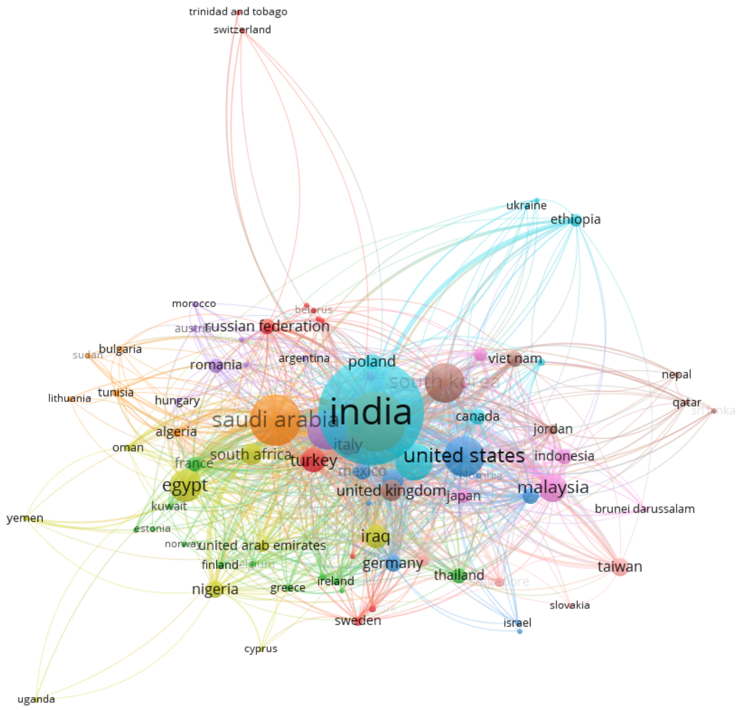

Figure 9: Network collaboration between the countries

2. Basics of nanoparticles

Nanoparticles are materials characterized by having at least one dimension in nanometer rang 1 and 100 nanometers. At this scale, materials behave differently from their bulk forms. High surface area to volume ratio is the main reason. It increases reactivity, surface energy, and binding capacity (Bhattacharyya *et al.*, 2012). Nanoparticles can be organic, inorganic, or hybrid. Organic nanoparticles include liposomes, micelles, and dendrimers. Inorganic nanoparticles include metals, metal oxides, and quantum dots. Hybrid nanoparticles combine features of both groups (Zhang *et al.*, 2016).

The unique features of nanoparticles make them attractive for biomedical use. They can cross biological barriers, such as cell membranes, and accumulate at specific sites. Their small size allows functionalization with ligands or drugs. Their optical, magnetic, and electrical properties are also useful in imaging and diagnostics (Gupta & Xie, 2018).

2.1 Conventional synthesis routes

Conventional nanoparticle synthesis uses chemical and physical techniques. These include sol-gel, hydrothermal, co-precipitation, chemical vapor deposition, and laser ablation. In chemical reduction, metal salts are reduced into nanoparticles using strong reducing agents such as sodium borohydride. Stabilizers are often added to prevent aggregation. In sol-gel method, nanoparticles are formed from precursors in a colloidal solution (Maarouf *et al.*, 2022). This is useful for oxides such as silica or titanium dioxide. Hydrothermal synthesis uses high pressure and temperature in aqueous systems to form nanoparticles with controlled size. Laser ablation and ball milling are physical methods. They rely on mechanical or energy-based breakdown of bulk materials (El-Nour *et al.*, 2010). These methods produce uniform nanoparticles but face challenges. The chemicals used can be toxic. The processes often require high energy, expensive equipment, and generate hazardous waste (Li *et al.*, 2018).

2.2 Drawbacks of conventional methods

Conventional methods for nanoparticle synthesis face several significant drawbacks that limit their practical applications, particularly in sensitive fields like biomedicine. One major concern is toxicity, as the use of hazardous reducing agents and organic solvents can leave harmful residues in the final product. These chemical processes also have a considerable environmental impact due to the large amounts of waste they generate. Additionally, physical synthesis techniques often require high energy inputs, involving extreme temperatures, pressures, or laser-based systems, which contribute to increased energy consumption. Scalability is another issue; while these methods may be effective at the laboratory scale, they are typically difficult and costly to implement on an industrial scale. Finally, biocompatibility is a critical limitation, as nanoparticles synthesized chemically may contain impurities or surface modifications that render them unsuitable or unsafe for biomedical use (Iravani, 2011). Because of these issues, researchers shifted toward green synthesis. It is cheaper, simpler, and safer. Biological systems produce nanoparticles under mild conditions. The resulting nanoparticles are often more biocompatible.

2.3 Properties of nanoparticles relevant to biomedicine

The properties of nanoparticles depend heavily on their size, shape, and surface chemistry. Smaller particles are more reactive and can penetrate tissues easily, making them useful in drug delivery and imaging. Different shapes (eg. spheres, rods, or stars) affect how they interact with cells. Surface modifications with biomolecules or polymers improve stability, targeting, and biocompatibility. Nanoparticles also have unique optical, magnetic, and electrical properties. For example, metal nanoparticles aid in imaging through surface plasmon resonance, magnetic ones can be guided for targeted therapy, and conductive particles are used in biosensors. (Jeevanandam *et al.*, 2018).

2.4 Importance of surface functionalization

Bare nanoparticles can be unstable. They may agglomerate or interact non-specifically with cells. To overcome this, surface modification is essential. Coating with polymers such as polyethylene glycol (PEG) improves stability. Ligands such as antibodies or peptides can be attached for targeting. Biocompatibility is also improved with surface modifications (Mahapatro & Singh, 2011).

