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Review Article

Eco-Friendly Nanoparticles in Drug Delivery: Insights from Plant-Based Systems

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ABSTRACT

The sustainable substitute for conventional nanomaterials, Plant-Derived Nanoparticles (PDNPs), employ green synthesis techniques to reduce their negative effects on the environment while increasing their medicinal effectiveness. Because of their low toxicity, biocompatibility, and biodegradability, these nanoparticles are perfect for targeted drug administration. Plant extracts' natural bioactive qualities, like their antibacterial and antioxidant capabilities, can work in concert to improve the therapeutic outcomes of medications that are encapsulated. This study addresses the synthesis, properties, and uses of PDNPs in medication delivery, emphasizing how they may combine better patient results with environmental sustainability. Green chemistry concepts combined with nanotechnology highlight the importance of PDNPs in developing sustainable drug delivery methods. This paper discusses how environmentally friendly nanoparticles especially those made from plant-based systems are emerging to transform medication delivery.

Keywords: Conventional Nanomaterials, Green synthesis, Biocompatibility, Biodegradability, Green Chemistry, Environmental sustainability.

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INTRODUCTION

Nanoparticles have significantly increased biomedical research and resulted in a new era of innovation because of enhanced payload protection and their remarkable loading capacity. Antibacterial drugs, biomedicine, bio-labelling, and agriculture are just a few of the fields where nanoparticles exhibit potential. Because of its numerous implementations in a range of domains, just like drug delivery, cancer treatments, biomarkers, cell identification, antimicrobial treatments, and diagnostics, nanoparticle research is gaining popularity (Eichhorn *et al*., 2022; Hassan *et al*., 2023; Bouafia *et al*., 2021). People have been using plant-based natural items as remedies to treat a variety of illnesses since ancient times. Based on customs and knowledge from the past, modern medications are mostly originated from herbs. These original natural resources provide approx 25% of primary pharmaceutical compounds along with their analogs that are now on the marketplace in general (Mohanty *et al*., 2017; Swamy *et al*., 2016). Novel drug discovery is based on natural molecules with diverse chemical bases. Recently, there has been interest in producing in synthetic form accessible lead compounds that mimic the biological properties of their equivalents in natural product-based medication development (Rodrigues *et al*., 2016). There are several physical, chemical, and biological ways to create nanoparticles, but biological methods are becoming more and more popular due to their ease of use, affordability, and capacity to modify the size, shape, and functions of nanoparticles (García-Quintero *et al*., 2021). Furthermore, the development of next-generation drug inventions, such as target-based drug delivery and discovery and the visualization of drug molecular interactions, has been facilitated by computational investigations. Considering these advantages, pharmaceutical companies are hesitant to increase their investments in drug delivery and research methods based on natural products. Instead, they are looking through the current chemical compound libraries to find promising novel medications. Neverthless, recent studies are looking into the use of natural chemicals to treat a number of serious illnesses, including diabetes, cancer, heart disease, inflammatory problems, and microbial infections. This is mostly due to the special benefits that natural medications offer, including reduced toxicity and adverse effects, cost effectiveness, and promising therapeutic outcomes. However, it is more difficult to use natural substances as medicine due to issues with their toxicity and biocompatibility. Many natural chemicals are not making it through the clinical testing stages as

