Toward Safer Nanotechnology: Eco-friendly Strategies for Nanoparticle Fabrication

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Abstract. Nanomaterials play a central role in various technological and biomedical applications due to their unique chemical and physical properties. Among the various fabrication methods, chemical reduction is the most widely used approach, offering high efficiency and precise control over particle size and concentration. However, the use of toxic reducing agents (e.g., $NaBH_4$, $N_2H_4{\cdot}H_2O$) and stabilizers (e.g., PVP) in conventional synthesis has serious environmental, health, and safety risks. In response to these issues, eco-friendly strategies such as green synthesis using plant extracts have gained increasing attention as sustainable alternatives. Plant-based extracts, including polyphenols and flavonoids, can work as reducing agents and stabilisers. These reagents enable nanoparticle formation under environmentally benign and less hazardous conditions. The eco-friendly approach offers advantages in biocompatibility, environmental safety, and additional bio-functionalities (e.g., antioxidant and antimicrobial effects). However, it also faces challenges, including a lower reaction rate, higher costs, and difficulty in storing reagents. This review discusses recent advances in nanoparticle fabrication, compares conventional and green synthesis methods, and evaluates their respective benefits and limitations.

Keywords: Nanoparticles Synthesis, Green Synthesis, Plant Extracts, Chemical Reduction.

1. introduction

In recent decades, nanomaterials—especially metallic nanoparticles—have garnered considerable attention due to their exceptional antibacterial, catalytic, and optical properties (e.g., surface plasmon resonance, SPR), which have enabled applications in biomedicine, sensing, and electronic manufacturing. However, the fabrication method plays a crucial role in determining the nanoparticle's size, shape, surface chemistry, and functionality, which in turn governs their performance and safety profiles.

A wide range of fabrication techniques has been developed, including physical, chemical, and biological approaches. Physical methods such as laser ablation or evaporation–condensation generally yield high-purity products but require substantial energy and complex equipment. Chemical routes, especially reduction-based syntheses, offer greater control over morphology and yield; however, they involve toxic reagents that pose a risk to both human health and the environment. These challenges have become increasingly pressing as nanomaterial production scales up, raising concerns about sustainability and ecological impact.

Consequently, growing efforts have been directed toward developing green synthesis strategies that replace conventional reductants and stabilizers with naturally derived biomolecules—particularly plant extracts rich in polyphenols, flavonoids, and proteins. These "green" methods not only minimize hazardous chemical exposure but also provide additional biofunctionalities, such as antioxidant or antimicrobial activities, offering dual benefits of safety and utility. However, despite their promise, green synthesis approaches face challenges in reaction consistency, efficiency, and large-scale standardization.

This review aims to evaluate recent advances in nanoparticle fabrication methods, with a focus on the transition from traditional chemical approaches to eco-friendly, green synthesis. It further compares their mechanisms, environmental implications, and prospects for achieving safer nanotechnology.

2. Overview of Nanoparticle Fabrication Methods

A variety of fabrication routes have been established to produce nanoparticles, each based on different physicochemical principles that ultimately determine their structure and functionality. Broadly, these can be classified as physical and chemical methods.

Physical synthesis approaches, such as evaporation–condensation, laser ablation, or ball milling, generate nanoparticles through mechanical or thermal fragmentation of bulk materials. These techniques minimize chemical contamination and provide high purity but require substantial energy input and often involve expensive apparatus. Moreover, large-scale operations can be impractical due to low production efficiency and significant carbon emissions.

Chemical synthesis routes—including sol–gel, co-precipitation, thermal decomposition, spray pyrolysis, and chemical reduction—remain the most widely adopted due to their high controllability of reactions and tunable product morphology. However, these methods typically rely on organic solvents, strong reducing agents, and synthetic stabilizers, producing hazardous by-products and non-biodegradable residues. The environmental cost of waste disposal and the risk of chemical exposure to researchers highlight the urgent need for greener alternatives.

In response to these drawbacks, biological or green synthesis methods have emerged as sustainable alternatives. Using plant extracts, microorganisms, or biomolecules as natural reducing and stabilizing agents, they can operate under mild conditions with minimal environmental impact. This paradigm shift reflects the growing importance of integrating nanotechnology development with environmental and occupational safety principles.

2.1 Physical Methods

Physical synthesis methods typically operate on the principle of breaking down bulk materials into nanoscale particles using mechanical force, high temperature, or irradiation. These are purely physical processes without chemical transformation.