2.5 Biomedical potential of nanoparticles

Nanoparticles are now part of diagnostics, imaging, and therapy. Lipid-based nanoparticles are used for vaccine delivery, as seen in mRNA COVID-19 vaccines. Gold nanoparticles are tested in photothermal therapy. Silver nanoparticles are explored as antimicrobials. Magnetic nanoparticles are investigated for imaging and hyperthermia in cancer treatment. However, toxicity remains a major concern. Small nanoparticles may cross the blood brain barrier. Metal based nanoparticles can generate reactive oxygen species. Careful assessment of safety is necessary before clinical translation (Mitragotri *et al.*, 2017).

3. Principles of green synthesis

Green synthesis is based on the principles of green chemistry. Green chemistry promotes safer solvents, renewable materials, and energy efficiency. It avoids hazardous chemicals and minimizes waste (Anastas & Warner, 1998). Nanoparticle synthesis usually requires three steps. These are reduction, nucleation, and stabilization. Green synthesis replaces harsh chemicals with natural reducing and stabilizing agents. Plants, microbes, and other biological systems provide these agents (Iravani, 2011).

3.1 Green chemistry principles applied

Green chemistry principles play a key role in sustainable nanoparticle synthesis. Waste prevention is prioritized by designing cleaner processes, while safer solvents like water or plant extracts replace toxic organics. Using renewable feedstocks such as plant or microbial sources reduces reliance on non-renewables. Reactions conducted at room temperature enhance energy efficiency, and the focus on reduced toxicity ensures safer nanoparticles for biomedical applications. Together, these strategies support eco-friendly and biocompatible nanomaterial production (Anastas & Eghbali, 2010). These principles ensure that the process is eco-friendly and cost-effective.

3.2 Biological systems in green synthesis

Biological systems offer a wide range of metabolites. These include alkaloids, flavonoids, terpenoids, sugars, and proteins. Such molecules reduce metal ions and cap nanoparticles to keep them stable (Mittal *et al.*, 2013). Biological systems are used in green synthesis of nanoparticles due to their natural reducing and stabilizing capabilities. Plants are commonly used, with extracts from leaves, roots, stems, and fruits providing phytochemicals that facilitate reduction and stabilization; these methods are simple and easily scalable. Bacteria can enzymatically reduce metal ions, allowing for both intracellular and extracellular nanoparticle synthesis. Fungi offer strong reducing metabolites and are capable of producing nanoparticles in greater quantities than bacteria. Algae, both marine and freshwater, contain pigments and polysaccharides that act as effective natural reducing agents. Each biological system offers advantages and limitations. Plants are fast and easy to use. Microbes require sterile conditions but offer more control. Fungi and algae can produce unique morphologies (Raghunandan *et al.*, 2011).

3.3 Mechanism

The mechanism depends on the biological source. In plants, phytochemicals such as flavonoids donate electrons to reduce metal ions. Polyphenols stabilize the nanoparticle surface by binding functional groups. Proteins and sugars may also control the shape and size of nanoparticles (Agarwal *et al.*, 2017). In microbes, enzymes play a role. For example, nitrate reductase in bacteria reduces silver ions into silver nanoparticles. Fungal extracellular metabolites can reduce gold or silver ions. Algal polysaccharides also act as reducing and capping agents (Singh *et al.*, 2016). Reaction conditions influence the process. Parameters such as pH, temperature, extract concentration, and metal ion concentration affect particle size, shape, and stability. Optimization of these factors is essential for reproducibility (Ahmed *et al.*, 2016).

3.4 Advantages of green synthesis

Green synthesis offers several advantages, including being eco friendly and non toxic, which reduces environmental and health risks. It is also low cost and energy efficient, often relying on simple aqueous processes. The nanoparticles produced are biocompatible, making them ideal for biomedical applications. Additionally, these methods are straightforward and have strong potential for scaling up production to meet larger demands. These benefits make green synthesis highly attractive compared to conventional methods.

3.5 Limitations of green synthesis

Despite advantages, green synthesis faces challenges. Variability in biological extracts is a major issue. Seasonal changes or environmental factors may alter phytochemical composition. This can affect reproducibility. Scale up is also not always straightforward. Microbial cultures need strict conditions. Plant extracts vary in concentration and stability. Controlling particle size distribution remains difficult (Patel *et al.*, 2015). Toxicity of green synthesized nanoparticles is not fully understood. Even if synthesis is natural, the nanoparticles may still show harmful effects depending on dose, exposure, and accumulation in tissues. More in vivo studies are needed before clinical translation.

3.6 Relevance to biomedical applications

Biomedical applications demand nanoparticles that are biocompatible, stable, and functional. Green synthesis aligns with these needs. The use of natural reducing agents increases the likelihood of compatibility with biological systems. This makes them attractive for drug delivery, imaging, and therapy. Nanoparticles synthesized by plants and microbes also provide functional surface groups. These groups can be used for further modification with drugs or ligands. The integration of green chemistry principles ensures that biomedical applications move toward sustainable nanomedicine (Iravani & Varma, 2019).

4. Types of nanoparticles in green synthesis

Green synthesis can produce different types of nanoparticles. These include metallic nanoparticles, metal oxide nanoparticles, and carbon-based nanoparticles. Each type has unique properties. They also have different biomedical applications (Mittal *et al.*, 2013).

