



Nanoparticle Fabrication and Optimization: Green Chemistry to Transformative Applications in Life Sciences, Medicine, and Public Health

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ABSTRACT

Nanotechnology has changed many fields by allowing scientists to work with matter at the atomic and molecular levels. NPs including metal (e.g., Ag, Au), metal oxide (e.g., ZnO, FeO), polymeric (e.g., PLGA), and carbon-based (e.g., carbon nanotubes), have special chemical, biological, and physical properties. This review paper discusses a lot of detail about making and improving nanoparticles, guided by the 12 principles of green chemistry ideas to make sure they are safe for living things and last for a long time. Traditional synthesis methods, employ toxic chemicals and use a lot of energy. Green synthesis methods, on the other hand, use microbes, plants, or materials inspired by biology to synthesize NPs. These environmentally friendly methods use renewable resources in a controlled setting to make biocompatible NPs with as little influence on the environment as possible. This review paper talks about how to change the size, shape, and surface chemistry of NPs using optimal reaction conditions and advanced characterization techniques. It focusses on groundbreaking uses in bioimaging, giving medicine, antimicrobial agents, cancer treatment, regenerative medicine, cleaning water, and food safety, among other fields of the life sciences, healthcare, and public health. They offer a lot of potential to help solve global challenges and pave the way for a future of nanotechnology that is both creative and sustainable.

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Introduction

1. Nanotechnology and Nanoparticles

Imagine a world where nanoparticles, engineered at scales as small as 1-100 nanometers in one dimension, revolutionize healthcare, energy, and environmental sustainability in coming future. Nanotechnology, an emerging and advanced field of manipulation of matter at

atomic, molecular, and supramolecular scales to generate nanoparticles (NPs) that are valuable for scientific and technological innovations. NPs manifest a variety of physical, chemical and biological properties as compared to their bulk counterparts [1,2]. These distinct properties are due to their very minute size, high surface-to-volume ratio and unique interaction with electricity, magnetism,

and light. The numerous applications of the NPs depend on the potential of how we optimize and the synthesis NP [3,4].

The revolutionary concept comes from Richard Feynman's visionary speech, "There's Plenty of Room at the Bottom." This gives the idea to scientists to revolutionized world by manipulating atoms, molecules and supramolecules to create potentially beneficial particles that unshared a new era of scientific research [5,6]. Subsequently, the field had developed various advanced methods of preparation of NPs, and sophisticated methods for characterization like the scanning tunneling microscope (STM) and atomic force microscope (AFM), and robust theoretical frameworks. The revolutionary evolution of nanotechnology has changed form a hypothetical idea to a palpable and impactful area of research having application in the field of healthcare, energy production, and environmental remediation due to its composition [7,8,9].

The synthesis of NPs is crucial in defining the size, shape, stability, and surface chemistry of the particles which in turn, greatly influence its performance, effectivity and safety in various applications [10]. The traditional methods of synthesis of NPs had produced effective and useful NPs but these methods of synthesis demand intensive conditions, involve toxic chemicals, require significant energy, and produce perilous by-products such as physical vapor deposition and chemical reduction method [11,12]. These types of concerns like those of health and environment have resulted in essential paradigm shift on the way to green chemistry principles. In nanotechnology, NPs are synthesized utilizing the renewable resources, the solvents that are safe to use and involving the techniques that are energy-efficient. For the development of environment friendly and sustainable NPs, this shift is crucial [1,13].

This review article explores how the nanotechnology is involved in various novel applications in the field of public health, medicine, and the life sciences, and also the sustainable methods for the synthesis of NPs, and strategies for managing NPs qualities in environmentally conscious way. Moreover, this review precisely analyzes the intricate link between synthesis, inherent properties, and practical applications, providing a holistic understanding of the immense potential of green-synthesized nanoparticles [14,15,16]. By highlighting how these eco-friendly materials can address significant global challenges, the review underscores their role in shaping a sustainable future for nanotechnology. It serves as an invaluable resource for students, professionals, and

researchers seeking to understand and contribute to the advancements in sustainable nanotechnology, integrating the latest research and technical breakthroughs.

2. Principles of Green Chemistry in Nanoparticle Fabrication

Some of the physical and chemical methods that have been utilized in the past to make nanoparticles are chemical reduction, sol-gel processes, and vapour deposition. These procedures work, but they are very risky for people and the environment because they involve scorching temperatures, toxic solvents, and harmful reducing agents. Because of this, the ideas behind green chemistry have become a model for making nanoparticles in ways that are good for the environment and last a long time [17,18].

The 12 Principles of Green Chemistry: A Nanotechnology Perspective

The 12 principles of green chemistry can help us think about making nanoparticles in a way that is better for the environment and the economy as described in the Fig. 1. [19].

