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GREEN SYNTHESIS OF NANOPARTICLES: MECHANISMS, CHARACTERIZATION, AND EMERGING APPLICATIONS

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Abstract

The pursuit of sustainable and biocompatible technologies has driven significant interest in the green synthesis of nanoparticles (NPs) for drug delivery applications. Green synthesis employs plant extracts, microorganisms, and biopolymers as reducing and stabilizing agents, eliminating the need for toxic chemicals typically used in conventional synthesis methods. This environmentally friendly approach produces nanoparticles with enhanced biocompatibility, tunable physicochemical properties, and inherent bioactivity, making them highly suitable for targeted therapeutics and diagnostics. Metallic nanoparticles (e.g., silver, gold), metal oxides (e.g., zinc oxide, magnetite), and biopolymeric carriers (e.g., chitosan) synthesized via green routes have demonstrated broad utility in oncology, antimicrobial therapies, vaccine delivery, gene transfection, and theranostic systems. Functionalization strategies such as PEGylation, surface ligand attachment, and hybridization with polymers further optimize their stability, targeting, and controlled release profiles. Despite these advantages, challenges remain, including variability in biological source composition, scale-up limitations, and regulatory hurdles regarding reproducibility and safety. This review highlights the mechanisms underlying green synthesis, summarizes representative nanoparticle systems, and examines their applications in drug delivery. Special emphasis is placed on recent advancements such as stimuli-responsive and multifunctional nanocarriers, as well as integrated theranostic platforms combining therapy and imaging. Future perspectives stress the need for standardized production protocols, scalable manufacturing, and in-depth preclinical and clinical evaluations to accelerate the translation of these eco-friendly nanotechnologies into pharmaceutical use. Green-synthesized nanoparticles, with continued innovation and regulatory alignment, hold promise as next-generation drug delivery systems offering safer, cost-effective, and sustainable solutions.

INTRODUCTION

Green synthesis refers to the production of nanoparticles (NPs) using biological entities such as plant extracts, microorganisms, and biopolymers, minimizing hazardous chemicals and environmental impact. Compared to conventional methods (chemical reduction, hydrothermal, or physical vapor deposition) green approaches are safer, cost-effective, and yield biocompatible materials suitable for drug delivery (1,2).

The use of biogenic agents as reductants and stabilizers reduces the reliance on toxic precursors and surfactants. Plant-mediated synthesis is particularly attractive due to its simplicity, scalability, and the ability of phytochemicals (polyphenols, flavonoids, proteins) to both reduce metal ions and stabilize nascent nanoparticles (1,3). Microbial synthesis also provides extracellular or intracellular routes to fabricate metallic and metal oxide NPs with controlled morphologies (4,5)

Since chemical and physical ways of creating nanoparticles produce dangerous compounds, the green method is taking their place. In order to create environmentally safe and sustainable NPs, biobased elements such as microorganisms, plants, and agricultural waste are used (5,6). Due to synthesis, the availability and diversity of various plant species have drawn a lot of attention because they provide a wide range of bioactive materials for the creation of nanoparticles (7–9). They can be made from a variety of plant parts that help produce nanoparticles and reduce metal ions. Table 1 shows green synthesis of nanoparticles with various biological sources. They are used in biological, agricultural, sensor, and chemical tracking applications.

Green-synthesized NPs are increasingly applied in drug delivery for their inherent bioactivity, tunable surface properties, and environmental sustainability. These systems have demonstrated efficacy in targeted delivery, pH- or magnetically responsive release, antimicrobial therapy, and anticancer treatment (3,6). Despite these advantages, challenges remain in standardization, scaling up production, and meeting regulatory standards for clinical translation.

