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Advances In Green Synthesis Of Nanoparticles: Sustainable Approaches And Environmental Applications

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ABSTRACT
Green synthesis (syn.) of nanoparticles (NPs) has been one of the methods replacing chemical ones. Traditionally, chemicals are utilised as agents for the syn. of NPs, while biogenic methods use organisms counting fungi, bacteria, green plants, and algae in the process. There are many advantages of this counting reduced toxicity of by-products, energy-efficient processes, and enhanced biocompatibility. Nanomaterials yielded through eco-friendly techniques have very distinctive physiochemical features which make them widely applicable in human and veterinary medicine, agriculture, environmental remediation, and even in industries. Finally, this review mentions different types of NPs synthesized greenly, along with their syn. phenomena, benefits, and environmental applications. Treatment, remediation of soil, and detection of different pollutants are the major areas for their use. Thus, green nanotechnology opens up a bright future in the invention of safer and more sustainable technologies.
Keywords: *Nanoparticles, Green syn., Sustainability and Environmental Benefits*

INTRODUCTION

Nanotechnology (NT) is an interdisciplinary field that combines physics, chemistry, biology, and engineering to create materials with a dimension between 1 and 100 nanometers. These NPs display unique properties counting increased surface area, reactivity, optical, magnetic, and quantum properties, making them relevant in various sectors counting medicine, electronics, agriculture, environmental remediation, and energy storage (Bayda et al., 2019). Nanoparticles have shown versatility in drug delivery systems, antimicrobial agents, biosensors, lightweight materials, and improved catalytic systems. Examples include titanium dioxide and zinc oxide NPs utilised in sunscreens, paints, and photocatalysis of pollutants. Silver and gold NPs in the medical domain produce anti-microbial and optical effects. However, conventional methods often use toxic chemicals and are high-energy-consuming.

Sustainable NT aims to make necessary amendments in the manufacturing and utilisation of nanomaterials to be harmonious with the ecosystem. Traditional chemical and physical methods can be harmful, produce hazardous waste, and interfere with natural green chemical reactions. Green syn. of NPs has emerged as a viable solution that aligns with eco-friendliness, environmental safety, and biocompatibility principles (Rabiee et al., 2022).

Green syn. utilises natural materials like plant extracts (PEs), bacteria, fungi, and algae instead of harsh chemicals, which act as reducing and stabilizing agents. These biological systems provide phytochemicals, good enzyme synergy, and functional properties of proteins, making it feasible to transform metal ions into NPs without utilising hazardous chemicals or harsh conditions. Green syn. is also the least expensive, scalable, and suitable for grafting with chemical compounds, making it suitable for applications in biomedicine and the environment (Wang et al., 2024).

This work looks to deliver a comprehensive overview of NPs, their unique properties, and wide-ranging applications, while emphasizing the need for sustainable syn. approaches. It highlights recent advancements in green syn. techniques, the biological sources utilised, and their potential to revolutionize NT by making it safer along with more environmentally responsible.

Categories of Nanoparticles Produced through Green Synthesis

This approach lies on different NPs of syn. in countingpects as metallic NPs (MNPs), metal oxide NPs (MONPs), polymeric NPs, carbon-grounded NPs, and quantum dots (QDs), emphasizing their unique features and applications.

Metal Nanoparticles (MNPs)

Metal NPs (MNPs) play a very important role in their application as antibacterial agents; thus, they find their utilises in biomedical applications counting wound healing, drug delivery, and antimicrobial coating. Recent studies highlight the role of these phytochemicals counting flavonoids, terpenoids, and polyphenols in the reduction of metal ions and stabilization of NPs (Sánchez-López et al., 2020; Velgosova et al., 2024; Edo et al., 2025).

Salix alba leaf-extracted gold NPs were very good for many pharmaceutical and biomedical applications due to their great antifungal activity and excellent antinociceptive and muscle relaxant properties. Gold NPs were also synthesized recently by various PEs counting Coffea Arabica, Croton Caudatus Geiseleaf extract and Aeromonas hydrophila (Fernando and Judan Cruz 2020). ZnO-NPs are typically found in sunscreens and are also useful in photocatalysis, while attention is being switched to CuNPs as a more promising antifungal and catalytic agent (Luque-Jacobo et al., 2023). Recent advances suggest great promise for MNPs in drug delivery systems as well as in the area of environmental remediation, counting heavy metal (HM) removal and wastewater treatment (Kazemi et al., 2023).