- *Prevention:* The easiest way to reduce our impact on the environment is to not throw away things in the first place. For example, using microorganisms or plant extracts as reducing and capping agents is better for the environment because it cuts down on waste and gets rid of the need for toxic chemical reductants.
- *Atom Economy:* The atomic economy says that synthetic processes should use inputs as little as feasible in the final product to get the most out of them. Chemical synthesis methods sometimes create a lot of trash, while green synthesis methods of NPs [20,21].
- *Less Hazardous Chemical Syntheses:* To make green nanoparticles safer for workers and the environment, plant-based polyphenols or microbial enzymes are used instead of toxic chemicals like hydrazine or sodium borohydride [22].
- *Designing Safer Chemicals:* When making chemicals, it's crucial to think about how hazardous they are and how useful they are. This is true for both the nanoparticles and the chemicals employed to make them. For example, adding biocompatible coatings from natural sources to green-synthesized nanoparticles makes them better for usage in biomedical applications [23].

- *Safer Solvents and Auxiliaries:* To make the procedure safer, it is important to cut back on or stop using solvents and other chemicals that could be dangerous. Green synthesis uses less volatile organic compounds (VOCs) and other traditional methods by replacing toxic solvents with water or plant extracts for synthesis of NPs [24].
- *Design for Energy Efficiency:* Many green synthesis methods for NPs synthesis, such as plant-mediated or microbial synthesis, occur under mild conditions, significantly reducing energy consumption compared to high-temperature chemical or physical methods [25].
- *Use of Renewable Feedstocks:* Raw materials should be renewable whenever possible. Green synthesis of NPs leverages renewable biological resources, such as plant biomass, agricultural waste, or microbial cultures, instead of finite petrochemical-based precursors, promoting sustainability [26,27]
- *Reduce Derivatives:* Unnecessary derivatization steps, such as protection and de-protection, should be avoided to minimize reagent use and waste. Green synthesis often employs one-pot, single-step reactions, simplifying the process and reducing the need for multiple purification steps for NPs fabrication [28,29].
- *Catalysis:* Catalytic reagents are preferable to stoichiometric ones due to their efficiency and selectivity. In green synthesis, enzymes or phytochemicals often act as natural catalysts, facilitating efficient reduction of metal ions and minimizing reagent use [30,31].
- *Design for Degradation:* Nanoparticles should be designed to degrade into non-toxic products after their functional lifespan to prevent environmental persistence. Green-synthesized nanoparticles often incorporate biodegradable coatings, ensuring they break down harmlessly in the environment [32,33].
- *Real-time Analysis for Pollution Prevention:* Synthesis processes can be watched and managed in

real time to stop the creation of dangerous chemicals. Due to in-situ characterization technologies like UV-Vis spectroscopy, researchers can now see how nanoparticles are made and change the settings to avoid unwanted by-products [34,35].

- *Inherently Safer Chemistry for Accident Prevention:* The chemistry used in synthesis should be safer by nature, which should lower the risk of chemical accidents like leaks or explosions during the NPs synthesis [36,37].

Advantages of Green Synthesis over Conventional Methods

Green synthesis is the best technique to do nanotechnology that is good for the environment because it has so many advantages over more traditional physical and chemical methods [38]:

- *Reduced Toxicity and Environmental Impact:* Green synthesis is better for the environment because it doesn't utilize hazardous solvents and reagents, which makes the production of nanoparticles far less harmful. Plant-mediated synthesis doesn't use sodium borohydride or other chemicals that could be damaging to the environment. This helps keep waste streams cleaner and reduces damage to the environment [39,40].
- *Cost-effectiveness and Energy Efficiency:* Green synthesis methods usually work at room temperature, so they don't need machines or processes that use a lot of power or need to be very hot [41].
- *Simplicity and Scalability:* A lot of green synthesis methods are one-pot, one-step procedures. This makes manufacturing easier, improves repeatability, and makes scaling up easier [42].
- *Biocompatibility:* Nanoparticles made using biological agents are more biocompatible because they often include natural coverings of biomolecules like proteins or polysaccharides [43,44].