Table 1 : Green synthesized nanoparticles with biological sources

Nanoparticle Type	Size (nm)	Biological Source	Drug / Use Case	Reference
AgNPs	~5	*Curcuma longa* flower extract	Antibacterial and as antibiotic carrier	(4)
AgNPs	5–50	*Rhizopus stolonifer*	Anticancer (HT-29 colon carcinoma)	(6)
AuNPs	10–100	Plant extracts (polyphenol-rich)	Photothermal therapy and targeted chemotherapy	(10,11)
PEG–ZnO NPs	20–50	Plant-mediated green precipitation	Doxorubicin delivery for triple-negative breast cancer	(6)
PEG–Fe_3O_4 NPs	~15	Sonochemical green synthesis + PEG coating	Sorafenib delivery and magnetic targeting (theranostics)	(12,14)
Chitosan NPs	100–200	Biopolymer-based green synthesis	Oral peptide and vaccine delivery	(13)
TiO_2 NPs (plant-mediated)	15–40	Leaf extracts (*Azadirachta indica*, *Camellia sinensis*)	Photodynamic cancer therapy and drug release	(3,9)
CuO NPs (green biosynthesis)	20–60	Microbial and plant-based reduction	Antifungal and antibacterial drug carriers	(5,9)
Chitosan–Au hybrid NPs	50–120	Chitosan + plant-reduced gold	Gene delivery (plasmid DNA, siRNA) and controlled release	(14)

2. Principles and Mechanisms of Green Synthesis

2.1 Phytochemical-Mediated Synthesis

Green synthesis of nanoparticles using plant extracts is an eco-friendly and cost-effective approach that integrates reduction, stabilization, and capping processes into a single step. Phytochemicals such as flavonoids, polyphenols, terpenoids, alkaloids, and reducing sugars act as electron donors, reducing metal

ions (e.g., Ag^{+}, Au^{3+}, Cu^{2+}, Zn^{2+}) into their zero-valent forms (1,3,). Additionally, biomolecules like proteins, amino acids, and polysaccharides serve as stabilizing agents, preventing nanoparticle aggregation and ensuring uniform particle morphology (5,11). The concentration of plant extract, reaction pH, temperature, mixing intensity, and incubation time are key parameters influencing the particle size distribution and stability (12,15). For example, *Curcuma longa* extract has been reported to yield ~5 nm silver nanoparticles (AgNPs) with potent antibacterial activity due to the presence of curcumin and other polyphenols (8,15). Similarly, *Azadirachta indica* leaf extract has been used to synthesize gold nanoparticles with controlled size and enhanced antioxidant properties.

2.2 Microbial and Fungal Routes

Microorganisms, including bacteria (e.g., *Lactobacillus fermentum*) and fungi (*Fusarium oxysporum)*, produce extracellular enzymes such as reductases and nitrate reductases, which catalyze the reduction of metal salts to nanoparticles (5,7). This biological pathway offers high yield and allows room-temperature synthesis, minimizing energy consumption. For instance, fungal-mediated synthesis of silver and gold nanoparticles often results in uniform shapes (spherical or triangular) with sizes ranging between 10–50 nm (9,11). Bacterial systems can also be genetically modified to enhance metal ion uptake and reduction efficiency, leading to more precise control over nanoparticle morphology and crystallinity

2.3 Metal Oxide and Hybrid Synthesis:

Green synthesis extends to the production of metal oxide nanoparticles such as zinc oxide (ZnO), titanium dioxide (TiO_2), and iron oxide (Fe_2O_3). Plant extract-mediated ZnO nanoparticles are typically synthesized via precipitation methods followed by low-temperature calcination, resulting in particle sizes ranging between 20–50 nm (12,13). Iron oxide nanoparticles have been synthesized using tea polyphenols and employed in magnetic drug delivery and environmental remediation (14,15). Sonochemical and microwave-assisted green methods further accelerate the synthesis, reducing reaction times to a few minutes while maintaining particle uniformity (16).

Hybrid nanostructures are designed by combining metallic or metal oxide cores with biopolymers such as chitosan, PEG, or alginate. These hybrids exhibit enhanced biocompatibility, mucoadhesion, and pH-responsive drug release, while reducing cytotoxic effects (17). Such composites are promising in drug delivery, cancer therapy, and biosensing applications.

3. Types of Green-Synthesized Nanoparticles

3.1 Silver Nanoparticles (AgNPs)

Green-synthesized AgNPs (5–50 nm) demonstrate strong antimicrobial, antiviral, and anti-cancer properties. *Rhizopus stolonifer* derived AgNPs loaded with anticancer drugs induced apoptosis in HT-29 colon carcinoma cells (11). AgNPs are also integrated into hydrogels and coatings for infection control. Figure 1 represents green synthesis of silver nanoparticles.