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a result of these problems (Bonifácio *et al*., 2014; Thilakarathna *et al*., 2013; Watkins *et al*., 2015). *In vivo* instability, restricted solubility and bioavailability, poor body absorption, issues with target-specific delivery and tonic effectiveness, and probable adverse pharmacological effects are the main barriers to the use of large materials for drug administration. Therefore, addressing these significant issues may include employing cutting-edge drug delivery methods to target medications to certain bodily areas (Jahangirian *et al*., 2017; Liu *et al*., 2009). Nanomaterials, which are materials with dimensions between 1 and 100 nm, have a wide range of applications, including tissue engineering, drug delivery, microfluidics, biosensors, and microarray testing. By utilizing medicinal chemicals at the nanoscale, nanotechnology creates nanomedicines. Biomedicine, comprising nanobiotechnology, drug delivery, biosensors, and tissue engineering applications, has been transformed by nanoparticles (Mirza *et al*., 2014; Patra *et al*., 2014; Joseph *et al*., 2017; Arayne *et al*., 2007). Usually formed from atomic or molecular components, nanoparticles are tiny spheres. Smaller materials can therefore travel through the human body more readily than larger ones. The structural, chemical, mechanical, magnetic, electrical, and biological characteristics of nanoscale particles are distinct. Because of their capacity to encapsulate and deliver therapeutic pharmaceuticals to certain tissues with controlled release, nanomedicines have become increasingly popular. Nanomedicine combines nanoscience techniques with medical biology to prevent and treat diseases (Lam *et al*., 2017; Rudramurthy *et al*., 2016; Wang *et al*., 2018). Numerous physical, chemical, and biological methods can be used to create nanoparticles; however, biological methods are gaining popularity due to their ease of use, affordability, and versatility in modifying the shape, size, as well as functionalities of nanoparticles. Implementation of nanoparticles has led to significant improvements in medicine and healthcare, particularly in the fields of therapy, diagnostics, and pharmaceutical delivery. Ultra-high-resolution imaging systems, which support early identification and therapy monitoring, have been made possible by nanoparticles. They also act like transporter in delivery systems of medications, enhancing therapeutic effectiveness along with reducing associated adverse effects. Effectively, nanoparticles are useful in regenerative medicine, wound care, and tissue engineering (Parashar *et al*., 2022).

Nanoparticle in Drug Delivery

While several drug delivery methods have been effectively implemented in recent years, there remain obstacles. To ensure effective medicine delivery to target areas, new technology must be created. Nano-based medication delivery systems are being researched for more improved drug delivery methods. Biocompatible nanoparticles and nanorobots are examples of nanoscale materials used in nanomedicine for diagnostics, delivery, sensing, and actuation in living things. Low solubility drugs have difficulties in biopharmaceutical delivery, such as restricted diffusion into the outer membrane, decreased bioavailability following oral ingestion, increased intravenous dosage, and possible adverse effects from conventional immunization methods. Such limitations can be overcome using nanotechnology, which can also enhance the administration of medications (Saadeh *et al*., 2014; Golovin *et al*., 2015; McNamara *et al*., 2015; De Jong *et al*., 2008). Some of the difficulties with low solubility medications' biopharmaceutical delivery include restricted bioavailability following oral administration, limited capacity to diffuse into the outer membrane, enhanced intravenous dosage, as well as possible adverse effects during conventional immunization regimens (Oliveira *et al*., 2014; Holzinger *et al*., 2014). These limitations can be overcome and medication delivery enhanced using nanotechnology. Because it can alter characteristics including solubility, drug release patterns, diffusivity, bioavailability, and immunogenicity, nanoscale drug design is the most sophisticated approach for nanoparticle applications, which may lead to improved biodistribution, a longer medication life cycle, less toxicity and adverse effects, and more practical delivery techniques (Blanco *et al*., 2015; Wong *et al*., 2015). Engineered drug delivery systems target specific locations and release therapeutic substances in a regulated manner. Self-assembly occurs when building blocks spontaneously organize into specific forms or patterns (Lu *et al*., 2016).

Drugs can be delivered via nanostructures in two ways: passively and actively. Hydrophobic effects are primarily responsible for the incorporation of drugs into the internal cavity of the structure. Because of their low content and hydrophobic environment, nanostructure materials target specific locations and release the desired amount of medication (Kumari *et al*., 2012). In contrast, the latter method involves directly conjugating medicines to a carrier nanostructure material for convenient delivery.