4.1 Metallic nanoparticles

Metallic nanoparticles such as silver, gold, platinum, copper, and palladium are commonly synthesized through green methods. Silver nanoparticles (AgNPs) are the most extensively studied due to their strong antimicrobial and antifungal properties, often synthesized using plant extracts like neem, aloe vera, and green tea, and applied in wound healing, coatings, and antimicrobial agents (Ahmed *et al.*, 2016). Gold nanoparticles (AuNPs) are valued for their biocompatibility and stability, with uses in imaging, photothermal therapy, and biosensing; their green synthesis involves fruit extracts, spices, and fungi, with unique optical properties arising from surface plasmon resonance (Dykman & Khlebtsov, 2012). Platinum nanoparticles (PtNPs) exhibit catalytic and antioxidant activities and are studied for anticancer and neuroprotective applications, with fungi and bacteria serving as efficient synthesis agents (Sankar *et al.*, 2014). Copper nanoparticles (CuNPs) offer antimicrobial effects and are more cost-effective than silver, produced using plants and microorganisms, although their stability and oxidation remain challenges (Rai *et al.*, 2014). Lastly, palladium nanoparticles (PdNPs) are being explored for catalytic and biomedical applications, synthesized through leaf extracts and microbial cultures, with ongoing research into their biomedical potential (Narayanan & Sakthivel, 2011).

4.2 Metal-oxide nanoparticles

Metal oxide nanoparticles synthesized via green methods have gained attention for their diverse biomedical and technological applications. Zinc oxide nanoparticles (ZnO NPs) exhibit strong antimicrobial, antioxidant, and wound healing properties, often synthesized using plant extracts like aloe vera, hibiscus, and neem. They are also being explored for anticancer potential (Agarwal *et al.*, 2017). Titanium dioxide nanoparticles (TiO_2 NPs) are widely used in photocatalysis, drug delivery, and biomedical coatings, with green synthesis achieved through algae, fungi, and plant extracts (Sharma *et al.*, 2019). Iron oxide nanoparticles (Fe_3O_4 NPs) are magnetic and can be directed by external magnetic fields, making them valuable in imaging, targeted therapy, hyperthermia, and biosensing. Green synthesis typically involves plant or bacterial systems. Additionally, magnesium oxide (MgO NPs) and nickel oxide nanoparticles (NiO NPs) are produced through eco-friendly routes and are noted for their antimicrobial and catalytic activities, although their medical applications are less extensively studied (Wu *et al.*, 2015).

4.3 Carbon based nanoparticles

Carbon-based nanomaterials such as carbon quantum dots (CQDs), graphene, and carbon nanotubes (CNTs) are increasingly explored for biomedical applications due to their unique physicochemical properties. CQDs are small, fluorescent, and biocompatible nanoparticles synthesized through green methods using sources like fruit juices, honey, and biomass. They are widely used in imaging, drug delivery, and biosensing (Iravani & Varma, 2019). Graphene oxide (GO) and reduced graphene oxide (rGO) can be produced using plant-derived polyphenols, offering high surface area and conductivity ideal for tissue engineering and biosensor applications (Chung *et al.*, 2013). Carbon nanotubes, though highly versatile and useful in biosensing and targeted drug delivery, raise concerns regarding biocompatibility and toxicity. Nonetheless, green functionalization methods have been developed to improve their safety and applicability in biomedical fields (Heister *et al.*, 2012).

4.4 Hybrid nanoparticles

Green synthesis can also produce hybrid nanoparticles. These combine metals with polymers, oxides, or carbon. For example, silver graphene hybrids show strong antimicrobial activity. Gold–polymer hybrids are tested for drug delivery. Hybrid nanoparticles benefit from multifunctionality (Rajeshkumar & Naik, 2018).

4.5 Comparative features

Each type of nanoparticle offers distinct advantages and limitations that influence their suitability for biomedical applications. Metallic nanoparticles are highly effective as antimicrobials but can exhibit toxicity at elevated concentrations. Metal oxide nanoparticles provide good stability along with magnetic or photocatalytic properties, making them useful in imaging and drug delivery. Carbon-based nanoparticles, such as carbon quantum dots and graphene, show great potential in imaging and biosensing due to their conductivity and biocompatibility, though their long-term toxicity still requires thorough evaluation. Hybrid nanoparticles, which combine different materials, offer multifunctionality and enhanced performance for advanced biomedical applications. Ultimately, the selection of nanoparticle type depends on the specific requirements of the intended biomedical use (Sharma *et al.*, 2019; Heister *et al.*, 2012).

5. Mechanisms of green synthesis

The mechanism of green synthesis is complex. It depends on the type of biological system used. Plants, microbes, fungi, and algae all contain molecules that act as reducing and stabilizing agents. These molecules donate electrons to metal ions. This reduces ions to nanoparticles. Other molecules bind to the nanoparticle surface and stabilize them (Ahmed *et al.*, 2016).

5.1 General steps

Green synthesis of nanoparticles typically involves three main steps. First is activation, where biological molecules act as reducing agents, converting metal ions like Ag^{+}, Au^{3+}, or Zn^{2+} into their neutral atomic form. This is followed by nucleation, during which these reduced atoms aggregate to form initial nanoparticle seeds. Finally, in the growth and stabilization phase, the nuclei grow into well-defined nanoparticles, while biomolecules cap their surface to prevent aggregation and ensure stability. The final size and shape of the nanoparticles are largely determined by the balance between nucleation and growth, while effective stabilization by biomolecules is essential for achieving monodispersity (Mittal *et al.*, 2013).

5.2 Role of phytochemicals in plants

Plants are the most extensively studied source for the green synthesis of nanoparticles due to their rich content of bioactive compounds. Plant extracts contain flavonoids, phenols, alkaloids, terpenoids, proteins, and sugars, each playing a specific role in nanoparticle formation. Flavonoids and phenols act as reducing agents by donating electrons to metal ions. Terpenoids and alkaloids help stabilize the nanoparticles by binding to their surface through functional groups, while proteins and polysaccharides serve as capping agents, controlling nanoparticle size and preventing aggregation. The concentration of phytochemicals significantly influences the synthesis process, higher polyphenol content, for instance, promotes faster reduction. Moreover, different plant species yield nanoparticles with varied sizes, shapes, and morphologies, making plant selection a critical factor in tailoring nanoparticle properties (Agarwal *et al.*, 2017).