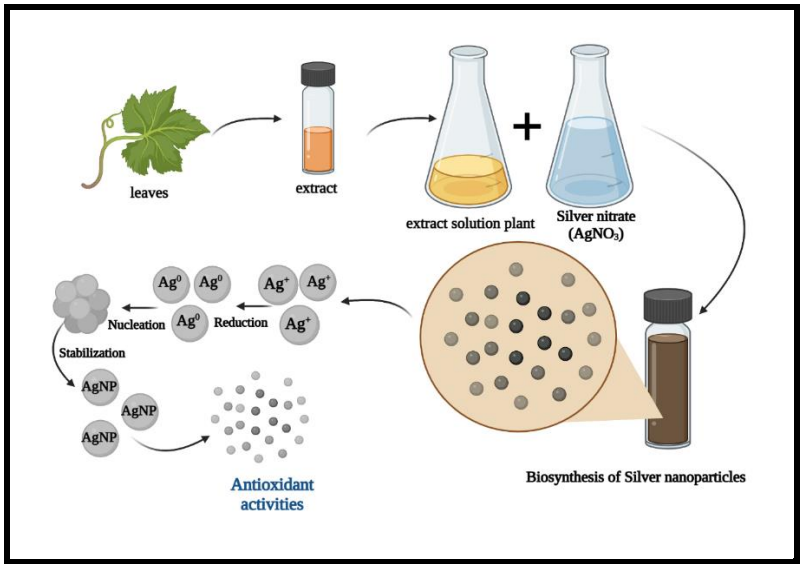


Figure 1: Green Synthesis of Silver Nanoparticles

3.2 Gold Nanoparticles (AuNPs)

Biogenic AuNPs (10–100 nm) exhibit tunable size and shape, with surface modifications (PEG, targeting ligands). They are used for photothermal therapy, targeted chemotherapy, and diagnostics, offering superior stability and biocompatibility over chemically synthesized counterparts (6,10)

3.3 Copper Nanoparticles (Cu NPs):

Cu NPs and CuO NPs have been produced widely using a range of plant extracts. In Cu NPs with a size range of 40 to 100 nm, the leaf extracts of *Magnolia kobus* and clove (*Syzygium aromaticum*) were discovered to have a broad variety of applications. Cu NPs were demonstrated to be produced by *Euphorbia nivulia* latex, and *Sterculi aureus* was discovered to be useful in the synthesis of CuONPs. CuONPs exhibit antimicrobial, antibacterial, and antioxidant properties against pathogenic strains of *Staphylococcus aureus* and E. coli. When used as bactericidal material, these NPs have decontaminating qualities against a variety of bacteria. (11)

3.4 Zinc Oxide (ZnO) and Ferrous Sulphate ($FeSO_4$) Nanoparticles:

For NPs used in therapeutic settings, ZnO green production has been considered potentially more productive and valuable than other metals. ZnO NPs were verified by a number of studies using various plant extracts. For instance, *Hibiscus rosasinensis* leaf concentrate and the plant *Cassia auriculata* were used as reducing specialists for zinc nitrate in order to create ZnO NPs.

ZnONPs synthesized via plant-based routes have demonstrated anticancer effects and pH-triggered drug release. Batool et al. showed PEGylated ZnO loaded with doxorubicin achieved ~65% loading efficiency and enhanced cytotoxicity in MDA-MB-231 breast cancer cells [6].

$FeSO_4$ NPs, produced via sonochemical or microbial methods, are utilized for magnetic drug targeting. PEG–$FeSO_4$ NPs combined with sorafenib improved tumor accumulation and MRI visibility in hepatocellular carcinoma (HCC) models. (18)

3.5 Palladium(Pd) And Platinum (Pt) Nanoparticles:

Both platinum and palladium are costly, silvery-white metals with a high density. Because it is environmentally friendly, sustainable, and cost-effective, the biosynthesis of both nanoparticles from plants has drawn the interest of numerous researchers. Numerous plant extracts, including those from *Cinnamomum camphora*, *Gardenia jasminoides*, *Pinus resinosa*, *Anogeis-suslatifolia*, *Glycine max*, *Ocimun sanctum*, *Curcuma longa*, *Musa paradisica*, *Cinnamom zeylanicum*, *Pulicaria glutinosa*, *Doipyros kaki*, and many

more, have been used to create Pd and Pt nanoparticles in a green manner.