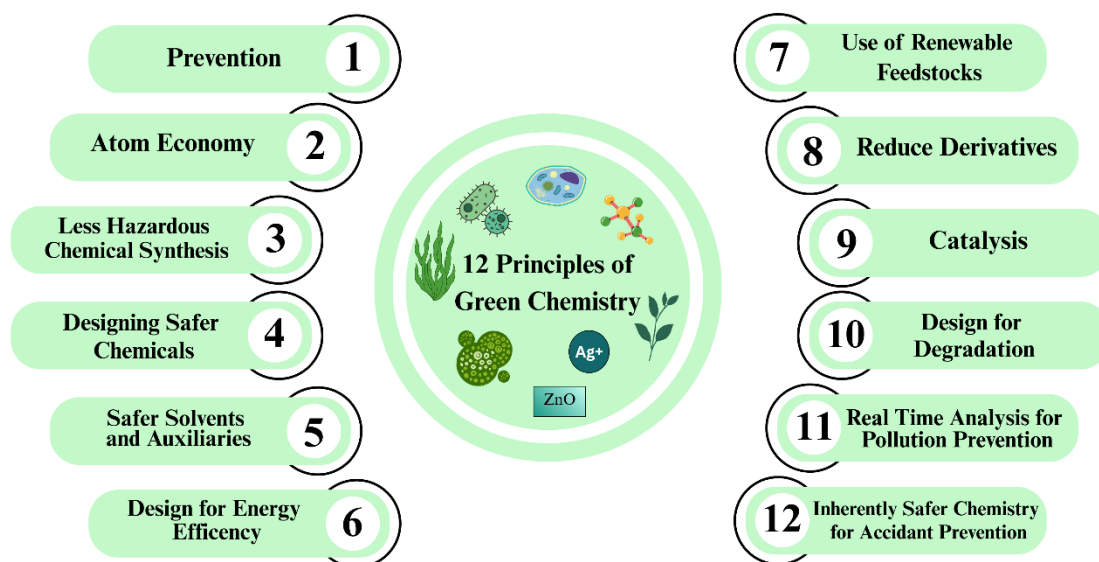


Figure 1. 12 Principles of Green Chemistry

Types of Green Synthesis

Biological things are utilized as stabilizers and reducing agents in green synthesis methods, which make nanoparticles in different ways as shown in Table 1.

- **Plant-mediated Synthesis:** Plant-mediated synthesis, or photosynthesis, is a widely adopted green approach that utilizes plant extracts or biomass to synthesize nanoparticles. This method involves mixing an aqueous plant extract with a metal salt solution, leading to the rapid formation of nanoparticles through reduction and stabilization processes [45,46].
- **Mechanism of Synthesis:** The phytochemicals in plant extracts, including flavonoids, terpenoids, polyphenols, alkaloids, and proteins, serve as reducing agents, converting metal ions (e.g., Ag^+ , Au^{3+}) into metallic nanoparticles (Ag^0 , Au^0). These biomolecules also act as capping agents, stabilizing the nanoparticles and preventing aggregation. The efficiency of reduction and the stability of the resulting nanoparticles depend on the phytochemical profile, which varies by plant species, part used (leaves, roots, fruits), and extraction conditions [47,48,49].
- **Examples of Plants and Nanoparticles:** Numerous plant species have been explored for nanoparticle

synthesis of silver, gold, copper oxide, and zinc oxide. For instance, Aloe vera, rich in polysaccharides and phenolic compounds, is commonly used to synthesize silver and gold nanoparticles. *Camellia sinensis* (green tea) extract, abundant in catechins, is effective for producing metal and metal oxide nanoparticles. These nanoparticles have different properties because of the biochemical makeup of the plants used to make them. *Eucalyptus globulus*, *Cinnamomum zeylanicum*, and *Azadirachta indica* (Neem) are some of these plants [50].

- **Advantages and Limitations:** Plant-mediated synthesis is easy, cheap, and good for the environment, as long as you stay away from toxic chemicals and harsh conditions. Nanoparticles that are made are often safe to utilize in biomedicine since they are biocompatible. However, variations in nanoparticle qualities caused by differences in phytochemical content due to ambient conditions or extraction techniques can make it hard to reproduce and standardize results [51,52].
- **Microorganism-based Synthesis:** Biosynthesis, which uses microorganisms like bacteria, fungi, algae, or yeast, can be used to synthesize nanoparticles either within the cell or in extracellular space.

Table 1: Summary of the types of green-synthesis of NPs

Synthesis Method	Biological Agent	Key Features	Advantages	Limitations	Citations
Plant-mediated	Plant extracts (e.g., Aloe vera, green tea)	Uses phytochemicals for reduction and stabilization	Simple, cost-effective, biocompatible	Variability in phytochemical composition, challenges in size control	[53,54]
Microorganism-based	Bacteria, fungi, algae (e.g., <i>E. coli</i> , <i>Fusarium oxysporum</i>)	Enzymatic reduction, intra/extracellular synthesis	Precise control, scalable via fermentation	Slower reaction rates, complex purification	[39,55]
Bio-inspired	Mimics natural biomineralization (e.g., diatoms)	Replicates natural processes for precise morphology	Advanced control, multi-functional NPs	Complex design, early-stage development	[56,57,58]

- Role of Microbes:** Microbes use metabolic or enzymatic processes to lower the amount of metal ions, which lets them make nanoparticles. Proteins, polysaccharides, and enzymes like nitrate reductases slow down the reduction process and stop the nanoparticles that come out of it from sticking together. Biomolecules that are secreted and parts of the cell wall also help stabilize things [59,60].
 - Specific Examples:** Bacillus subtilis and Escherichia coli are two typical types of bacteria used to make gold and silver nanoparticles. Fungi like Aspergillus niger and Fusarium oxysporum can make metal and metal oxide nanoparticles very well because they secrete a lot of enzymes. Using algae, like Chlorella vulgaris, to make nanoparticles is good for the environment [61,62].
 - Pros and Cons:** Microbial synthesis lets you manage the size and shape of nanoparticles gently, and fermentation makes it possible to make things on a huge scale. It can be hard to clean up microbiological broths, and occasionally the response rates are slower than those of chemical methods [63,64]. Further challenges include handling the risk of contamination and keeping sterile environments.
- Bio-inspired and Biomimetic Synthesis:** The shape and properties of NPs can be changed via bio-inspired and biomimetic synthesis, which copies how minerals form in nature. This method's purpose is to make inorganic materials in the same complicated way that living creatures do.