5.3 Role of enzymes in microbes

Bacteria and fungi are effective biological agents for green nanoparticle synthesis due to their ability to produce enzymes that reduce metal ions. In bacteria, enzymes such as nitrate reductase play a central role in reducing silver and gold ions. Fungi contribute through extracellular enzymes and metabolites, which not only reduce metal ions but also stabilize the resulting nanoparticles. Similarly, yeast cells generate proteins and peptides that function as natural capping agents, aiding in nanoparticle stability. Microbial synthesis can be intracellular, where metal ions are taken up and reduced within the cells, or extracellular, where secreted enzymes act outside the cells. Among these, extracellular synthesis is more practical for large-scale production, as it simplifies downstream processing and recovery of nanoparticles (Singh *et al.*, 2016).

5.4 Role of algal metabolites

Algae contain pigments such as chlorophyll, carotenoids, and phycobiliproteins. These molecules act as reducing agents. Algal polysaccharides cap nanoparticles and improve stability. Marine algae are rich in sulfated polysaccharides, which are effective stabilizers (Raghunandan *et al.*, 2011; Ouahabi *et al.*, 2023).

5.5 Influence of reaction conditions

Reaction conditions play a critical role in determining the efficiency and characteristics of green nanoparticle synthesis. The pH value significantly affects the reduction rate and particle size and higher pH levels typically lead to faster reduction and the formation of smaller nanoparticles. Temperature also influences the reaction kinetics; while increased temperatures can speed up the synthesis, they may also promote aggregation, reducing nanoparticle stability. The concentration of plant extracts or microbial enzymes is another key factor; higher concentrations provide more reducing and stabilizing agents, resulting in quicker reduction and smaller, more uniform particles. Conversely, high metal ion concentrations can lead to the formation of larger nanoparticles or polydispersity, which may compromise consistency. Therefore, optimization and control of these parameters are essential to ensure reproducibility and the production of uniform nanoparticles with consistent biomedical properties (Patel *et al.*, 2015).

5.6 Stabilization mechanisms

Stabilization prevents agglomeration. Biomolecules bind nanoparticles through hydroxyl, carbonyl, carboxyl, or amine groups. Electrostatic repulsion and steric hindrance both help maintain dispersion. Surface capping also improves biocompatibility. Functional groups can later be used for drug conjugation or targeting ligands (Mahapatro & Singh, 2011).

5.7 Examples of reported mechanisms

Several case studies highlight the mechanisms involved in green nanoparticle synthesis using different biological sources. Silver nanoparticles (AgNPs) Silver nanoparticles (AgNPs) synthesized from green tea extract are reduced by catechins and stabilized by polyphenols, which prevent aggregation. Gold nanoparticles (AuNPs) produced using neem leaf extract are reduced by terpenoids and capped by proteins, ensuring stability and biocompatibility. Iron oxide nanoparticles (Fe3O4 NPs) synthesized from bacterial cultures utilizes the enzyme nitrate reductase for metal ion reduction. In the case of zinc oxide nanoparticles (ZnO NPs), aloe vera extract provides anthraquinones that reduce Zn^{2+} ions, leading to nanoparticle formation. These examples demonstrate how specific biomolecules from various biological sources drive both reduction and stabilization during green synthesis (Ahmed *et al.*, 2016).

5.8 Challenges in mechanistic understanding

Despite progress, the exact mechanisms are not fully understood. Biological extracts are complex. They contain many molecules, each with different roles. Identifying the main reducing and stabilizing agents is difficult. Standardization of extracts is lacking. More advanced analytical studies are needed to clarify pathways (Iravani, 2011).

6. Characterization of green nanoparticles

Characterization is essential for understanding nanoparticles. It confirms their formation, structure, size, and stability. It also provides insight into surface chemistry and functional groups. Without proper characterization, biomedical applications cannot be evaluated (Verma & Mehata, 2016).

6.1 Importance of characterization

Nanoparticles show different properties than bulk materials. Their small size and high surface area lead to unique optical, magnetic, and catalytic behaviors. These properties must be measured. In green synthesis, biomolecules play dual roles as reducing and capping agents. Characterization helps identify these molecules. It also verifies reproducibility of synthesis (Iravani, 2011).

6.2 Spectroscopic methods

UV–Visible spectroscopy: This is the simplest tool to monitor synthesis. Metal nanoparticles show surface plasmon resonance (SPR). For silver nanoparticles, SPR appears at 400–450 nm. Gold nanoparticles show bands at 500-550 nm. The peak position shifts with particle size and shape (Jain *et al.*, 2008).

Fourier transform infrared spectroscopy (FTIR): FTIR detects functional groups on nanoparticle surfaces. Biomolecules such as proteins, phenols, and flavonoids produce characteristic peaks. Shifts in OH, C=O, and NH bands confirm their binding to nanoparticles (Agarwal *et al.*, 2017).

X-ray diffraction (XRD): XRD confirms crystal structure. It shows characteristic diffraction peaks corresponding to metallic or oxide phases. The Debye–Scherrer equation allows calculation of crystallite size. Sharp peaks indicate high crystallinity (Dhanalakshmi *et al.*, 2018).

6.3 Microscopic methods

Transmission electron microscopy (TEM): TEM gives direct images of nanoparticles. It provides information on size, shape, and distribution. High-resolution TEM can also show lattice fringes, indicating crystallinity.

