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Review article

Insights Into Green Synthesized and Chemical Synthesized Nanoparticles for Biomedical and Animal Health Applications

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Abstract
Nanotechnology has gained considerable attention due to its ability to modify the chemical, physical, and optical properties of metals through nanoscale engineering. Consequently, substantial efforts have been directed toward developing novel approaches that employ biological sources for the synthesis of nanoparticles with controlled sizes and compositions. Many conventional synthesis methods are costly, environmentally hazardous, and inefficient in terms of material and energy consumption. The properties of nanoparticles are influenced by several factors, including time, temperature, pH, and ambient conditions. Eco-friendly nanoparticles also demonstrate significant potential in agriculture and animal sciences, where they contribute to environmental protection, improved productivity, and enhanced animal health. Comprehensive characterization of synthesized nanoparticles is essential, particularly for their applications in drug delivery, biomedicine, and veterinary sciences. Green-synthesized nanoparticles offer advantages in biocompatibility and sustainability, whereas chemically synthesized nanoparticles provide greater control over particle properties and functional versatility. The selection of an appropriate synthesis approach depends on application-specific requirements, economic considerations, and sustainability goals. This review primarily focuses on green and chemical synthesis methods, their economic implications, and applications in biomedicine, veterinary, and animal science–related fields.

Keywords: Green synthesis; chemical synthesis; economic impact; biomedical and veterinary applications

1. Introduction

Nanotechnology is a multidisciplinary field focused on the manipulation of materials at the nanometer scale, typically involving nanoparticles (NPs) with dimensions ranging from 1 to 100 nm [1]. At this scale, nanomaterials exhibit unique physicochemical properties, including a high surface-area-to-volume ratio, enhanced reactivity, and distinct mechanical, optical, and electrical characteristics, which make them highly attractive for biological and medical applications [2]. Due to these properties, nanoparticles have demonstrated significant potential in antibacterial therapies, disease diagnostics, and therapeutic interventions. As reported by El-Belely et al. [3], nanoparticles are widely applied in medicine, environmental protection, cosmetics, and related life-science fields.

Despite these advantages, researchers in materials science continue to face challenges in developing biocompatible and sustainable nanomaterials, particularly for biomedical and animal health applications. Considerable effort is required to address issues associated with conventional plastics used in medicine and the increasing prevalence of antibiotic-resistant microorganisms. Variations in the physical and chemical composition of nanocomposite materials significantly influence their mechanical strength and biological performance (Figure 1) [4]. Compared with bulk materials of the same composition, nanoparticles exhibit superior functional properties, including enhanced flexibility, mechanical strength, and electrical conductivity, enabling their application across diverse biological systems [5].

Nanoparticles synthesized through biological or green approaches are often more stable and uniform in size due to the mild reaction conditions involved, such as ambient temperature, neutral pH, and atmospheric pressure, which also reduce production costs and environmental impact [5,6]. Advanced characterization techniques play a crucial role in determining the suitability of synthesized nanoparticles for applications in drug delivery, biomedicine, and veterinary sciences. In addition, nanoparticles are increasingly utilized in environmental remediation and agricultural systems, including water purification and nutrient management, which indirectly influence animal health and ecosystem stability. For example, zinc oxide (ZnO) nanoparticles have been employed for the removal of arsenic and sulfur contaminants due to their high surface reactivity.

However, conventional chemical synthesis methods often suffer from limitations such as high energy requirements, complex processing conditions, potential toxicity, and the accumulation of hazardous chemical residues on nanoparticle surfaces, which restrict their safe application in biological systems [7]. In contrast, green synthesis approaches offer environmentally friendly alternatives with improved biocompatibility. This review therefore compares green and chemical synthesis strategies, with particular emphasis on their economic implications and applications in biomedicine, animal sciences, and related life-science fields.