Additionally, protein-rich soybean leaf extract including amino acids was used to create palladium nanoparticles. Ultra-violet-visible and Fourier transform infrared spectroscopy were used to establish the production of the nanoparticles, and transmission electron microscopy was used to check their morphology, which showed nanoparticles of a size of 15 nm. In the production of Pd nanoparticles, an extract from renewable and non-toxic black tea leaves (*Camellia sinensis*) was also utilized as a stabilizing and reducing agent. (19)

3.6 Titanium Oxide (TiO_2) Nanoparticles:

Nanoparticles of titanium oxide are very interesting because of their unique surface chemistry and morphologies. These nanoparticles are highly beneficial in the production of fabrics, plastics, papers, food items, colors, and cosmetics,

Many plants have been utilized for the synthesis of TiO_2 nanoparticles. A plant extract reacting with TiO_2 salt initiates the synthesis. A change in the reaction mixture's color can first be used to validate the preparation of nanoparticles, and morphological and spectroscopic tests can then confirm their formation. The reported color of these nanoparticles ranges from pale green to dark green. At room temperature, an aqueous solution of TiO_2 salt and leaf extract from *Annona squamosa L.* reacted to create spherical TiO2 nanoparticles. Similarly, irregularly shaped 25–110 nm TiO_2 nanoparticles were created using *Catharanthus roseus* leaf extract. Aliphatic amines and alcohols were the cause of the nanoparticles in the leaf extract.

Similarly, *Calotropis gigantea* leaf extract was used to create nanoparticles in 6 hours. The extract's primary amines were the cause of the high bioreduction. These nanoparticles demonstrated long-lasting acaricidal action against *Rhipicephalus microplus* and *Haemaphysalis bispinosa* larvae. (20)

3.7 Biopolymeric Nanoparticles

Chitosan, alginate, and cellulose derivatives, synthesized through green methods, yield biodegradable carriers for oral peptides and vaccines. Their mucoadhesive nature improves bioavailability and prolongs release (14)

4. Factors Affecting Green Synthesis of Nanoparticles:

4.1 pH

One important factor influencing the synthesis of NPs using green innovation techniques is pH. Researchers have discovered that the size and surface of the orchestrated NPs are affected by the pH of the arrangement medium. Therefore, altering the media solution's pH can control the size of NPs. (21)

4.2 Temperature of Reaction

One crucial factor influencing the shape, size, and synthesis of NPs is the reaction temperature.

With the increase in temperature, the process of synthesis becomes faster. It is also estimated that the production of NPs also increases with the increase in size. While chemical techniques demand a temperature below 350°C, the physical strategy itself requires a maximum temperature (>350°C). Generally, temperatures below 100°C are needed to combine NPs using green innovation. The response medium's temperature determines the concept of the NPs generated in terms of their size and shape. (22)

4.3 Reaction Time

The type and quality of NPs generated using green technology are greatly influenced by the reaction medium's incubation period. The properties of the produced nanoparticles were significantly influenced by the synthesis process, light exposure, storage conditions, and other variables, and these changes occurred over time. The length of the incubation period is also influenced by the organism used for the synthesis. Particle size can also be influenced by exposure duration.

4.4 Other factors

Some other factors like extract volume also impact the metal NPs synthesis as the extract plays a key role in reducing metal ions. Additionally, the quantity and quality of the NPs are influenced by the purification process of choice. The properties of the NPs are also impacted by the separation process using chromatographic and centrifugation techniques. (23).