For evaporation–condensation, a metal source is first heated in a high-temperature furnace until it vaporizes, and then rapidly condenses into nanoparticles. The technique produces particles with identical size [1]. It has been demonstrated that copper nanoparticles synthesized via arc evaporation–condensation exhibit an average particle size of 4–50 nm, with a size variation of ±10%. However, this method requires substantial energy and complex temperature control.

Laser ablation utilizes a high-power laser beam to irradiate a solid metal target in a liquid or gas medium. The laser energy is very strong. Hence, atoms and clusters are released from the target. They immediately nucleate to form nanoparticles. This method avoids chemical contamination and allows precise control. Still, it can only be used in small-scale production, as the yield rate is too low [2]. It is highlighted that the typical productivity of pulsed laser ablation in liquids (PLAL) is generally in the range of 1–10 mg/h, which is far below the requirements for industrial-scale production of nanoparticles.)

In ball milling, bulk solids are placed in a rotating chamber with grinding balls. The repeated collisions fragment the material into nanoparticles. While the operation is much more equipment-accessible, it often yields particles with broad size distributions and potential surface defects. In a study by Feng et al. [3], tungsten nanoparticles synthesized via high-energy ball milling exhibited an average grain size of 46.8 nm, with a standard deviation of ±32.9 nm—a variation amounting to nearly 70% of the mean.

2.2 Non-Reductive Chemical Methods

Some chemical methods synthesize nanoparticles through non-reductive processes.

Sol–Gel Method involves the transition of a solution (sol) into a solid network (gel) through hydrolysis and polycondensation reactions of metal alkoxides or salts. After drying and strong heating, the gel produces nanostructured oxides or composites. The method allows for excellent compositional control but may require long processing times and post-synthesis treatment. A detailed Sol–Gel procedure for zirconia nanoparticles noted that gel drying requires approximately 48 hours, followed by calcination for 20–30 hours, resulting in total process times of up to 60 hours per batch.

Co-Precipitation uses metal ions are precipitated by adjusting the pH of an aqueous solution. When metal hydroxides or oxides are nucleating and aggregating, nanoparticles are formed. This method is relatively simple and cost-effective, but may result in limitations of control over particle shape. Agnihotri et al. [4] demonstrated that the size of silver nanoparticles can range from 5 to 100 nm when produced by the co-reduction method.

Thermal Decomposition involves controlled heating of metal precursors (often organometallic compounds) in high-boiling organic solvents to form nanoparticles. It provides good size uniformity and crystallinity, but uses hazardous solvents and requires precise thermal control [5].

Spray pyrolysis involves first aerosolizing a solution containing metal precursors into fine droplets and then passing them through a high-temperature furnace. The rapid thermal decomposition of these drops leads to the formation of nanoparticles. This continuous-flow method is measurable, but operators may struggle with the complexity of the equipment.

3. Chemical Reduction Methods: Mechanisms and Reagents

The chemical reduction method is the most widely used strategy for synthesizing metallic nanoparticles, particularly silver nanoparticles (AgNPs) and gold nanoparticles (AuNPs). This method requires two key reagents: a reducing agent that converts metal ions (e.g., Ag^+ or Au^{3+}) into their elemental form, and a stabilizer that prevents agglomeration and controls the morphology of the nanoparticles.

Strong reducing agents are commonly added to nanoparticle synthesis. Sodium borohydride ($NaBH_4$) reduces metals rapidly through a nucleophilic hydride transfer, resulting in the formation of small nanoparticles due to its high reaction rate. An equation using NaBH4 to reduce Ag ions is shown as an example:

$$Ag^+ + BH_4^- + 3H_2O \rightarrow Ag^0 + B(OH)_3 + 3.5H_2$$

This rapid reaction yields nanoparticles with average diameters as small as 6–19 nm, often exhibiting high monodispersity when combined with appropriate stabilizers.

•Hydrazine hydrate ($N_2H_4 \cdot H_2O$) is a highly efficient chemical reducing agent commonly used in the production of non-noble metal nanoparticles such as Cu and Fe. It enables rapid reduction under mild conditions, resulting in significantly smaller particles. An equation using hydrazine hydrate to reduce Cu ions is shown as an example:

$$Cu^{2+} + N_2H_4 \rightarrow Cu^0 + N_2 + 2H^+$$

Stabilisers are also essential to prevent nanoparticle aggregation. Polyvinylpyrrolidone (PVP) is a sort of non-ionic polymer that is widely used as a stabilizer. It adsorbs on the nanoparticle surface through its carbonyl groups and forms a protective shell that prevents aggregation.