2. Green Synthesis/Methods of Extractions

Green-synthesized nanoparticles, which are made using eco-friendly processes, have several benefits. They are ideally suited for biomedical functions because of their innate biocompatibility, which lowers the possibility of negative reactions when interacting with biological systems [7]. These nanoparticles are a perfect fit for the expanding need in healthcare for environmentally friendly and sustainable solutions. When natural or renewable materials are used in their synthesis, the environmental impact is reduced and a more conscientious approach to nanoparticle synthesis is encouraged. Additionally, some green synthesis techniques can be economical, which could result in more reasonably priced medical diagnoses and therapies. Furthermore, biomolecules can be easily functionalized onto these nanoparticles to enable targeted drug administration, molecular imaging, and the development of customized medicine strategies [1,7,8].

Green synthesis is the process of making materials, chemicals, or nanoparticles in a way that is good for the environment and has a small amount of environmental damage. This method often involves using resources that can be replenished, things that break down, and reaction conditions that do not harm the environment. Upadhyay et al. [8] say that the sizes of avocado fruits were cut and washed six times by double distillation and three times by ethanol to make them smaller. A magnetic mixer was used to keep heating 16 g of avocado and 170 mL of double-distilled water for 30 minutes. The watery solution made from avocado extracts was filtered with Whatman paper and kept at room temperature until needed. Using a triple bean balance, 10 g of $Zn(NO_3)$, $2.6H_2O$ was weighed and dissolved in 30 mL of double-distilled water for 30 minutes using a high-speed magnetic stirrer at a constant temperature. Then, 1.75 M of avocado extract was added to the $Zn(NO_3)_2.6H_2O$ mixture, which was mixed all the time for 1 hour. Now, the solutions had sat for 24 hours at room temperature. Papaya and mango were handled in the same way.

3. Chemical Synthesis Methods of Nanoparticles

Nanoparticles that are chemically manufactured offer exact control over their dimensions, form, and surface characteristics. Because of their accuracy, nanoparticles may be customized to fit certain biological needs, which makes them useful for applications like cancer treatment, drug administration, and imaging [9]. Chemical synthesis's consistency and reproducibility guarantee the dependability of medical interventions and diagnostics, which is essential for regulatory approval and clinical application. Furthermore, the chemically produced nanoparticles' functional diversity allows for the attachment of diverse functional groups, increasing their versatility for a range of biomedical applications, such as the targeted delivery of medicines. These approaches for chemical synthesis remain the focus of much study, which is pushing the frontiers of biomedical innovation with the discovery of new materials and processes [9].

As salt precursors, $Zn(NO_3)_2.6H_2O$, $Zn(CH_3COO)_2.2H_2O$, and $ZnSO_4.7H_2O$ were used in the chemical synthesis. NaOH, PVA, and KOH were used as reducing agents. Zinc oxide nanoparticles were made using the method described in Brar et al. [9]. By using a beam balance, all of the zinc salts and reducing agents were analyzed. Twelve grams of the sodium hydroxide (NaOH) solution were mixed with 70 milliliters of water distilled twice—thirty minutes under a soft magnetic mixer. Again, 4 g of $Zn(NO_3)_2.6H_2O$ was mixed into 30 mL of double-distilled water and stirred for 20 minutes. Drop by drop, the $Zn(NO_3)_2.6H_2O$ solution was added to the NaOH solution, which was constantly mixed for 2 hours at 60°C. At this point, gel-like solutions were made and left to cure in a 160°C oven for 10 hours overnight. Then, the sample was put in a kiln (Model: MC2-5/5/10-12, BIOBASE, China) and calcined at 300°C for 6 hours. Upadhyay et al., [8], did the same thing with zinc acetate ($Zn(CH_3COO)_2.2H_2O$) and zinc sulphate hydrate ($ZnSO_4.7H_2O$).

4. Economic Impact Synthesis of Green and Chemical Nanoparticles

The economic impact of green and chemical nanoparticles is multifaceted. Green nanoparticles, crafted through environmentally friendly processes, hold the promise of reducing environmental costs, opening up novel market opportunities, fostering innovation, and potentially offering cost efficiencies. As global sustainability gains prominence, demand for green nanoparticles in agriculture, energy, and healthcare is growing, stimulating economic growth. Moreover, these eco-friendly materials can navigate regulatory pathways more smoothly, further contributing to economic benefits [10].