Metal Oxide Nanoparticles (MONPs)

Agarwal & Shanmugam, (2020) have indicated that is lemon-grounded development of ZnO NPs. The developed NPs had greater inhibition zones versus gram-negative and gram-positive bacteria compared to the chemically synthesized ones. The phytochemicals coated on the surface of synthesized green NPs proved to be biologically neutral and compatible. Such NPs are also produced utilising plants and PEs as a mode of syn. without having to keep up all the aseptic conditions required for the growth of bacterial along with fungal cultures. Kumar et al. also provided how Taghavi and his collaborators described carrying out research on MgO NPs development with the utilisation of Acacia (Arabian) gum. Here, gum Arabic is utilised to lower the precursor for MgO NP extraction at around 5.3 nm size of magnesium oxide NPs. This same group also mentioned how one can take another example of successful development of green synthesized MgO NPs described in the work made by Dobrucka, et al., utilising Artemisia abrotanum. This herb is utilised as a reducing agent in preparing MgO NPs. The MgO NPs synthesized were about 10 nm, and they enhanced antioxidant activity (Praveen Kumar et al., 2020).

Polymeric Nanoparticles

With biocompatibility, biodegradability, and tunable release profiles, polymeric NPs (PNPs) are the most widely applied nanocarriers for drug delivery, biomedical applications, and environmental remediation. PEs as reducing agents are useful for the biosyn. of chitosan NPs. The resultant NPs are biocompatible and biodegradable and are therefore potential candidates for applications in controlled-release drug formulations and tissue engineering. They also promise to be a bit safer in medical applications since there are no toxic by-products associated with toxic syn. methods. Green polymeric NPs obtained from renewable resources impart a green syn. with eco-friendly methods, as a sustainable solution for almost every automatic application of polymeric NPs (Wahab et al., 2024).

Carbon-Based Nanoparticles

The application of oils in spray pyrolysis has demonstrated the production of both MWCNTs and SWCNTs. Neem oil pyrolysis facilitated the formation of uniformly aligned multi-walled carbon nanotubes (MWCNTs), while eucalyptus and turpentine oils yielded single-walled carbon nanotubes (SWCNTs) with a thickness ranging from 0.79 to 1.71 nm (Saleh et al., 2024). Carbon nanotubes (CNTs) synthesized from turpentine oil were formed within 60 minutes at 700 °C, exhibiting dimensions smaller than those created from eucalyptus oil. Additionally, the CNTs based on turpentine oil had a significant level of graphitization and featured well-defined concentric shells. Additionally, carbon nanotubes derived from turpentine oil exhibited fewer flaws and had significantly enhanced current density capacity and field emission strength. A castor oil–ferrocene mixture in an ammonia solution produced nitrogen-containing CNTs via spray pyrolysis, yielding CNTs characterized by a unique bamboo morphology and a wavy tubular structure with a thickness of 50–80 nm (Osman et al., 2024).

Quantum Dots (QDs)

Quantum dots are unique semiconductor NPs that possess distinct optical properties, which include size-tunable fluorescence. Thus, they can be extensively utilised in imaging, sensors, and photovoltaics. Traditionally, quantum dots are produced by toxic chemicals and in high temperatures but greener ways of synthesizing the QDs have been sought, counting utilising PEs or other natural stabilizers. PEs like Coriandrum sativum (coriander) developed quality and high-stable fluorescent CdSe quantum dots. These green-synthesized QDs provide a safer and greener promise in taking up patients in biomedical imaging and diagnostics than the conventional QDs (Moradialvand et al., 2025).

Mechanism of Green Synthesis

Biologically synthesized NPs are the greenest alternative compared to chemical methods and utilize microorganisms, plants, and enzymes to produce metal and metal oxide NPs for various applications.

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Microorganisms counting bacteria, fungi, and algae are of utmost importance in biosyn. Bacteria like Pseudomonas and Bacillus can reduce metal ions by enzymatic processes resulting in NP formation. Fungi are even more efficient sources given the fact that they exhibit high tolerance to metals and secrete a number of proteins and enzymes necessary for NPs biosyn. Algae of Chlorella vulgaris and Sargassum species have also been involved in the syn. of silver, gold, and zinc oxide NPs taking advantage of their vast pool of phytochemicals (Karunakaran et al., 2023)

Plant-mediated syn. utilises extracts from various parts of plants, like leaves, fruits, or roots, to help reduce and stabilize substances. Phytochemicals like polyphenols, flavonoids, terpenoids, and alkaloids found in plants counting neem, tea, and garlic can help turn metal ions into NPs . The procedure entails the transfer of electrons from these phytochemicals to metal ions, leading to nanoparticle production. Neem leaf extract is extensively utilized for the syn. of gold NPs, while garlic extract is utilised for the syn. of silver NPs (Thatyana et al., 2023).