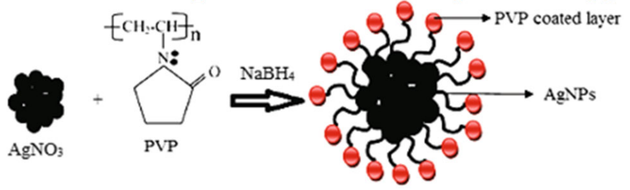

Figure 1. Figure of AgNO3 Nanoparticles Reacting with PVP. Source:[6]

Trisodium citrate, a mild stabilizer and weak reducing agent, is frequently used in reduction methods for silver, Iron (III) oxide, and gold nanoparticles. Citrate ions protect the nanoparticles by coordinating to the surface and providing electrostatic repulsion.

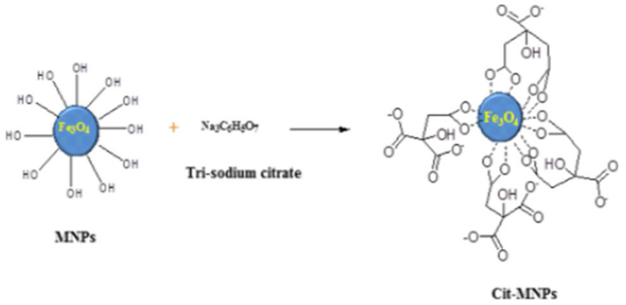

Figure 2. Figure of Fe3O4 Nanoparticles Reacting with Trisodium citrate. [7]

The colour and optical density of nanoparticle colloids could be obvious visual indicators of particle size, owing to the surface plasmon resonance (SPR) effect. For instance, in silver nanoparticles, smaller particles (~10–20 nm) typically exhibit bright yellow coloration with SPR absorption around 400 nm, while larger particles (30–50 nm) cause a redshift of the SPR band and result in darker brown hues. Similarly, gold nanoparticles transition from red to blue as their size increases, reflecting a shift in the SPR band from ~520 nm to over 580 nm [8].

4. Limitations of Traditional Chemical Approaches

Although traditional chemical reduction methods are efficient and controllable, they raise serious environmental, health, and safety concerns that increasingly outweigh their advantages. The reagents commonly used—such as sodium borohydride and hydrazine hydrate—are toxic, flammable, and corrosive. Their handling requires strict containment, and accidental release can lead to hydrogen evolution and explosion hazards. Moreover, residues such as borates and synthetic stabilizers, like polyvinylpyrrolidone (PVP), are poorly degradable and persist in both aquatic and terrestrial ecosystems.

The necessity for extensive safety measures, personal protective equipment, and waste management systems significantly increases operational costs. Disposal of residual heavy metals and reactive by-products adds further environmental burden. These drawbacks underline the urgency for developing safer and more sustainable synthetic routes, motivating the exploration of plant-based green synthesis as a viable alternative.

The reagents used in traditional chemical reduction are highly hazardous to the human body. For instance, sodium borohydride ($NaBH_4$) is extremely corrosive and flammable. When it comes into contact with water, it can rapidly release hydrogen gas, creating a significant explosion risk. Exposure to $NaBH_4$ can also cause severe irritation to the eyes, skin, and respiratory system. Similarly, hydrazine hydrate ($N_2H_4 \cdot H_2O$), a reducing agent used in the production of copper and iron nanoparticles, is toxic and volatile. It is also considered a kind of substance that is very likely to trigger cancers. Short-term exposure to high concentrations of hydrazine may still cause liver and kidney damage, neurological dysfunction, or death.

Chemical methods often produce non-biodegradable or environmentally persistent byproducts. For example, borate produced from a reaction involving $NaBH_4$ can accumulate in aquatic systems. Polyvinylpyrrolidone (PVP), a widely used stabilizer, is a synthetic polymer with very low degradability. Once released into the environment, PVP may persist in soil and water for extended periods, presenting risks to terrestrial and aquatic ecosystems.

The toxic and reactive properties of reagents like $NaBH_4$ and hydrazine necessitate the use of extensive personal protective equipment (PPE), fume hoods, and specialized handling protocols. Such requirements significantly increase the cost of both research and industrial production, particularly in facilities that aim to meet strict safety standards.

The disposition of chemical effluents is another pressing issue. Reaction byproducts may contain toxic residues, unreacted reductants, and heavy metal ions. This substance must be handled with care to prevent environmental contamination. This significantly increased financial and logistical barriers to sustainable scale-up.

5. Green Synthesis: Plant-Based Reducing and Stabilizing Agents

Many plant extracts are rich in naturally occurring reagents that could be used in the chemical reduction process of producing nanoparticles as reducing agents and stabilizers.