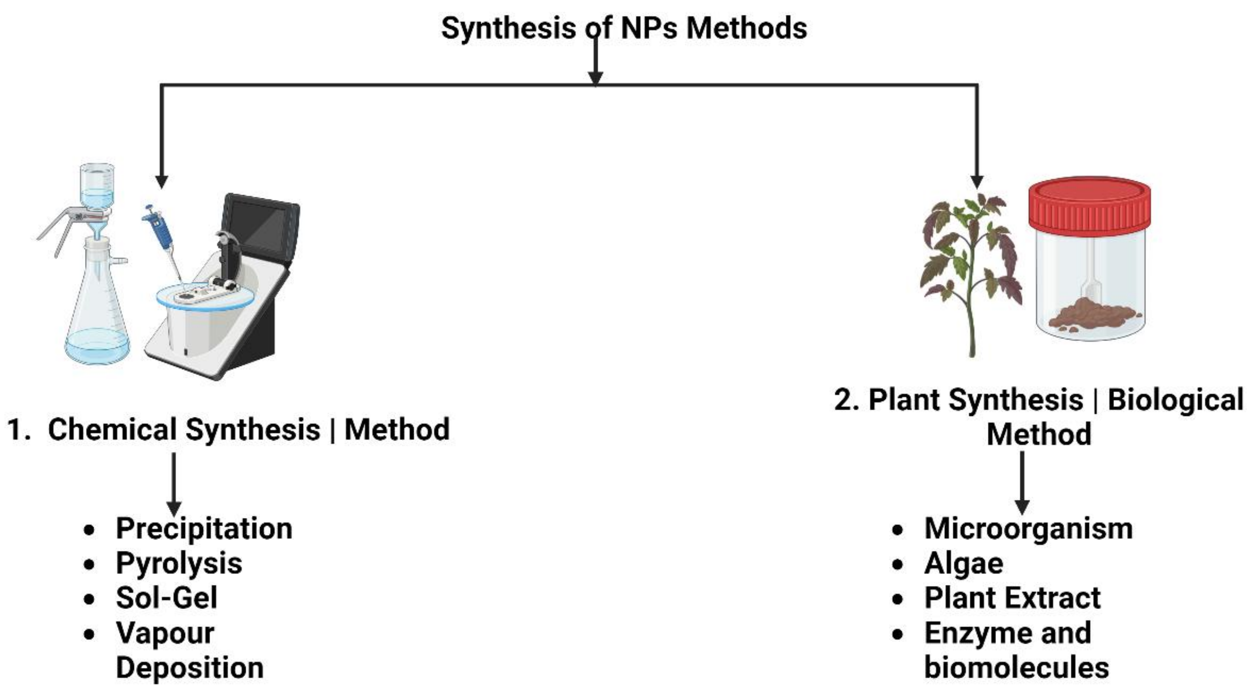

Figure 1 Chemical and plant methods for the synthesis of nanoparticles.

On the other hand, chemical nanoparticles, renowned for their diverse applications, advanced materials, and research-driven innovations, play a pivotal role in industries ranging from electronics to pharmaceuticals. This versatility generates economic impacts through enhanced product quality, job creation, and participation in a global market. Ultimately, the economic impact of both green and chemical nanoparticles is influenced by market dynamics, governmental policies, and the quest for sustainable solutions. Balancing economic gains with environmental and health considerations is imperative for ensuring the long-term viability of the nanoparticle industry [9].

Certain conditions must be met when making nanoparticles to get the best results and shape you want. Some of these conditions and factors are the ratio of the volume of the extracting solvent to the amount of plant material, the temperature, the concentration of the precursor solution, the pH of the solution, the reaction, and the time it is left to sit. Iron oxide NPs are one of the most common metal oxide NPs. Because ferrous oxide nanoparticles (IONPs) have a unique property, they can be used in medicine and many other fields, like gas monitors, electrochemical, magnetic, and energy storage [10, 11].