Various factors affecting the synthesis of nanoparticles are shown in figure 2

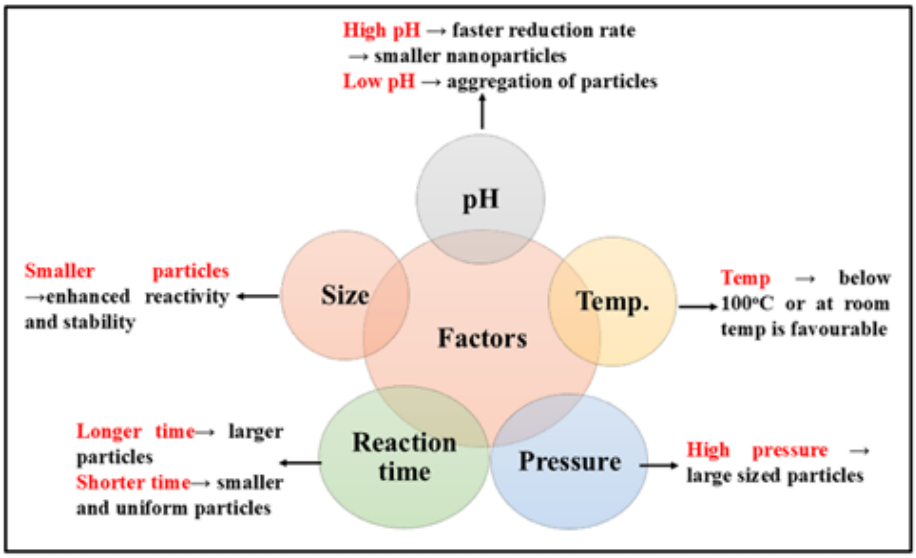


Figure 2 : Different factors affecting green synthesis of Nanoparticles

5. Analysis of Green Synthesized Nanoparticles

The analysis of green-synthesized nanoparticles is a crucial step in determining their physicochemical properties, stability, and suitability for specific applications. Common analytical techniques include UV–Vis spectroscopy, which monitors the surface plasmon resonance and confirms nanoparticle formation; X-ray diffraction (XRD) for determining crystalline structure; and Fourier-transform infrared spectroscopy (FTIR) to identify functional groups from biomolecules responsible for reduction and stabilization. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) provide detailed insights into morphology, particle size, and distribution, while dynamic light scattering (DLS) measures hydrodynamic diameter and zeta potential, indicating stability in suspension. Additionally, thermogravimetric analysis (TGA) is employed to evaluate thermal stability and organic content on nanoparticle surfaces. Combining these methods ensures comprehensive characterization, aiding in the optimization of synthesis protocols and enhancing reproducibility for industrial applications (24)

6. Benefits of Green Synthesis of Nanoparticles

Green synthesis offers several advantages compared to conventional chemical and physical methods as shown in Figure 3. The use of plant extracts, microbial cultures, and biopolymers as reducing and stabilizing agents eliminates the need for toxic solvents and high-energy inputs, thereby minimizing environmental impact. The biomolecules present in these sources—such as polyphenols, proteins, and sugars—not only facilitate reduction of metal ions but also cap and stabilize nanoparticles, improving biocompatibility and reducing cytotoxicity (25). Green-synthesized nanoparticles typically exhibit enhanced aqueous dispersibility, tunable size and morphology, and surface functional groups suitable for further conjugation, which make them ideal for drug loading, targeting, and controlled release. Furthermore, these methods are often cost-effective and scalable when optimized for batch or flow systems, and they frequently impart inherent bioactivity (e.g., antimicrobial or anticancer properties) derived from the phytochemicals adsorbed on nanoparticle surfaces (26)