5.1 Polyphenols

Polyphenols, including catechins and tannins, are the most abundant and effective reducing agents in plant extracts. Their multiple hydroxyl groups donate electrons, reducing metal ions such as Ag^+ and Au^{3+} to their neutral metallic forms. Additionally, their aromatic ring structures can attach to the surface of nanoparticles, acting as stabilizers that prevent aggregation and enhance colloidal stability [9]. For example, Iravani [13] successfully produced silver nanoparticles (AgNPs) by using Camellia sinensis (green tea) extract. The experiment ultimately produced particles with an average size of 20–40 nm, and these particles also exhibited effective antibacterial activity.

5.2 Flavonoids and Terpenoids

Flavonoids, such as quercetin and kaempferol, play both the roles of reducing agent and stabilizer in nanoparticle formation. Their hydroxyl and carbonyl functional groups provide strong reduction potential, while their ability to chelate metal atoms enables effective surface capping and stabilization. Additionally, some terpenoids present in plant matrices assist in nucleation through metal complexation. Shankar et al. [10] showed that Pelargonium graveolens (rose geranium) extract (rich in flavonoids and terpenoids) could synthesize gold nanoparticles (AuNPs) without the need for additional stabilisers [9].

5.3 Proteins and Polysaccharides

Proteins and polysaccharides serve primarily as natural stabilizers in green synthesis. Proteins can stabilize nanoparticles via interactions between amino ($–NH_2$) and carboxyl (–COOH) side chains and the nanoparticle surface. It offers steric and electrostatic protection. Polysaccharides (starch and cellulose derivatives) could naturally form physical barriers due to their long-chain, hydrophilic nature. Sometimes, sugar moieties within polysaccharides may also contribute to a weak reduction capability, facilitating early-stage nucleation (Jahangeer et al. [11], 2023; Nasrollahzadeh [12]). An example is the work by Jahangeer et al. [11], who utilized Zingiber officinale (ginger) extract—rich in flavonoids and polysaccharides—to produce AgNPs with potent antioxidant and antimicrobial properties.

6. Comparison: Advantage of Using Plant Extracts to Produce Nanoparticles

Green synthesis using plant extracts offers a safer, cleaner, and more sustainable approach to manufacturing nanoparticles.

Substances (reducing agents & stabilisers) used in green synthesis are derived from plants and are far less hazardous than traditional chemical reagents, such as $NaBH_4$ or hydrazine. Because plant-mediated synthesis reduces the need for toxic chemicals, thereby decreasing risks of chemical burns, respiratory irritation, or explosions. The use of aqueous-based systems further enhances operator safety and reduces laboratory hazard profiles.

The plant-based synthesis method utilizes renewable raw materials, including agricultural byproducts and herbal residues, to produce sustainable products. According to Nasrollahzadeh [12], these bio-waste-derived reagents are biodegradable, and the process avoids the use of synthetic polymers or heavy metal byproducts common in traditional synthesis. This significantly reduces the environmental impact associated with producing nanoparticles.

Green synthesis typically takes place at room temperature and pressure, using water as the solvent. Shankar et al [10]. Demonstrated the synthesis of AuNPs using Pelargonium graveolens leaf extract at room temperature. The entire process utilized no inert gases or elevated temperatures. This makes the process energy-efficient and suitable for resource-limited settings.

Some plant extracts used in the production of nanoparticles, such as polyphenols, flavonoids, and proteins, not only reduce metal ions but also stabilize the resulting nanoparticles. In some studies [9], compounds such as quercetin can reduce metal atoms while simultaneously covering the surface of formed particles, eliminating the need for external stabilizers like PVP. This multifunctionality simplifies the synthesis process and reduces the amount of chemicals required.

Nanoparticles produced by the green synthesis method always maintain some properties derived from the reagents used. For example, bioactive molecules retained on nanoparticle surfaces often enhance their antioxidant and antibacterial properties. Iravani [13] noted that AgNPs synthesized using green tea extract showed stronger antibacterial activity. Similarly, Jahangeer et al. [11] found that ginger-mediated AgNPs demonstrated better antioxidant effects compared to chemically synthesized counterparts.

7. Existing Challenges of Green Synthesis

Although the green synthesis method has many advantages, including low toxicity and biodegradability, there are still some challenges that researchers need to overcome.

7.1 Lack of Standardization

Due to the different substances contained in plant extracts, variations in concentration and purity of the reagents can affect the quality of the formed nanoparticles. Based on Mittal et al.[3], One of the major limitations of green synthesis is the inconsistency in the composition of plant extracts used, which varies with season, geographical location, and method of extraction.