Magnetotactic bacteria and diatoms are two types of organisms that make magnetic nanoparticles and complex silica structures, respectively, in ways that are similar to how things happen in nature [65]. By looking at the environmental cues and molecular interactions that control these processes, scientists can make synthetic pathways that work as well and as accurately as nature does [66].

Diatoms' nanoscale accuracy in creating silica shells and magnetotactic bacteria's-controlled manufacturing of magnetite nanoparticles are two instances of natural events. Biomineralization examples discovered in mollusks shells and coral structures inspired nanoparticles with hierarchical structures and several functions [67].

The idea that bio-inspired synthesis may make high-tech nanoparticles with certain properties is fascinating since

Table 2: Summary of Effect of Reaction Parameters on Nanoparticle Morphology

Parameter	Effect on Size	Effect on Shape	Effect on Stability	Optimization Strategy	Citation
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Temperature	Higher temp: smaller NPs due to faster nucleation	Influences shape (e.g., rods at higher temp)	High temp may cause aggregation	Optimize temp range for desired size/shape	[65,68,37]
pH	Affects reduction rate, smaller NPs at optimal pH	Directs shape (e.g., spherical at neutral pH)	Alters surface charge, impacts aggregation	Adjust pH to enhance reduction/stability	[69]
Concentration	Higher precursor: smaller NPs; excess extract: larger NPs	Affects nucleation vs. growth	Optimal ratio prevents aggregation	Use DoE/RSM for precise control	[70]

it could lead to new discoveries in areas of materials science, catalysis, and medicine [71].

3. Optimization of Nanoparticle Properties through Green Methods

The size, shape, surface chemistry, and stability of nanoparticles all affect how effectively they operate in particular situations.

- **Controlling Size, Shape, and Surface Chemistry:** The size, shape, and surface chemistry of nanoparticles have a big effect on their optical and electrical properties and how they interact with living things. It is very important to know the pH, temperature, concentration of precursors, and reaction time in order to figure out morphology. The pH of the reaction mixture affects the ionization states of biomolecules, which in turn affects their ability to reduce and cap. Temperature has an effect on reaction kinetics, and as the temperature rises, particles often get smaller and more uniform. The size and grouping of particles are affected by the reaction time, and the concentrations of the precursors and extracts govern the rates of nucleation and growth [72]. pH, temperature, and concentration can be adjusted to attain certain synthesis results. For example, changing the pH can change the shape of nanoparticles from round to triangular to rod-shaped. In addition to the temperature, the precursor ratio must also be controlled to stop aggregation and ensure monodispersity [17,21]. Nanoparticles made from plants usually have natural biomolecules on their surfaces that help them stay stable at first. Polymers (like PEG and chitosan) or targeting ligands (like antibodies and peptides) can make the material even

more useful by making it more stable, biocompatible, and selective for things like imaging or drug delivery [13,73].

- **Role of Reaction Parameters:** Parameters' optimizing reaction is perilous for achieving reproducible, high-quality NPs. Temperature, pH, and concentration are the most persuasive factors as showed Nucleation and reduction at higher temperatures usually make smaller particles, while slower nucleation at lower temperatures can make larger particles. The right temperature ranges balance these changes so that the right size and form are reached [39,38]. pH affects how well metal precursors dissolve and how well biomolecules can reduce and cap. Some pH values are used to stabilize nanoparticles by changing their surface charge and stopping them from sticking together, or to make reduction more effective [54,65]. The concentration, which is the ratio of the biological agent to the metal precursor, has an effect in Table 2. The best ratios make sure that reduction and stabilization happen quickly. On the other hand, higher precursor concentrations can make smaller particles since there are too many reducing agents [49]. Statistical tools like the Design of Experiments (DoE) and the Response Surface Methodology (RSM) make it possible to systematically improve these factors. These approaches look at how different variables affect each other and how they work together to identify the best conditions for maximizing yield, monodispersity, and other traits [64].
- **Characterization Techniques:** To make sure that nanoparticles are made, find out what they are like,

and figure out how they may be used, they need to be fully characterized as follow:

- UV-Visible Spectroscopy (UV-Vis): Ultraviolet-visible spectroscopy (UV-Vis) can find surface plasmon resonance (SPR) bands to make sure that nanoparticles, notably metals like gold and silver, have been made. The position and strength of the SPR peak show the shape, size, and concentration [10].
- Dynamic Light Scattering (DLS): Dynamic light scattering (DLS) is one approach to check aggregation and stability. It does this by measuring hydrodynamic size and polydispersity in solution. The size distribution data it gives is a good addition to other methods [59].
- Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM): Scanning electron microscopy (SEM) and transmission electron microscopy (TEM): SEM displays how surfaces are shaped and where they are, whereas TEM exhibits nanoparticles in great resolution, including their size, shape, and crystallinity. Both are needed for morphological analysis [40].
- X-ray Diffraction (XRD): X-ray diffraction (XRD) can tell you the size of crystallites, the purity of the phase, and the structure of the crystals. The Scherrer equation uses peak broadening to figure out the size of crystallites [65].
- Fourier Transform Infrared Spectroscopy (FTIR): Fourier Transform Infrared Spectroscopy (FTIR) can show which functional groups are on the surfaces of nanoparticles when biomolecules from plant extracts or microbial cultures are present and help keep them stable [41].