Scanning electron microscopy (SEM): SEM gives surface morphology. It is useful for larger particles. Coupled with energy-dispersive X-ray spectroscopy (EDX), SEM can confirm elemental composition.

Atomic force microscopy (AFM): AFM provides 3D surface profiles at nanoscale resolution. It can measure height, roughness, and aggregation. AFM is useful for analyzing thin films of nanoparticles (Kora & Arunachalam, 2011).

6.4 Other analytical methods

Dynamic light scattering (DLS): DLS measures hydrodynamic size in suspension. It gives average diameter and polydispersity index (PDI). It also provides zeta potential, an indicator of surface charge and stability (Bhattacharjee, 2016).

Thermo gravimetric analysis (TGA): TGA determines thermal stability. Weight loss patterns reveal the presence of organic capping molecules.

X-ray photoelectron spectroscopy (XPS): XPS gives information on oxidation states of elements. It also reveals chemical bonding at the nanoparticle surface (Sastry *et al.*, 2003).

Raman spectroscopy: Raman detects vibrational modes of surface molecules. It is complementary to FTIR (Agarwal *et al.*, 2017).

6.5 Typical characterization workflow

A comprehensive characterization of green-synthesized nanoparticles requires multiple analytical techniques to ensure accuracy and reliability. For example, silver nanoparticles synthesized from neem extract can be analyzed using UV–Vis spectroscopy to confirm the surface plasmon resonance (SPR), indicating nanoparticle formation. Fourier-transform infrared spectroscopy (FTIR) helps identify functional groups involved in capping and stabilization. X-ray diffraction (XRD) reveals the crystalline structure of the nanoparticles. Transmission electron microscopy (TEM) provides detailed information on particle size and morphology, while dynamic light scattering (DLS) assesses size distribution and colloidal stability in suspension. Additionally, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM–EDX) confirms elemental composition, verifying the presence of silver. Using this combination of techniques ensures a thorough understanding of the nanoparticles' physical, chemical, and structural properties (Mittal *et al.*, 2013).

6.6 Significance for biomedical applications

Biomedical applications require detailed knowledge of nanoparticle properties. Small nanoparticles (<50 nm) are better for cellular uptake. Surface charge affects interactions with membranes. Biocompatible coatings reduce toxicity. Characterization ensures that nanoparticles meet these criteria before testing in vitro or in vivo (Mahapatro & Singh, 2011).

6.7 Limitations and challenges

Characterization of green nanoparticles is challenging. Extracts contain many biomolecules, making identification of capping agents difficult. Variability in plant or microbial extracts leads to batch-to-batch differences. Advanced tools such as nuclear magnetic resonance (NMR) and mass spectrometry can provide deeper insights but are less commonly used in routine studies (Iravani, 2011).

7. Biomedical applications of green nanoparticles

Green-synthesized nanoparticles have attracted much interest in medicine. Their eco-friendly preparation makes them safer for clinical translation. Biological molecules on their surface often improve compatibility with living systems. The small size allows interaction with cells, biomolecules, and tissues. Several biomedical uses have been explored, from infection control to cancer therapy (Iravani, 2011).

7.1 Antimicrobial activity

Nanoparticles synthesized through green methods show strong antimicrobial effects. Silver nanoparticles (AgNPs) are the most studied. They disrupt bacterial membranes, generate reactive oxygen species (ROS), and bind to proteins and DNA. This leads to cell death (Rai *et al.*, 2012).

- Plant-mediated AgNPs inhibit both Gram-positive and Gram-negative bacteria. For example, neem and aloe extracts produce AgNPs effective against Staphylococcus aureus and Escherichia coli.
- Gold nanoparticles (AuNPs) also show antibacterial activity, though weaker than AgNPs.
- Zinc oxide nanoparticles (ZnO NPs) synthesized using plants display antifungal activity. They damage fungal cell walls and alter membrane permeability.
- Biologically synthesized nanoparticles also act against multidrug-resistant strains. Their multi-target mechanism reduces resistance development (Sirelkhatim *et al.*, 2015).

7.2 Antiviral potential

Green nanoparticles also show antiviral effects. AgNPs block viral entry and replication. They bind to viral glycoproteins and prevent attachment to host cells. Studies report inhibition of HIV, influenza, and hepatitis viruses. Gold nanoparticles functionalized with biomolecules also interfere with viral fusion. Plant-based ZnO NPs show activity against herpes simplex virus. These results suggest promise in designing broad-spectrum antiviral agents (Lara *et al.*, 2010).

7.3 Anticancer applications

Nanoparticles synthesized via green methods have demonstrated significant cytotoxic effects against cancer cells, largely due to their small size, which enables efficient penetration into tumor tissues. The surface-bound biomolecules from plant or microbial extracts enhance selective uptake by cancer cells, improving therapeutic targeting. Their anticancer mechanisms include the induction of oxidative stress, leading to apoptosis, DNA damage through reactive oxygen species (ROS) generation, and disruption of mitochondrial function. For instance, silver nanoparticles (AgNPs) synthesized from green tea extract have shown cytotoxicity against breast and lung cancer cells, while gold nanoparticles (AuNPs) from neem extract inhibited the proliferation of cervical cancer cells. Similarly, zinc oxide nanoparticles (ZnO NPs) derived from aloe vera extract induced apoptosis in liver cancer cells. Importantly, these green-synthesized nanoparticles often exhibit lower toxicity toward normal cells, making them more biocompatible than their chemically synthesized counterparts and promising candidates for cancer therapy (Ali *et al.*, 2016).