Enzyme-mediated syn., or microbially mediated NP syn., means that certain enzymes help turn metal salts into NPs. Enzymes like nitrate reductase and NADH-dependent reductase catalyze the reduction of metal ions . For instance, fungal systems have demonstrated the nitrate reductase-mediated syn. of silver and gold NPs. Compared with harsh chemical methods, these enzymatic processes are specific and bear some advantages, counting milder reaction conditions. Compared to traditional chemical syn., green syn. techniques are eco-friendly since they avoid the utilisation of toxic chemicals and high energy input. More compatible and functional properties of NPs are achieved utilising green syn. methods (Deka et al., 2025).

Advantages of Green Synthesis

Green syn. of NPs (NPs) is a sustainable and eco-friendly method that utilises nutrients like PEs, bacteria, fungi, and algae to transform metal ions into NPs without toxic chemicals or high energy inputs. These extracts contain phytochemicals like flavonoids and phenolics, enhancing their biocompatibility and functional properties. Green NPs have antimicrobial, antioxidant, and anticancer properties, making them ideal for drug delivery, tissue engineering, and environmental remediation. The process is generally performed under mild experimental conditions, low energy consumption, and cost-effective. Green syn. aligns with global efforts to minimize environmental damage and develop biomedical and industrial applications.

Challenges in Green Synthesis

Green syn. of NPs utilises biological agents like PEs and microorganisms, but faces challenges like inconsistency in extract composition, factors like plant species, growth conditions, extraction methods, and reaction parameters. Scaling up from laboratory to industrial level also poses challenges. Seasonal and geographical availability of biological resources limit practicality for large-scale production. Despite these challenges, green syn. is emerging as a promising area with further research needed to optimize protocols and make applications more reproducible.

Environmental Applications of Green Synthesized Nanoparticles

Green NPs (GNPs), synthesized via eco-friendly methods utilising biological agents, have emerged as promising tools for environmental remediation. Their applications span wastewater treatment, soil decontamination, bioremediation, air pollution control, and the development of environmental sensors.

Wastewater Treatment

GNPs have shown effectiveness in being entitled to the removal of HMs and organic pollutants from wastewater. Nanocomposites include carbon-grounded materials, polymer-grounded materials, and semiconductor-grounded materials that show a lot of adsorption capacity and photocatalytic activities so that toxic metals could be efficiently removed, counting chromium, mercury, and arsenic. Graphene-grounded nanomaterials have been widely reported to be utilised in removing HMs from wastewater due to their large surface area and functional groups.

In this regard, GNPs removed HMs and organic pollutants from waste-waters. Nanocomposites include carbon-grounded materials, polymer-grounded materials, and semiconductor materials that show much adsorption capacity and photocatalytic activities such that toxic metals could be well removed, counting chromium, mercury, and arsenic. Graphene-grounded nanomaterials have been widely reported for the removal of HMs from waste-waters due to their large surface area and multifunctional groups (Ahmad et al., 2023).

Heavy Metal Removal

Nanomaterials have been extensively utilized for the removal of HMs from water due to their remarkable capabilities. Abou-Zeid et al. (2018) created three bioadsorbents: tetramethyl piperidine oxide-oxidized

2,3,6-tricarboxylic cellulose nanofibers (T-CNFs) and TPC-cellulose nanofibers (TPC-CNFs), both with and without the polyamide-amine-epichlorohydrin crosslinker (PAE). They evaluated the efficacy of these adsorbents in purifying water contaminated with copper, lead, and calcium ions. The adsorption capabilities of crosslinked TPC-CNFs for lead and copper ions. Yuan et al. (2018) synthesized porous three-dimensional carbon composites from chitosan, demonstrating significant adsorption efficacy for Pb2+ and Cd2+ ions in aqueous solutions. The adsorption mechanism entails coordination and electrostatic interactions with functional groups found in carbon compounds generated from chitosan. Chitosan-grounded NPs exhibit potential for diverse environmental applications, especially in the removal of HMs from water, due to their distinctive characteristics and multifunctional capabilities. Continued research and innovation are essential to improve their efficacy and facilitate their practical application in water treatment operations.