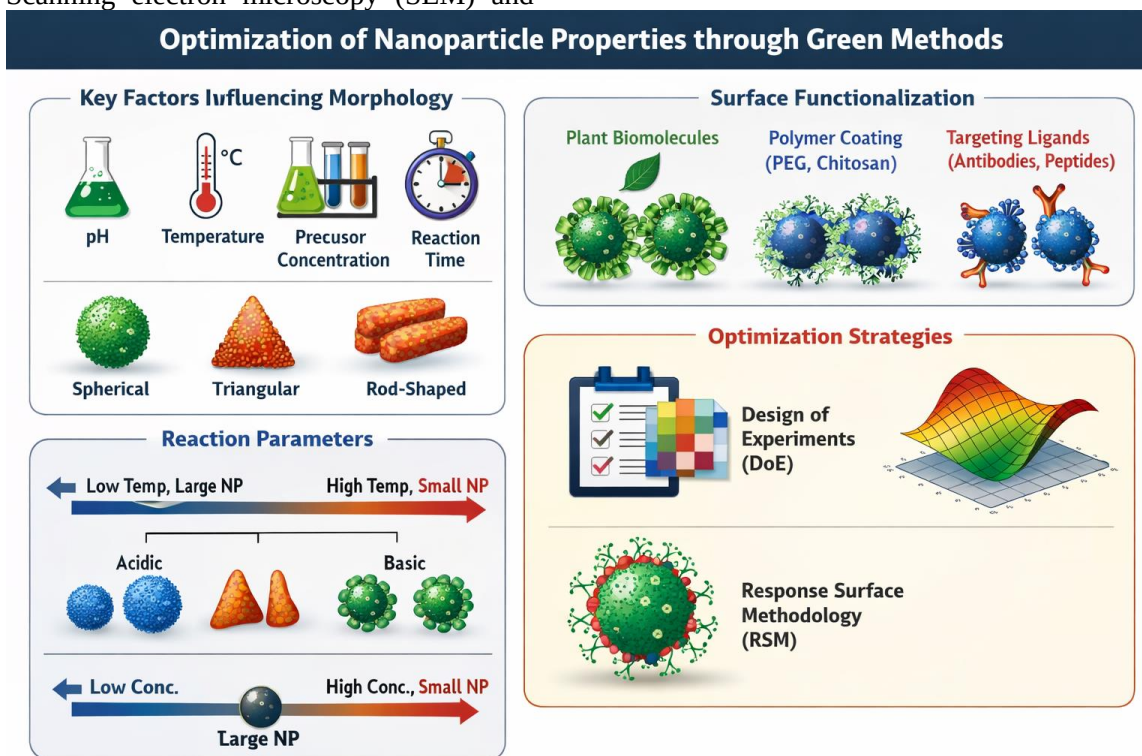


Figure 2. Schematic illustration showing how green synthesis parameters, including pH, temperature, precursor concentration, reaction time, and surface functionalization, govern the morphology, stability, and optimization of nanoparticles.

- *Enhancing Stability and Biocompatibility:* Before nanoparticles manufactured from sustainable resources can be utilized in the real world, they need

to be stable and safe for living things to use. This is especially important in medicine [39]. Natural biomolecule coatings provide the surface its first

stability, but PEG or chitosan coatings make it more stable in the long term under physiological situations. These coatings lower protein adsorption, stop aggregation, and lengthen circulation duration [28]. The nanoparticles' integrity is affected by how they are stored, including the temperature and light exposure, as well as the choice of solvent. By making nanoparticles that break down and improving storage methods, they can stay stable until they are needed, and then they can be safely broken down [50].

Bioimaging and Diagnostics (In-vitro and In-vivo Imaging): Nanoparticles make diagnostics and bioimaging better because they are more sensitive, specific, and have higher resolution than more traditional methods. Fluorescent nanoparticles, like quantum dots, give off steady and bright fluorescence. This makes it possible to use them for imaging both in vitro and in vivo, such as cellular tracking and multiplexed imaging. Gold nanoparticles used for optical methods like photoacoustic imaging and surface-enhanced Raman scattering. Magnetic nanoparticles like iron oxide make inflammation or tumors easier to see by making the MRI contrast stronger [23]. Functionalized nanoparticles can be used to find cancer, infectious diseases, and neurological problems early since they can target disease-specific biomarkers. One example is the use of gold nanoparticles with antibodies attached to them. These nanoparticles improve the accuracy of tests by finding cancer biomarkers at very low levels [58].