7.4 Drug delivery systems

Green nanoparticles can act as carriers for drugs. Their surfaces can be functionalized with therapeutic molecules. Plant-based capping agents improve stability and reduce toxicity. Gold nanoparticles are widely studied for drug delivery. They can transport anticancer drugs like doxorubicin. Magnetic iron oxide nanoparticles are used for targeted delivery under external magnetic fields. Polysaccharide-capped nanoparticles improve circulation and bioavailability. Green synthesis ensures that the drug carriers themselves are non-toxic and eco-friendly (Mahapatro & Singh, 2011).

7.5 Imaging and diagnostics

Nanoparticles possess unique optical properties that make them highly valuable for imaging and diagnostic applications. Gold nanoparticles (AuNPs), for example, exhibit surface plasmon resonance (SPR), which significantly enhances contrast in optical imaging. Green-synthesized AuNPs are widely used in colorimetric biosensors for detecting biomolecules like glucose, cholesterol, and DNA. Similarly, silver and iron oxide nanoparticles function as probes in various diagnostic assays. Notably, magnetic nanoparticles produced by microbial synthesis improve contrast in magnetic resonance imaging (MRI), enhancing diagnostic. Additionally, plant-based carbon nanoparticles have been explored as fluorescent probes due to their strong photoluminescence. The presence of biological capping agents derived from green synthesis improves nanoparticle solubility and stability in physiological environments, making these nanomaterials especially practical and effective for biomedical diagnostics accuracy (Laurent *et al.*, 2008).

7.6 Tissue engineering and regenerative medicine

Nanoparticles support tissue regeneration. Green-synthesized ZnO and hydroxyapatite nanoparticles promote bone cell growth. AgNPs incorporated into wound dressings accelerate healing due to antimicrobial action. Biocompatible nanoparticles are also integrated into scaffolds for cartilage and skin engineering. Their controlled release of growth factors helps in tissue repair (Choudhury *et al.*, 2013).

7.7 Antioxidant and anti-inflammatory effects

Phytochemical-coated nanoparticles retain bioactive compounds from plants. These compounds provide antioxidant and anti-inflammatory activities. Such nanoparticles reduce oxidative stress in cells. They also modulate cytokine release, making them useful in inflammatory diseases (Ahmed *et al.*, 2016).

7.8 Examples of in-vivo studies

Animal studies have provided strong evidence supporting the biomedical potential of green-synthesized nanoparticles. For instance, silver nanoparticles (AgNPs) produced using garlic extract significantly accelerated wound closure in rat models, highlighting their wound healing capabilities. Similarly, gold nanoparticles (AuNPs) synthesized from turmeric extract demonstrated the ability to reduce tumor growth in mice, showcasing their anticancer potential. Additionally, zinc oxide nanoparticles (ZnO NPs) derived from various plant extracts have been shown to enhance bone healing in rabbits, indicating their promise in regenerative medicine. These in vivo results reinforce the therapeutic value and biocompatibility of nanoparticles synthesized via green methods. (Agarwal *et al.*, 2017). These studies highlight translational promise, though clinical trials are still limited.

7.9 Limitations in biomedical applications

Despite positive results, challenges remain. Variability in nanoparticle size and composition affects reproducibility. Long-term safety is not fully understood. Clinical data are lacking. Standardization of synthesis and characterization is essential before large-scale biomedical use (Patra & Baek, 2014).

8. Toxicity and safety aspects

Nanoparticles hold great biomedical potential, but safety remains a major concern. Green synthesis is assumed to improve biocompatibility. Plant and microbial capping agents reduce chemical residues. However, nanoparticles can still interact with biological systems in harmful ways. Understanding toxicity is essential for clinical applications (Patra & Baek, 2014).

8.1 General toxicity concerns

Nanoparticles can enter cells and tissues due to their small size. They may cross biological barriers like the blood-brain barrier. Their large surface area increases reactivity. These properties can cause oxidative stress, inflammation, and DNA damage (Nel *et al.*, 2006). Even green synthesized nanoparticles can generate reactive oxygen species (ROS). At high doses, they may alter cell function and trigger apoptosis. Toxicity depends on size, shape, surface charge, and coating molecules (Arora *et al.*, 2012).

8.2 In-vitro toxicity

Cell culture studies are essential for evaluating the safety and therapeutic potential of green-synthesized nanoparticles, with common assays including the MTT assay, lactate dehydrogenase (LDH) release, and flow cytometry to assess viability, membrane integrity, and apoptosis. Silver nanoparticles (AgNPs) synthesized via plant extracts often exhibit dose-dependent cytotoxicity, typically showing greater toxicity toward cancer cells than normal cells, which is advantageous for anticancer therapy (Gurunathan *et al.*, 2015). Gold nanoparticles (AuNPs) are generally considered biocompatible, but their toxicity can vary depending on surface ligands; capping with biomolecules usually reduces adverse effects. Meanwhile, zinc oxide nanoparticles (ZnO NPs) can release Zn^{2+} ions that generate reactive oxygen species (ROS), contributing to cytotoxicity. Aloe-mediated ZnO NPs, for example, showed cytotoxic effects at higher concentrations (Sirelkhatim *et al.*, 2015), emphasizing the need for dose optimization in biomedical applications.

8.3 In-vivo toxicity

Animal studies offer valuable insights into the biodistribution and potential organ toxicity of nanoparticles. Typically, nanoparticles tend to accumulate in the liver and kidneys, where high doses can disrupt enzyme levels and cause histological changes. Some nanoparticles have the ability to cross the blood–brain barrier, raising concerns about possible neurotoxicity. Additionally, nanoparticles may interact with the immune system, potentially activating immune cells and triggering inflammation. Importantly, research suggests that nanoparticles capped with green, biologically derived agents tend to pose fewer risks in these areas compared to their chemically synthesized counterparts, likely due to improved biocompatibility and reduced toxicity (Patil *et al.*, 2016).