4.1. Cost of nanoparticles

Facilitating the widespread utilization of nanoparticles in contemporary applications necessitates regulating and controlling their production costs. Hence, a pivotal factor influencing nanoparticle manufacturing is the cost-effectiveness of the production process. While the chemical synthesis method offers rapid returns, it aligns poorly with cost-saving endeavours. Consequently, the feasibility of producing nanoparticles through chemical and physical approaches may be constrained, whereas the biological approach presents a more economical and scalable alternative [11].

The properties of nanoparticles are intricately linked to their size. Akbari et al. [11] established that their melting points decrease as nanoparticles reach the nanometer scale. Moreover, nanoparticles exhibiting different shapes possess comparable energy levels, rendering them amenable to shape alteration. The energy typically employed for nanoparticle investigation plays a role in inducing shape changes. Baer et al. [12] demonstrated that the morphology and mobility of synthesized nanoparticles significantly impact their chemical properties, underlining the significance of such aspects.

4.2. Time

The duration the reaction medium can remain undisturbed significantly influences the quality and characteristics of nanoparticles produced through green technology. Baer et al. [12] observed that the attributes of the synthesized nanoparticles also underwent alterations over time, with substantial sensitivity to the synthesis method, light exposure, storage conditions, and similar factors. Temporal variations can manifest in various ways, such as particle aggregation due to prolonged storage, size alteration due to extended storage duration, or even due to inherent shelf-life effects, all collectively impacting their potential [11].

4.3. pH

The pH level becomes a crucial factor when employing green technology approaches to synthesize nanoparticles. Studies have revealed that the size and morphology of the resulting nanoparticles are significantly influenced by the pH of the solution medium [13]. Consequently, adjusting the pH of the fluid can lead to modifications in the size of nanoparticles. Specifically, in the case of silver nanoparticles, altering the pH can directly impact their shape and size during the synthesis process [14].

It has been found that the pH, which is a measure of how acidic or basic the reaction medium is, is an important factor in making IONPs and other metal oxide NPs from plant materials. Jacob et al. [15] have written about how the pH of the solution medium affects the size and shape of NPs made from plant extract. So, Huang et al. [16] found that changing the pH of the fluid was a good way to control and change the shape and size of the NPs that were made. Lenders et al. [17] found that the best way for Aeromonas hydrophile to make IONPs was when the pH of the basic medium was between 7 and 9.