4. Transformative Applications in Life Sciences

Nanoparticles made in a more environmentally friendly method are changing the life sciences since they have unique properties and are safe for living things. They are used in many different imaging and diagnostic tests, as well as in medicine administration and ways to kill microorganisms [66]

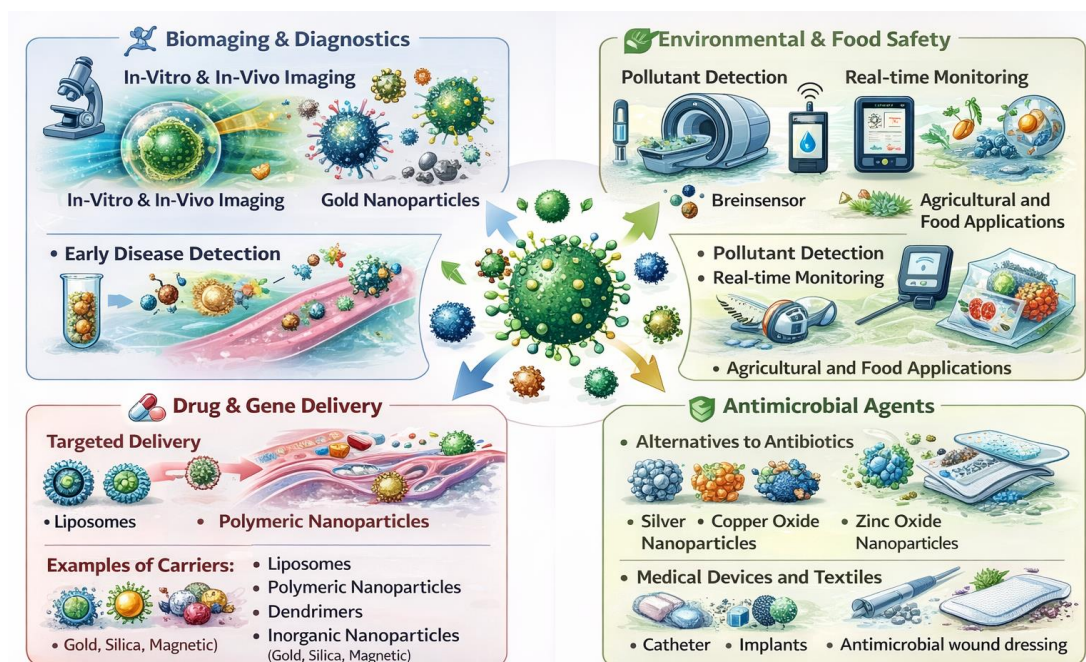


Figure 3. Overview of major life-science applications of nanoparticles, including bioimaging and diagnostics, environmental and food safety monitoring, targeted drug and gene delivery, and antimicrobial technologies.

Biosensors for Environmental and Food Safety: Nanoparticle-based biosensors provide rapid, sensitive

detection of environmental pollutants and food contaminants.

- *Pollutant Detection:* Carbon nanotubes, graphene, and metal nanoparticles detect heavy metals, pesticides, and pathogens in water, soil, and air. Gold and silver nanoparticles enable colorimetric and electrochemical sensing [45].
- *Real-time Monitoring:* Portable nanosensors facilitate on-site environmental assessment, detecting pollutants like volatile organic compounds or bacteria in real time [30].
- *Agricultural and Food Applications:* Nanosensors detect plant diseases, soil nutrients, and foodborne pathogens, while smart packaging with nanosensors monitors food freshness, reducing waste [72].

Drug and Gene Delivery: Nanoparticles overcome limitations of conventional drug delivery, such as poor solubility and systemic toxicity, by enabling targeted delivery and controlled release.

- *Targeted Delivery:* Passive targeting via the EPR effect and active targeting with ligands ensure precise drug delivery to diseased tissues, reducing side effects. For example, antibody-functionalized nanoparticles target cancer cells overexpressing specific receptors [17].
- *Overcoming Biological Barriers:* Nanoparticles protect drugs from degradation and facilitate passage through barriers like the blood-brain barrier, enabling treatment of neurological disorders [49].

Examples of Carriers:

- *Liposomes:* Encapsulate hydrophilic and hydrophobic drugs, with clinical formulations like Doxil, a liposomal formulation of doxorubicin.
- *Polymeric Nanoparticles:* Made from biodegradable polymers (e.g., PLGA, PLA), these nanoparticles offer tunable release kinetics for small molecules and nucleic acids.
- *Dendrimers:* Highly branched, monodisperse polymeric nanoparticles with a well-defined structure, offering multiple surface sites for drug conjugation and targeting ligands.
- *Inorganic Nanoparticles:* Gold, silica, and magnetic nanoparticles enable photothermal therapy and guided delivery.

Antimicrobial Agents: Nanoparticles offer potent antimicrobial activity, addressing the global challenge of antibiotic resistance. Silver, copper oxide, and zinc oxide nanoparticles exhibit broad-spectrum activity against bacteria, fungi, and viruses. Their mechanisms include membrane disruption, reactive oxygen species generation, and interference with DNA replication [20]. Nanoparticle coatings on catheters, implants, and textiles prevent infections and biofilm formation, improving patient outcomes and hygiene [68].