8.4 Factors affecting toxicity

Nanoparticle toxicity depends on several factors. Smaller particles (under 10 nm) can enter cell nuclei and mitochondria, raising genotoxic risks. Shape matters too rod and wire like particles tend to be more toxic than spherical ones. Surface charge influences safety, with neutral or negatively charged particles generally less harmful than positively charged ones. Higher doses and longer exposure increase toxicity, while the administration route (inhalation, ingestion, injection) affects how nanoparticles distribute in the body. Considering these factors is crucial for designing safer nanoparticles for biomedical use (Elsaesser & Howard, 2012).

8.5 Strategies to reduce toxicity

Surface functionalization, such as coating nanoparticles with polysaccharides, proteins, or polyethylene glycol (PEG), enhances their safety by reducing toxicity and improving biocompatibility. Encapsulating nanoparticles within biopolymers allows for controlled release, minimizing sudden ion release that can cause damage. Optimizing the dose to use the minimal effective amount helps lower side effects, while standardizing synthesis methods to produce consistent particle size and shape improves the predictability of toxicity and therapeutic outcomes. These strategies are essential for developing safer and more effective nano materials for biomedical applications (Arora *et al.*, 2012).

8.6 Risk assessment and regulation

Currently, there are no universal regulations for nano particle based medicine. Regulatory agencies demand thorough preclinical testing. Toxicity must be evaluated at cellular, tissue, and systemic levels. Long-term studies are essential. Standard protocols for green nano particles are still lacking (Krug, 2014).

8.7 Knowledge gaps

Although green synthesis reduces risks, it does not eliminate them. Many studies focus only on short-term toxicity. Few evaluate chronic exposure or reproductive effects. Mechanisms of toxicity are not fully understood. More in vivo studies and clinical trials are needed before medical approval (Fadeel & Garcia-Bennett, 2010).

9. Challenges and limitations

Green synthesis of nanoparticles has gained wide interest. It offers an eco-friendly alternative to physical and chemical methods. Despite progress, several challenges limit translation into biomedical applications. These include reproducibility, scalability, stability, and regulatory issues. Addressing these limitations is essential for clinical success.

9.1 Reproducibility issues

One of the biggest challenges is reproducibility. Plant extracts contain diverse metabolites such as alkaloids, flavonoids, terpenoids, and phenols. Their concentrations vary with species, season, age, and extraction methods (Ahmed *et al.*, 2020). This variation affects nanoparticle size, shape, and activity. Even small changes in synthesis conditions may lead to inconsistent results. Standardization of biomaterials is lacking. Few studies provide detailed chemical profiles of the plant or microbial sources used. This makes it difficult to reproduce findings across laboratories (Khan *et al.*, 2023).

9.2 Scalability

Scaling green synthesis from laboratory to industrial production is complex. Plant-based synthesis is usually performed in small batches. Large-scale production requires stable supply of biomass and optimization of reaction conditions (Nasrollahzadeh *et al.*, 2019). Microbial synthesis faces additional problems. Cultivation, contamination control, and maintaining consistent metabolic activity require specialized facilities (Rai *et al.*, 2021). Continuous flow systems and bioreactors are being explored to address scalability. However, few commercial processes exist for biomedical grade nanoparticles (Mahapatra *et al.*, 2023).

9.3 Stability and storage

Nanoparticles often face aggregation during storage. Capping with biomolecules provides some stability, but long-term data are limited. Oxidation, ion release, and surface changes may reduce biomedical effectiveness (Aljabali *et al.*, 2022). Stability studies under physiological conditions are also limited. Nanoparticles may behave differently in blood plasma compared to water-based buffers. Protein corona formation can alter functionality and toxicity (Saptarshi *et al.*, 2013).

9.4 Lack of mechanistic understanding

Although many studies demonstrate biological activity, mechanisms remain unclear. For example, anticancer properties of silver nanoparticles are often reported. But detailed pathways of apoptosis or ROS generation are not well defined. This makes it difficult to optimize design for targeted therapy (Iqbal *et al.*, 2022).

9.5 Toxicity and biosafety uncertainty

As discussed in "toxicity and safety aspects", green synthesis may reduce but does not eliminate toxicity. Lack of long-term in vivo studies is a barrier. Many reports focus on in vitro cytotoxicity. There are very few advances to preclinical animal models or clinical evaluation. Dose optimization, biodistribution, and clearance mechanisms are often poorly understood. Regulatory agencies require detailed toxicological data before approval. This gap slows translation into medical practice (Singh *et al.*, 2021).

9.6 Regulatory barriers

Regulation of nanomaterials for biomedical use is still evolving. Agencies such as the FDA and EMA require data on synthesis, reproducibility, stability, and safety. Lack of standardized testing protocols delays approval. Green synthesis is particularly challenging to regulate. Plant or microbial extracts are complex mixtures, making it hard to identify active capping agents. Without chemical standardization, regulatory acceptance is limited (Murthy *et al.*, 2022).

9.7 Intellectual property issues

Patentability of green nanoparticles is another concern. Many natural extracts are traditional or widely used. This makes intellectual property protection difficult. As a result, companies may hesitate to invest in commercialization (Rautela *et al.*, 2019).

9.8 Economic and market challenges

The cost of biomass collection, extraction, and quality control may be higher than expected. Traditional chemical synthesis, though less eco-friendly, is often cheaper and more predictable. For biomedical applications, additional costs include sterilization, GMP compliance, and toxicology studies (Iravani *et al.*, 2022).