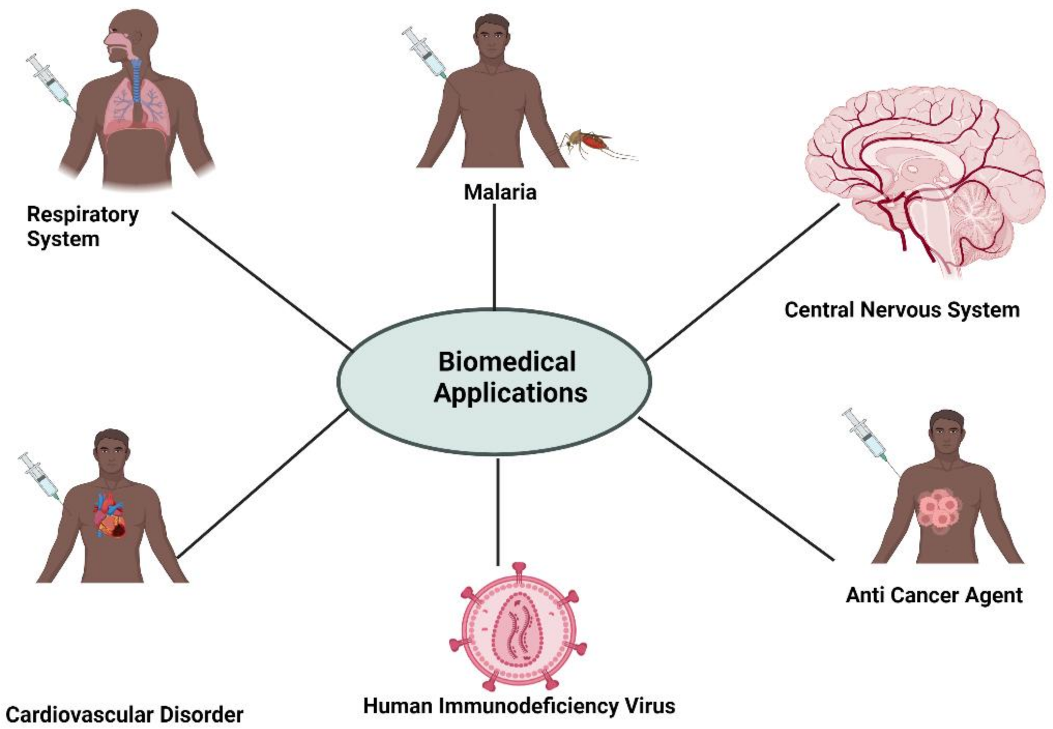

Figure 2 Green synthesis of metal nanoparticles and their applications

It has been said that the biosynthesis that happens at pH 12 and 4 totally slows down the making of IONPs. This showed that conditions that are too acidic or too basic are not good for making IONPs from plant material [17].

4.4. Temperatures

Temperature stands out as one of the paramount factors influencing the physical, chemical, and biological methods of nanoparticle (NP) synthesis. According to Patra et al. [18], the green production of iron oxide nanoparticles (IONPs) via plant extracts necessitates a temperature range spanning 25 to 100 °C. However, many researchers lean towards room-temperature synthesis for IONPs due to the instability of secondary molecules within plant extracts required to bio-reduct iron ions at elevated temperatures. Notably, the shape of NPs is influenced by the temperature of the reaction solution, as highlighted by results from Patra et al. [18]. UV-visible studies of IONPs produced from various plant components within the temperature range of 30 to 40 °C demonstrated that completion of the synthesis occurred at 48 to 72 hours, indicating accelerated synthesis at higher temperatures. Conversely, the study revealed suboptimal IONP synthesis above 40°C due to the deactivation of biomolecules responsible for reducing the iron precursor, as elucidated by Rajendran & Sen [19].

4.5. Environment

The surrounding environment profoundly shapes the properties of nanoparticles, emerging as a pivotal determinant. Frequently, the transformation of a solitary nanoparticle into a core-shell nanoparticle occurs due to its interaction with the external milieu. This interaction involves absorbing materials from the surroundings or engaging with other substances, a process often facilitated by factors such as oxidation. This phenomenon underscores the intricate interplay between nanoparticles and their environment in sculpting their characteristics and behavior [21]. In biological systems, manufactured nanoparticles tend to develop a thicker and larger coating, altering their characteristics [22]. Additionally, the environment significantly impacts the resulting nanoparticles' physical shape and chemical composition. While limited instances demonstrate how the environment influences nanoparticle synthesis, specific observations stand out. For instance, their crystallinity immediately changed when zinc sulfide nanoparticles were transferred from a wet environment to a dry one. Similarly, the chemical properties of cerium nitrate nanoparticles vary according to the concentration of peroxide present in the surrounding fluid [13].

5. Applications of Nanoparticles

5.1. Biomedical Applications

Nanoparticles find extensive applications across diverse industries, the realm of biomedical sciences, the electronics sector various markets, the energy domain, and notably in the field of chemistry [23]. This multifaceted utility has sparked an escalating commercial demand for nanoparticles. Mainly, nanoparticles such as silver and gold, which rank among the most prevalent, have garnered significant attention due to their utilization in biomedical applications, the emergent nanotechnology field, and beyond [9].

Researchers have identified that naturally synthesized nanoparticles exhibit superior efficacy in treating diseases than nanoparticles produced through other physicochemical techniques. Plant-extracted metal nanoparticles manifest stability and easy degradability into distinct types, achieved by controlling variables like pH, temperature, retention time, and mixing proportions. Noteworthy examples of green metal nanoparticles stem from plant sources such as neem (Azadirachta indica) leaves, tulsi (Ocimum tenuiflorum) leaves, curry (Murraya koenigii) leaves, guava (Psidium guajava) leaves, and mango (Mangifera indica) leaves [25].