Both active and passive drug delivery are possible using nanomaterials or nanoformulations. Active targeting is the process of binding to receptors at the target region by combining compounds such as peptides and antibodies with a medication delivery system. A drug transporter complex moves within the systemic circulation during passive targeting as well as, attaches itself with the target site in response to variables like pH, temperature, molecular site, and shape. Lipid components, cell membrane receptors, and antigens or proteins on cell surfaces are the body's main targets (Chen *et al*., 2016).

Types of Nanoparticles

Nanomaterials are fundamental components of nanotechnology. Nanomaterials are defined as having at least one dimension smaller than 100 nm. Figure 1 illustrated that, Categorization of nanomaterials can be done into four groups with respect to their dimensions and three groups according to the structure of the nanoparticles (Kolahalam *et al*., 2019).

Ecofriendly Nanoparticles

With uses in energy, agriculture, medicine, environmental remediation, and other fields, green nanoparticles have the potential to completely transform industries and help create a more sustainable future. Academics and companies looking for greener alternatives find green synthesis procedures interesting since they are economical, biocompatible, and ecologically benign. However, improving nanoparticle stability, repeatability, and size and shape control is crucial for their practical application (Osman *et al*., 2024). Research is primarily focused on cleaner and more environmentally friendly synthesis techniques. With enormous potential for creating nanoparticles, bio-based nanomaterial synthesis is a prospective substitute for conventional technologies. Numerous studies have shown microbes can manufacture nanomaterials. These particles can be retained intracellularly by bacterial species for use in navigation. Biomolecules like enzymes are used by living things, alike algae, plants, fungi, bacteria, along with animals, to create nanoparticles and decrease metal ions like silver (Gupta *et al*., 2023; Kulkarni *et al*., 2023). Compared to physicochemical methods, biological synthesis yields nanoparticles that are safer, more pure, and uniformly sized. Biological synthesis is an environmentally beneficial process since it adheres to green chemistry principles. The microbial activity of biologically generated nanoparticles is enhanced when biomolecules are used as stabilizing and capping agents. Microorganisms can deactivate pollutants through cooperative interactions, generate a variety of secondary metabolites, and multiply swiftly in confined spaces. Nanozerovalent iron particles can be produced by microbes (Monga *et al*., 2020).

Advantages and Limitations of Ecofriendly Nanoparticles

The advantages and disadvantages of these delivery systems are further examined in three sections: sustainable synthesis methods, improved drug delivery efficiency, and biocompatibility and safety.

Sustainable synthesis methods

Sustainable synthetic techniques may light the path for greener nano-delivery systems because they attempt to reduce environmental problems while maintaining performance. These strategies revolve on the use of biodegradable and nontoxic materials from renewable resources, green solvents, energy-efficient procedures with less hazardous waste, and correspond very closely with the concepts of green chemistry (Cerbu *et al*., 2025). Biosynthesis techniques: Despite conventional methods, bio-synthesis depends mostly on plant extracts to serve as the reducing agents and stabilization agents required to create nanoparticles, consequently offering a greener alternative (Bhardwaj *et al*., 2020). Plants contain an abundance of natural phytochemicals (e.g., polyphenols and flavonoids) that reduce metal ions and stabilize the produced nanoparticles. Meanwhile, crucial variables like pH, temperature, and plant extract quantity can be changed to modify the nanoparticles' size and structure (Miu *et al*., 2022; Mishra *et al*., 2024).

Improved Drug Delivery Efficiency

Novel sustainable nanodelivery technologies have opened up a new channel and demonstrated potential in improving drug delivery by increasing efficiency and overcoming limitations associated with old delivery tactics. These methods promote stability, restrict early breakdown, and even allow for tailored administration by utilizing biocompatible/biodegradable components (e.g., polysaccharides, lipids, or plant-derived polymers) (Mishra *et al*., 2013). Because of their nanoscale dimensions, they enable medications to transcend physiological barriers that are typically difficult to overcome with traditional therapies (for example, the blood-brain barrier). This increases therapeutic efficacy through local delivery while reducing systemic negative effects by concentrating the active material at the place of application (Hersh *et al*., 2022).