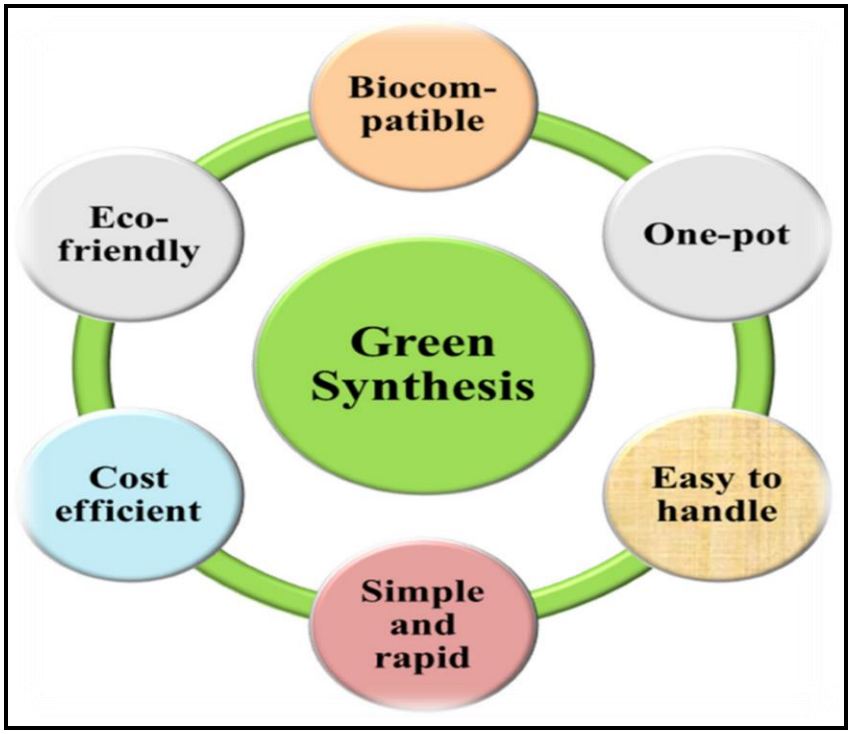


Figure 3: Advantages of green synthesis of nanoparticles

7. Limitations:

Despite these advantages, green synthesis faces several challenges that hinder large-scale translation. Several limitations of green synthesized nanoparticles are shown in figure 4. Batch-to-batch variability in the composition of plant extracts or microbial metabolites can result in inconsistent nanoparticle size, morphology, and yield . The presence of multiple biomolecules complicates mechanistic understanding and standardization, making regulatory approval and quality control difficult . Additionally, many green-synthesized nanoparticles lack uniformity in size distribution compared to chemically synthesized counterparts, which may impact bio distribution and pharmacokinetics. Scale-up remains challenging, as biological extracts often degrade quickly, and large-scale microbial synthesis requires stringent growth control to avoid contamination (18). Comprehensive toxicological and pharmacokinetic studies are still limited, and the absence of standardized protocols complicates comparison across studies. Addressing these limitations will require integrated process optimization, isolation of active biomolecules for reproducibility, and regulatory frameworks tailored to green nanotechnology.