Soil Remediation

Nano-enabled soil remediation has surfaced as a viable and sustainable method to restore degraded soil resources. Nanotechnology applications are economical and user-friendly, providing effective treatment and remediation methods to substantially reduce soil pollution. This investigates the capabilities of NT in soil remediation, focusing on HMs, pesticides, their residues, and persistent organic pollutants (POPs), while assessing their contribution to phytoremediation and bioremediation.

In soil remediation, GNPs have been utilised to cleanse dirty soils, mainly by applying nanoscale zero-valent iron (nZVI), which has been tested versus trichloroethylene, polychlorinated biphenyls, and organochlorine pesticides. The application of surfactants enhances the treatment efficiency for organic contaminants in soil in combination with Fe-grounded NPs (Vu & Mulligan, 2023).

Bioremediation

The diminutive dimensions of NPs render them appropriate for application in wastewater treatment. They possess distinct chemical, physical, and biological features that augment their use in many contexts. Various nanomaterials, including carbon-grounded nanocomposites and nanotubes, as well as metal and metal oxide-grounded nanomaterials, have been utilised for the removal of effluents from wastewater. Wastewater treatment techniques include photocatalytic degradation, adsorption, filtering utilising NPs, and monitoring various contaminants and pollutants (Palit & Hussain, 2020).

GNPs greatly facilitate the bioremediation effect regarding toxic and organic contaminants, counting pesticides. Studies showed that nano-TiO_2 could have a photocatalytic effect on organophosphorus and carbamate pesticides. Moreover, green syn. of NPs provides an agroecologically friendly method for the remediation of environmental waste, which can effectively affect carcinogens and HMs and hazardous water contaminated with dyes and pesticides (Singh et al., 2023).

Gas sensing

Gas sensing technologies hinge on metal oxide NPs counting zinc oxide (ZnO) and titanium dioxide (TiO2). These NPs are highly surface active, leading to increased interaction of target gases, counting carbon monoxide, nitrogen dioxide, and sulfur dioxide, with the gas sensing device. Their resistance varies with different exposed gases and thus can be utilised for real-time applications. The response time and selectivity of the sensing devices may be altered more by the additives and surface functionalization incorporated (Soni, 2024).

Air – Pollution

Efficient air pollution management commences with precise and dependable pollutant detection, which yields essential data for formulating control plans and assuring adherence to environmental regulations. Conventional detection technologies, although successful for certain pollutants, frequently exhibit drawbacks counting bulkiness, elevated operational costs, and inadequate sensitivity to trace-level contaminants. Nanotechnology has transformed pollutant detection with the introduction of improved materials and methodologies that demonstrate enhanced sensitivity and miniaturization potential (Svitlana Tsekhmistrenko et al., 2020).

Soil Enhancement

Chitosan NPs, which are generated from chitin, a natural polymer that can be found in the cell walls of fungi and crustaceans, have the potential to positively influence the growth and development of plants. Chitosan NPs display antifungal and antibacterial activity, which protects plants versus a variety of diseases. Their innate antimicrobial and antioxidant qualities contribute to the beneficial roles that they play in agriculture. By chelating metal ions and making it easier for plant roots to absorb them, they improve the plant's ability to take in nutrients effectively. Nanoparticles of chitosan stimulate cell division and enhance water retention, both of which contribute to the growth of roots and the improvement of seed germination. Nanoparticles of lignin increase the quality of soil by boosting the structure of the soil, increasing the capacity of the soil to retain water, and encouraging the activity of microorganisms. By expanding the surface area for nutrient adsorption and raising the availability of nutrients to plants, they make it easier for plants to take in minerals and nutrients. Through its ability to influence hormone syn. and regulate gene expression, lignin NPs are able to effectively stimulate root formation and increase plant growth (Sunil Kumar Verma et al., 2024).

CONCLUSION

In conclusion, there is a sustainable and environmentally friendly alternative to the conventional methods of syn. This alternative reduces the amount of harmful by-products that are produced and makes utilisation of natural resources counting PEs, microbes, and biopolymers within the production process. This is because these processes adhere to the principles of green chemistry, which makes them both environmentally and economically viable. As a result of the improvements, they have also found applications in various disciplines, primarily in the domains of water treatment, agriculture, and biomedical fields, and a significant scope of their application on a broad scale has been shown. The optimization of syn. parameters, stability, and mechanisms behind the syn. should be the primary focus of future research. This will allow for a more comprehensive consideration of the potential of green NT for applications in both the industrial and environmental sectors.

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