Compared to the traditional chemical reduction method, green synthesis, which controls morphology by adjusting the temperature and intensity of light, emphasizes external parameters such as pH and concentration of bioactive compounds. As a result, nanoparticles synthesized via green routes often have a wider range of sizes or inconsistent morphologies. For example, Nasrollahzadeh [12] reported that varying the pH from 4 to 10 when using Aloe vera extract to synthesize AgNPs could result in a change in particle diameter from approximately 42 nm to 7 nm. The change also affected the morphology from irregular polyhedral shapes to uniform spherical particles. Such sensitivity reflects the difficulty of achieving consistent nanoparticle quality under green synthesis conditions.

7.2 Limitation in Reducing Capacity

Not all plant extracts are equally effective in nanoparticle synthesis, and their reducing efficiency can be significantly weaker than that of strong chemical reductants used in traditional chemical reduction methods, such as $NaBH_4$ and $N_2H_4 \cdot H_2O$. Even within the same class of phytochemicals (such as polyphenols or flavonoids), reduction rates and yields can vary significantly. Nasrollahzadeh [12] and Ahmed [9] both noted that some plant extracts may be able to reduce Ag^+ efficiently (e.g., within minutes under optimal conditions). In contrast, they exhibit limited activity with ions such as Au^{3+} or Cu^{2+}, which require extended reaction times or ultimately prove unsuccessful. For example, Stamenic leaf extract required over 30 minutes to form visible AgNPs but was ineffective at reducing Au^{3+} in the same conditions. In contrast, chemical reduction with the reducing agent $NaBH_4$ typically completes within tens of seconds to a few minutes, yielding highly monodisperse nanoparticles.

7.3 Stability and Preservation of Active Compounds

The plant extracts used as reducing agents and stabilizers are generally unstable during long-term storage or under poor environmental conditions. The decomposition of these active components could significantly impact the reproducibility and efficiency of nanoparticle synthesis. Thus, the difficulties in delivering and storing these reagents are significantly increased, resulting in higher costs for operators.

Polyphenolic compounds are susceptible to changes in conditions due to their multiple hydroxyl groups. They are very likely to be oxidised when exposed to light, oxygen, or heat. As a result, their plant extracts need to be stored in sealed, dark containers at low temperatures (2–8°C), and it is preferable to store them in an environment with a high nitrogen content. Even under proper conditions, their activity is short-lived, which makes long-term storage and large-scale applications challenging.

The structures of flavonoids and terpenoids are highly vulnerable to conditions of alkalinity, high temperatures, or ultraviolet exposure. Additionally, their reducing capacity can decrease significantly in aqueous solutions, so they are often used immediately after preparation or storage at sub-zero temperatures. The storage environment also demands strict control of humidity and oxygen levels. In some cases, inert gas packaging is necessary to prevent oxidative decomposition.

These substances are sensitive to other microbes and high temperatures. They typically require low-temperature storage (≤−20°C) when in aqueous conditions. In dry powder form, they must be stored in a condition with no microbes and water to avoid hydrolysis and structural deterioration.

8. Conclusion

Traditional chemical reduction methods have the advantages of high reaction efficiency, controllability, and scalability. These features make them the most prevalent method for producing nanoparticles currently. However, hazardous reducing agents (e.g., $NaBH_4$, hydrazine) and toxic stabilisers are always needed in this process, which pose environmental and health risks. Additionally, the cost of installing safety measures and proper disposal systems is significant.

In contrast, green synthesis methods that use plant extracts instead of traditional reagents present fewer threats to operators and the environment. It utilises renewable natural resources and often integrates both reduction and stabilisation in a single step. This method is widely regarded as a promising future direction in nanomaterial fabrication, as it aligns with the principles of sustainable development.

Nonetheless, green synthesis still has some significant limitations, including slower reaction rates, lower yields, and difficulties in standardizing the composition of plant extracts. Moreover, the sensitivity of biomolecules to experimental conditions (e.g., temperature, light, pH) makes storage and large-scale production more difficult.

Therefore, although green synthesis has made a pivotal advancement toward safer and eco-friendly nanotechnology, further efforts are required to enhance its reaction efficiency, reduce costs, and develop standardized protocols for general industrial applications.

Acknowledgments

Jianxiao Gao, Chenyang Zhang, Wuyang Zhu, Yiran Xin, Yifan Feng, Yale Zhu, Guanyu Chen, Jiamo Wu, Yiyan Xu, Sichen lin.

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