5. Revolutionary Impact on Medicine

Nanomedicine leverages nanoparticles to advance diagnostics, therapeutics, and regenerative strategies, offering precision and efficacy in addressing medical challenges.

Targeted Cancer Therapy: Nanoparticles transform cancer therapy by enabling targeted drug delivery and physical therapies like hyperthermia. Nanoparticles in precision medicine can target cancer cells while causing as little damage as possible to healthy tissues. This is possible because of active targeting or the EPR effect. Theranostic nanoparticles combine testing and treatment for personalized care [59]. Drug delivery methods like liposomes, polymeric micelles, and inorganic nanoparticles are used to make chemotherapeutic treatments, gene therapies, and immunomodulators work better and have fewer adverse effects. Doxil is a liposomal form of doxorubicin that lowers the drug's toxicity to the heart without lowering its ability to fight cancer [43].

Regenerative Medicine and Tissue Engineering: Nanoparticles enhance tissue regeneration by providing scaffolds and delivering growth factors [27]. Nanoparticle-incorporated scaffolds mimic the extracellular matrix, promoting cell adhesion and differentiation for bone, cartilage, and skin regeneration (wound healing). For instance, electrospun nanofiber scaffolds containing bioactive nanoparticles can guide the regeneration of bone, cartilage, nerve tissue, and skin [48]. Nanoparticles serve as efficient carriers for the controlled release of growth factors, cytokines, and genetic material (e.g., genes, siRNAs) that promote cell

differentiation and tissue repair. Furthermore, nanoparticles are being used to enhance the survival, proliferation, and differentiation of stem cells, making stem cell-based regenerative therapies more effective. They can also facilitate the targeted delivery of stem cells to specific damaged tissues [67].

Medical Implants: Nanoparticle coatings improve the performance of medical implants by reducing infections and enhancing integration [63]. Nanoparticle coatings on medical implants (e.g., orthopedic implants, dental implants, cardiovascular stents) can significantly reduce the risk of bacterial colonization and subsequent biofilm formation. Antimicrobial nanoparticles like silver, copper, or titanium dioxide can be incorporated into the coating to provide sustained antimicrobial activity [71]. Coatings must be non-toxic, non-immunogenic, and

stable in physiological environments. Research focuses on developing coatings that not only prevent infection but also actively promote tissue healing and integration, leading to better patient outcomes and reduced revision surgeries [72,70].

Vaccines and Immunotherapy: Nanoparticles enhance vaccine efficacy and immunotherapy outcomes by improving antigen delivery and immune stimulation [40]. Nanoparticles act as adjuvants, improving antigen presentation and immune activation. Virus-like particles and polymeric nanoparticles deliver antigens and adjuvants, enhancing vaccine efficacy for diseases like COVID-19. Nanoparticles deliver immunomodulators to the tumor microenvironment, reprogramming immune cells and enhancing anti-tumor immunity.

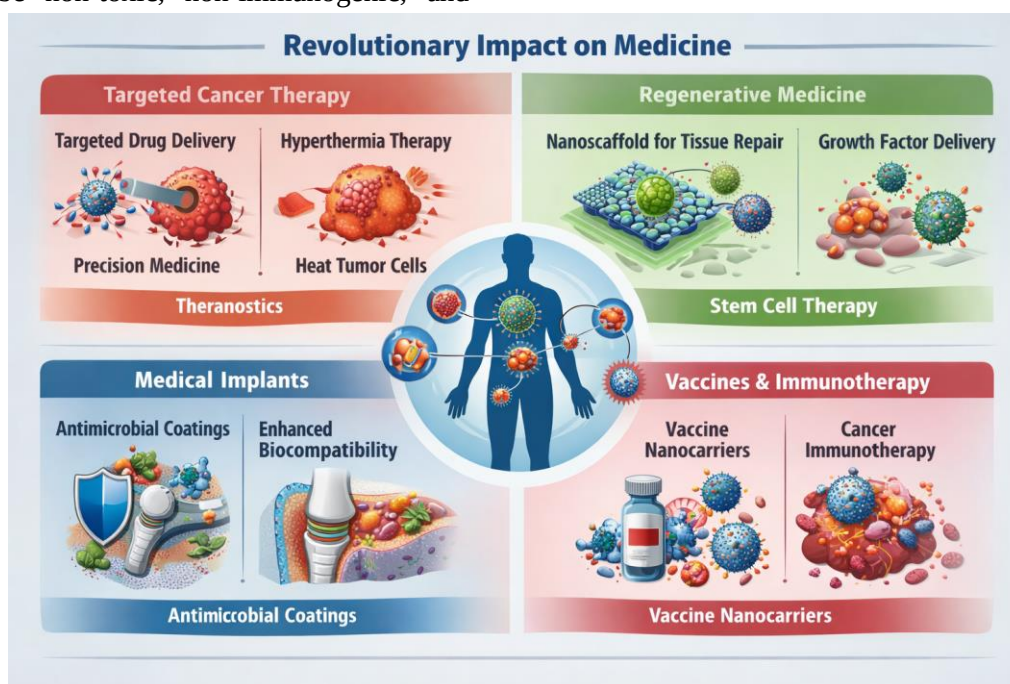


Figure 4. Schematic illustration of the diverse biomedical applications of nanoparticles, highlighting their roles in targeted cancer therapy, regenerative medicine, improved medical implants, and enhanced vaccine and immunotherapy strategies.