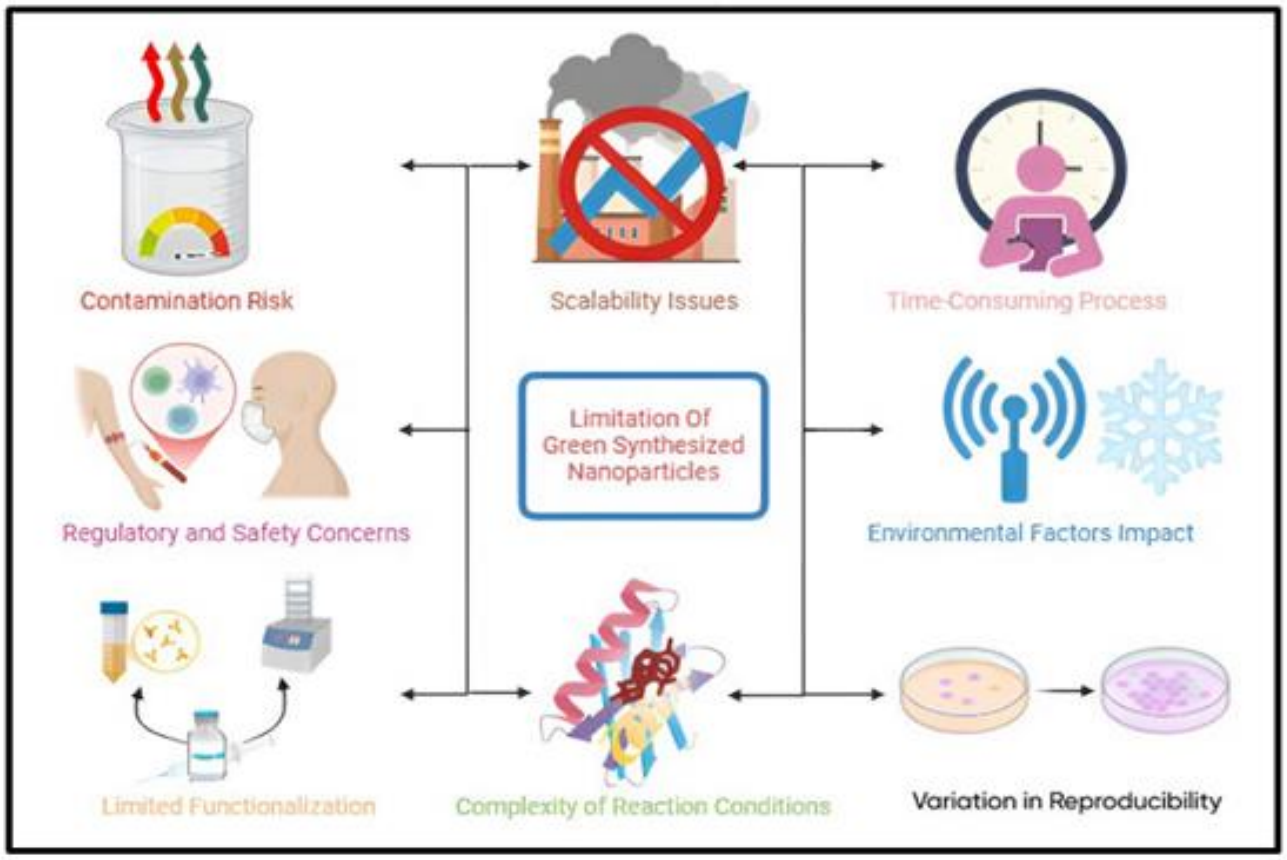


Figure 4 : Limitations of green synthesized nanoparticles

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8. Applications in Drug Delivery:

8.1 Targeted and Stimuli-Responsive Systems:

Green-synthesized NPs can be functionalized with folate, antibodies, or peptides for active targeting. PEG–ZnO and PEG–$FeSO_4$ NPs release drugs in acidic tumor microenvironments or under magnetic fields, allowing spatially controlled delivery.

8.2 Anticancer Therapeutics:

AgNPs, AuNPs, ZnO, and Fe_3O_4 NPs serve as carriers for chemotherapeutics (doxorubicin, sorafenib, cisplatin). These platforms enhance intracellular uptake, and enable photothermal or magnetic synergy, improving tumor cytotoxicity while sparing normal tissues

Gold nanoparticles have also been used specifically in cancer therapy for the detection of cancer cells, protein assay, immunoassay, and capillary electrophoresis. In the medicine field, gold nanoparticles have of great interest. For biological screening tests, they can be used as biomarkers.

To kill cancers, these treat as accurate and influential heaters after cellular uptake. Along with these, they can induce apoptosis in B cell-chronic lymphocytic leukemia. Significant antioxidant capacity was revealed by gold nanoparticles produced by the leaf of *Suaeda monoica*, and DPPH radical-scavenging activity of these was found 43% at 1 mg/ ml (27)

8.3 Antimicrobial Formulations:

AgNPs and ZnO NPs inhibit bacteria (*S. aureus*, *E. coli*), fungi (*Candida*), and viruses at low concentrations. They are incorporated into wound dressings and coatings for infection control.

Silver nanoparticles have drawn considerable attention from researchers and scientists due to their wide area of applications like biolabeling, sensors, antimicrobial activity, antibacterial activity, cell electrodes, integrated circuits, etc. Due to showing

antimicrobial activity, these are applicable in numerous fields such as medicine, health, packaging, cosmetics, and accessories. Against infectious organisms such as *Staphylococcus aureus*, *Vibria cholera*, Bacillus subtilis, *Syphillis typhus*, *Pseudomonas aeruginosa*, and *Escherichia coli*, these nanoparticles showed potential antimicrobial effects (28)

8.4 Delivery of Biologics and Vaccines

Vaccination is still the most cost-effective way to combat infectious illnesses. Conventional vaccinations may have low immunogenicity and, in most situations, only provide partial protection. A new class of nanoparticle-based vaccinations has shown considerable promise in addressing the majority of the shortcomings of traditional and subunit vaccines. Chitosan NPs act as mucoadhesive carriers for insulin, peptides, and nucleic acids, improving absorption and stability in the gastrointestinal tract (29)

8.5 Nanoparticles in gene therapy :

NPs in gene therapy Polynucleotide vaccines induce an immune response by transferring genes encoding appropriate antigens to host cells, expressed and creating the antigenic protein in the presence of effective antigen-presenting cells. Because intracellular protein synthesis, as an opponent to extracellular deposition, stimulates immune system arms, these vaccines generate both humoral and cell-mediated immune responses. (30)

8.6 Cellular Imaging :

Study displayed self-bio-imaging (in-vivo) of malignant growth cells utilizing fluorescent gold nano-cluster. It was intra cellular intracellularly synthesized by chloro auric acid reduction arrangement inside destructive cell cytoplasm into Au NP. Further, Au IP was in grouped structure with fluorescence which specifically analyzes destructive cells by in-vivo imaging (fluorescence). In another report, scientists incorporated carbon NPs utilizing a high level green strategy, which yielded NPs with blue shaded photoluminescence. This NP found to be biocompatible, less cytotoxic, high water solvency and had enhanced quantum yield. It was viewed as a decent contender for cell imaging, as it displayed cell take-up by Human HeLa cells and at 488 nm fluorescence green (31).