Metallic nanoparticles synthesized from various medicinal plants have demonstrated significant therapeutic attributes encompassing antimicrobial, insecticidal, antioxidant, wound-healing, antidiabetic, immunomodulatory, hepatoprotective, and anticancer activities (Fig. 2) [23]. Notably, Muhammad et al. [22] established that metallic nanoparticles sourced from medicinal plants offer substantial benefits within the biomedicine domain. The core concept driving the integration of green nanotechnology into agriculture revolves around its potential to mitigate environmental harm and reduce the expense associated with chemical applications. Green nanoparticles (GNPs) derived from diverse plant sources have additionally shown efficacy in curbing harmful emissions such as carbon dioxide, nitrous oxide, and methane. Furthermore, these nanoparticles augment agricultural productivity and mitigate health concerns among farmers.

The inherent phytochemical constituents within plants make them a valuable resource for this approach. Such constituents are cost-effective and environmentally benign. Green nanoparticles play a pivotal role in addressing the imperative of eliminating heavy metal pollutants from the environment. Notably, Jadoun et al. [23] demonstrated green nanoparticles' role in alleviating environmental toxicity, especially concerning heavy metal contamination in soil and water.

Given that various phytochemicals are distributed across different plant parts—roots, stems, leaves, seeds, and fruits—the method of synthesizing metallic nanoparticles through green synthesis is not only cost-effective but also less environmentally detrimental, proving more efficacious than other biological methods [9]. Generating green nanoparticles involves washing specific plant parts with tap or distilled water following extraction, filtration, and introducing specific salt solutions. Observable changes in solution colour signify successful nanoparticle production. Throughout the metallic nanoparticle synthesis process, phenolic acids such as ellagic acid, caffeic acid, protocatechuic acid, and gallic acid play a crucial role. Ali et al. [24] elaborate on the role of phytochemical agents that facilitate the reduction and stabilization of laboratory-produced metal nanoparticles.

5.2. Applications in Animal Sciences and Zoology

Beyond biomedical applications, green- and chemically synthesized nanoparticles are increasingly gaining importance in animal sciences and zoological research [24]. In veterinary medicine, nanoparticles are being explored for targeted drug delivery, improved vaccine formulations, antimicrobial treatments, and diagnostic imaging in livestock and companion animals [26]. Their nanoscale size enhances bioavailability and therapeutic efficiency while reducing toxicity.

In animal nutrition and aquaculture, nanoparticles contribute to improved feed efficiency, disease resistance, and water quality management [27]. Green-synthesized nanoparticles, in particular, are considered safer for animal systems due to their biocompatibility and reduced environmental footprint.

Furthermore, nanoparticles play a role in ecological and zoological studies by assisting in pathogen control, wildlife health monitoring, and environmental remediation that indirectly affects animal populations [28]. These emerging applications highlight the relevance of nanoparticle research within zoology, animal health, and conservation biology, thereby expanding their significance beyond conventional biomedical fields.

6. Conclusion

Nanoparticles are increasingly utilized across the medical, food, pharmaceutical, agricultural, and animal science sectors. Growing interest has focused on developing efficient, eco-friendly, non-toxic, and sustainable approaches for nanoparticle synthesis through green biotechnology. The use of plant-based resources for green nanoparticle production represents a rapidly advancing area of nanotechnology, offering significant environmental benefits and contributing to the sustainability of nanoscience. Ongoing and future research in green nanotechnology is expected to provide deeper insights into the factors influencing nanoparticle synthesis and advanced characterization techniques, thereby enabling their more effective and safer application in biomedical, veterinary, pharmaceutical, and zoological research.

Data Availability statement

The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

All authors declare that, they have no conflict of interest.

Author Contributions

Mahreen Fatima - Methodology, original draft preparation ; Maham Fatima - Helped in revision, give suggestion and correction. Both authors read and granted to the published this version of manuscript.

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