6. Innovations in Public Health

Nanoparticles contribute to public health by addressing environmental, food safety, and disease surveillance challenges.

Water Purification: Nanoparticles enable efficient water treatment by removing contaminants [74]. Iron oxide nanoparticles adsorb heavy metals, silver nanoparticles

inactivate pathogens, and titanium dioxide degrades organic pollutants via photocatalysis. Nanoparticle-enhanced membranes improve filtration efficiency, removing viruses and dissolved solids.

Pest and Vector Control: Nanoparticles offer sustainable alternatives to conventional pesticides [19]. Encapsulated pesticides enhance efficacy, reduce environmental

impact, and target pests specifically. Nanoparticle-based pest control minimizes runoff and non-target effects, supporting eco-friendly agriculture.

Food Preservation: Nanoparticles extend food shelf life and enhance safety through smart packaging [73]. Silver and zinc oxide nanoparticles inhibit microbial growth in packaging, preserving food quality. Nanosensors detect spoilage indicators, reducing food waste and ensuring safety.

Public Health Surveillance: Nanoparticles qualify hasty, delicate uncovering for disease and environmental monitoring [68]. Gold nanoparticle-based assays provide point-of-care diagnostics for diseases like malaria and COVID-19. Nanosensors track air and water quality, supporting epidemiological efforts to manage health risks.

7. Challenges and Future Directions

Despite their promise, green-synthesized nanoparticles face challenges that must be addressed for widespread adoption.

- *Scalability:* Scaling up green synthesis while maintaining quality and reproducibility is challenging due to variability in biological materials [69].
- *Reproducibility:* Variations in plant or microbial composition hinder standardization, affecting regulatory approval [70].
- *Cost-effectiveness:* While cost-effective at small scales, large-scale production requires optimization to compete with chemical methods [75].

Regulatory and Safety Concerns: The environmental fate of nanoparticles, including persistence and ecological effects, requires further study [76]. Understanding the health risks of nanoparticles, such as oxidative stress or organ accumulation, is critical for safe use [50]. Equitable access, societal impacts, and responsible governance are essential for ethical nanotechnology development [51].

Emerging Technologies and Research Areas: The field of green nanotechnology is dynamic and rapidly evolving, with several exciting trends shaping its future. Future research will likely focus on developing multi-functional nanoparticles that combine diagnostic and therapeutic capabilities (theranostics), exploring novel biological

resources for synthesis (e.g., extremophiles, marine organisms), and designing smart nanoparticles that respond to specific stimuli (e.g., pH, temperature, light) for controlled release [66].

Integration with AI and Machine Learning: Artificial intelligence (AI) and machine learning (ML) are poised to revolutionize green nanoparticle synthesis and optimization. AI/ML algorithms can analyze vast datasets from synthesis experiments, predict optimal reaction conditions, and even design novel nanoparticles with desired properties. This data-driven approach can significantly accelerate the discovery and development of new green synthesis routes, reduce experimental time, and improve the efficiency and reproducibility of nanoparticle production [74].

8. Conclusion

Green-synthesized nanoparticles represent a transformative leap in nanotechnology, aligning innovation with sustainability through the principles of green chemistry. By leveraging plant-mediated, microorganism-based, and bio-inspired synthesis, these eco-friendly methods minimize environmental impact, reduce toxicity, and enhance biocompatibility, offering a viable alternative to conventional approaches. The precise optimization of nanoparticle properties including, size, shape, and surface chemistry, enables their revolutionary applications in life sciences, medicine, and public health, from targeted cancer therapies and regenerative medicine to water purification and food safety. Despite their promise, challenges including, scalability, reproducibility, and nanotoxicity require ongoing research to ensure safe and effective implementation. Emerging trends, including AI-driven optimization and multi-functional nanoparticle designs, signal a bright future for green nanotechnology. By addressing regulatory and ethical considerations, green-synthesized nanoparticles can deliver impactful solutions to global challenges, fostering a healthier, more sustainable world. This review underscores their potential to redefine nanotechnology, emphasizing responsible innovation to balance efficacy with environmental stewardship, paving the way for advancements that benefit humanity while preserving the planet for future generations.

Authors' contributions

ICMJE criteria	Details	Author(s)
1. Substantial contributions	Conception, OR	1
	Design of the work, OR	2
	Data acquisition, analysis, or interpretation	3,4
2. Drafting or reviewing	Draft the work, OR	1,2
	Review critically for important intellectual content	3,4
3. Final approval	Approve the version to be published	1,2,3,4
4. Accountable	Agree to be accountable for all aspects of the work	1,2,3,4

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Declarations

Ethics approval and consent to participate

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Consent for publication

Not applicable.

Competing interests

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