9.9 Knowledge gaps

Despite promising results, the clinical translation of green-synthesized nanoparticles faces several challenges. There are limited clinical trials evaluating their safety and efficacy. Comparative studies between green and chemically synthesized nanoparticles under standardized conditions are scarce, making it difficult to directly assess advantages. Additionally, the interactions between nanoparticles and proteins in vivo remain poorly understood, hindering predictions of biological behavior. Data on long-term stability and degradation of these nanoparticles are also insufficient. Finally, the lack of harmonized global regulations complicates their development and approval for biomedical use. Addressing these gaps is crucial for advancing green nanotechnology into clinical practice.

10. Future perspectives

Green synthesis of nanoparticles has already established itself as an eco-friendly and biocompatible strategy. However, future progress requires addressing reproducibility, scalability, and clinical translation challenges. Advancements in material science, biotechnology, and artificial intelligence (AI) are expected to redefine the biomedical applications of these nanoparticles.

10.1 Personalized nanomedicine

The future of biomedical applications lies in personalization. Green-synthesized nanoparticles can be tailored with plant or microbial metabolites for specific therapeutic needs. Their biocompatibility and functionalization capacity make them suitable for individualized drug delivery (Barani et al., 2021). Omics technologies (genomics, proteomics, metabolomics) may help select plant or microbial sources with the best phytochemicals for targeted synthesis. Such approaches could create patient-specific nanomedicines with improved safety profiles (Chauhan *et al.*, 2023).

10.2 Integration with artificial intelligence and machine learning

AI and machine learning are becoming powerful tools for nanotechnology. They can predict nanoparticle size, shape, stability, and biological effects based on synthesis conditions. For green synthesis, AI could analyze phytochemical data and optimize extraction and reaction parameters (Suresh *et al.*, 2023). Deep learning models may also be used to predict nanoparticle protein interactions and toxicity. This reduces the need for repeated in vitro and in vivo testing. Combining AI with green chemistry can accelerate discovery and reduce costs (Chen *et al.*, 2024).

10.3 Nanorobotics and smart drug delivery

Green-synthesized nanoparticles can be integrated into nanorobotic systems. Magnetic and enzymatic nanoparticles derived from green routes may function as micro- and nanorobots for precision therapy. In cancer treatment, such systems could deliver drugs to tumor sites while minimizing side effects (Shen *et al.*, 2023). Stimuli-responsive nanoparticles are another direction. Particles that respond to pH, temperature, or enzymes may be engineered through plant-derived biomolecules. These smart carriers could improve drug release control (Patra *et al.*, 2021).

10.4 Clinical translation and regulatory pathways

Clinical translation of green nanoparticles remains limited. Future progress requires standardized synthesis protocols, toxicity testing, and long-term in vivo studies. Developing Good Manufacturing Practice (GMP) processes will be essential. Collaboration among researchers, regulators, and industry is necessary. International agencies are beginning to draft nanomedicine-specific guidelines. Incorporating green synthesis principles into these frameworks may support faster approval (Murthy *et al.*, 2022).

10.5 Hybrid nanomaterials

Future research may focus on hybrid nanoparticles. These combine metals with polymers, lipids, or biomolecules for multifunctionality. For example, gold polymer hybrids can combine imaging and therapy. Plant-derived capping agents may add antioxidant or antimicrobial benefits (Iravani *et al.*, 2022). Biogenic carbon-based nanomaterials, such as graphene and carbon quantum dots, are also gaining interest. Their fluorescence and conductivity properties offer new opportunities for biosensing and diagnostics (Khan *et al.*, 2023).

10.6 Environmental and economic sustainability

Green synthesis aligns with the global shift toward sustainability. Future efforts will emphasize reducing waste, energy use, and reliance on hazardous chemicals. Valorization of agricultural and food industry waste as raw materials for nanoparticle synthesis is a promising area. Economic feasibility will also improve as bioreactor and continuous-flow technologies become more accessible. Partnerships with pharmaceutical industries could accelerate commercialization (Hussain *et al.*, 2023).

10.7 Expanding biomedical applications

Future applications of green-synthesized nanoparticles hold great promise across various biomedical fields. In neuro-nanomedicine, their ability to cross the blood–brain barrier could enable targeted treatment of neurodegenerative diseases. They also have potential in immunomodulation, where engineered green nanoparticles may help regulate immune responses in cancer or autoimmune disorders. In tissue engineering, these nanoparticles can be integrated into scaffolds to enhance regenerative medicine approaches.

10.8 Outlook

The convergence of green chemistry, biotechnology, AI, and clinical medicine offers enormous promise. Green synthesis can move beyond being an alternative method to becoming a mainstream technology for biomedical nanomaterials. However, success depends on overcoming technical and regulatory challenges. With growing interest from both academia and industry, green-synthesized nanoparticles may soon enter advanced clinical trials and therapeutic pipelines.

Conclusion

Green synthesis has emerged as a promising alternative to conventional nanoparticle production, offering a safer, more sustainable approach for biomedical applications. By using plant extracts, microbes, and biopolymers, this method avoids toxic chemicals and introduces biologically active surface features that enhance compatibility and functionality. This review outlined the principles, types, mechanisms, and biomedical uses of green-synthesized nanoparticles, emphasizing their potential in drug delivery, imaging, antimicrobial therapy, and tissue engineering. Despite clear advantages, challenges remain, particularly in reproducibility, large-scale production, and understanding long-term toxicity. Limited clinical data and regulatory frameworks also hinder translation to practice. However, future advances in personalized medicine, AI-driven synthesis, and sustainable raw materials may help overcome these barriers.

In summary, green nanotechnology bridges sustainability and innovation in medicine. With continued interdisciplinary research and regulatory support, green-synthesized nanoparticles have the potential to become a key component of next-generation healthcare solutions.

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