Table 2 shows applications of green synthesized nanoparticles in drug delivery

Table 2. Green-Synthesized Nanoparticles in Drug Delivery Applications

Nanoparticle System	Drug / Function	Mechanism of Action	Test Model (In vitro / In vivo)	Reference
AgNPs (*Curcuma longa* extract)	Antibiotics (broad-spectrum)	Reactive oxygen species (ROS) generation and membrane disruption	*E. coli*, *S. aureus* (in vitro)	[4]
AgNPs (*Rhizopusstolonifer*)	Anticancer (HT-29 colon carcinoma cells)	Induces apoptosis via ROS and mitochondrial disruption	HT-29 cells (in vitro)	[11]
PEG–ZnO NPs (plant-mediated)	Doxorubicin (anticancer)	pH-triggered release, enhanced cytotoxicity to TNBC cells	MDA-MB-231 (in vitro)	[6]
PEG–Fe_3O_4 NPs (green + PEGylated)	Sorafenib (anticancer + MRI imaging)	Magnetic targeting, MRI-guided drug localization	HCC mouse model (in vivo)	[12,14]
Chitosan NPs (biopolymeric)	Oral insulin and peptide vaccines	Mucoadhesion, improved stability, and sustained release	Rat and mouse models (in vivo)	[13]

Nanoparticle System	Drug / Function	Mechanism of Action	Test Model (In vitro / In vivo)	Reference
AuNPs (plant-synthesized)	Photothermal cancer therapy (with drugs)	Light-induced hyperthermia with synergistic drug release	Breast cancer xenografts (in vivo)	[6,10]
AgNPs (green synthesis)	Antiviral activity (against influenza virus)	Inhibition of viral entry and replication via surface interaction	MDCK cell culture and mouse models	[9]
Chitosan–Au hybrid NPs	Gene delivery (plasmid DNA, siRNA)	Electrostatic loading and enhanced endosomal escape	HEK293 cells (in vitro)	[13]

9. Safety, Functionalization, and Regulatory Perspectives

Green-synthesized NPs often show **lower cytotoxicity** due to natural surface moieties and absence of harmful residues. However, particle size, dose, and surface charge remain critical determinants of safety. Smaller AgNPs (<10 nm) can penetrate cells and elicit ROS, necessitating careful dose control (32)

Functionalization with PEG or biopolymers (e.g., chitosan) prolongs circulation, reduces immunogenicity, and improves stability Regulatory bodies (FDA, EMA) require standardized characterization—particle size, surface chemistry, purity, and stability—before clinical approval.

10. Future Prospects:

Green synthesis of nanoparticles offers a sustainable pathway for developing next-generation drug delivery systems, but its clinical translation will depend on overcoming several key challenges. Future research must focus on standardizing plant and microbial sources by isolating and characterizing bioactive phytochemicals responsible for nanoparticle nucleation and stabilization, thereby minimizing variability in size, shape, and yield. Integration of green synthesis with modern technologies such as microfluidics, continuous flow systems, and high-throughput screening will allow reproducible, scalable production suited for pharmaceutical standards. There is also a growing interest in developing multifunctional hybrid nanocarriers that combine therapy, targeting, and imaging—theranostic systems such as PEGylated Fe_3O_4 nanoparticles for cancer treatment exemplify this trend. However, for these systems to advance beyond research, comprehensive in vivo studies on bio distribution, pharmacokinetics, immunogenicity, and long-term safety are essential, along with clear regulatory frameworks to define quality and safety benchmarks. With coordinated advances in synthesis, characterization, functionalization, and regulation, green nanotechnology has the potential to transform drug delivery and bring safer, more effective, and eco-friendly therapeutics to clinical use. (33)

11. Conclusion

Green synthesis is revolutionizing nanoparticle-based drug delivery by combining sustainability, biocompatibility, and functional versatility. Through plant, microbial, and biopolymeric routes, metallic and metal oxide NPs can be produced with unique features for antimicrobial, anticancer, and biologic delivery applications. Standardization, scalability, and regulatory alignment remain the primary hurdles, but with continued innovation in synthesis, functionalization, and manufacturing, green nano medicine is poised to advance into clinical use.

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