Biocompatibility and Safety

The biocompatibility and safety of eco-friendly nano-delivery technologies are critical for their effective application in various industries, particularly biomedicine. Biodegradable and green nanomaterials, especially those manufactured using ecologically friendly processes, have promising safety characteristics. However, toxicological studies are crucial since nanoparticles can cause serious health problems through a variety of exposure pathways, including ingestion and inhalation (Zaheer *et al*., 2022; Shin *et al*., 2015). Toxicity is controlled by nanoparticle parameters, including size and surface area. While acute toxicities have been addressed, long-term effects remain poorly understood. This highlights the necessity for rigorous chronic toxicity evaluations, not only for the eco-friendly nanodelivery system itself, but also for its combination with the active substance that is being delivered.

Synthesis of Eco-friendly Nanoparticles

Green nanoparticle production using plant components is a sustainable and environmentally beneficial strategy. This novel method reduces metal salts and produces nanoparticles by using plant extracts from leaves, stems, roots, and fruits (Figure 2). This technology produces nanoparticles with unique properties without using harsh chemicals or energy-intensive processes, reducing environmental impact. One common biosynthetic method for creating metal nanoparticles is the creation of nanozerovalent iron via plant-mediated synthesis (Majeed *et al*., 2021). Phytochemical substances with a range of functional groups can decrease metal ions into iron nanoparticles. Through processes fueled by superoxide, metallothioneins, glutathione, ascorbates, polyphenols, can chelate metal ions and also encourage the formation of stable nanoparticles. Combining metal ions (such as ferric or ferrous chloride) with a plant extract with an aqueous solution is such a typical synthesis method. Within minutes to hours, the extract's phenolic hydroxide groups combine with ferric or ferrous ions to form iron nanoparticles (Sahoo *et al.*, 2022). By acting as stabilizers, biomolecules reduce the aggregation of nanoparticles. They act as stabilizing and capping agents and reduce metal ions. When it comes to producing nanozerovalent iron, plant extracts provide a number of benefits. For example, they are less poisonous and more soluble in water. Furthermore, plant extracts generate a greater number of nanoparticles with longer half-lives and a variety of forms, including irregular, square, and round. Biomolecules are used in plant extracts from leaves, stems, seeds, roots, and fruits to lower metal ions. Many different types of secondary metabolites can be found in plant components, such as proteins, enzymes, amino acids, vitamins, polysaccharides, alkaloids, flavonoids, polyphenols, and organic acids (Wu *et al.*, 2021).

Mechanism of Nanoparticles in Drug Delivery

Green biosynthesis of nanoparticles uses biological systems like bacteria, fungi, plants, or microorganisms to produce nanoparticles and decrease metal ions. Enzymes, proteins, and metabolites are examples of biomolecules that are essential to this process. Because they may take part in complicated synthesis and catalytic events, enzymes hold great promise for biotechnology research and applications. Attaching enzymes or substrates to nanoparticle surfaces has been proven to boost catalysis (Bishnoi *et al.*, 2018). Enzymes catalyze metabolic reactions, contributing significantly to cellular activity. Because reaction components naturally interact at the active site, the catalytic efficiency is high. Folded nucleic acids and peptides work together to arrange materials at the active site and activate heme due to their chemical complementarity (Teli *et al.*, 2025; Bilal *et al.*, 2023). These discoveries have major implications for developing supramolecular enzyme mimics (Chapman *et al.*, 2019; Dhingra *et al.*, 2010). The unique catalytic properties of enzymes are attributed to their three-dimensional folding, which organizes crucial functional groups with respect to their active site (Liu *et al.*, 2017). One of the hardest things in catalyst design is to replicate the intricate 3-dimensional structure of the active site of an enzyme.

Applications in Drug Delivery

In industries like biomedicine, agriculture, the environment, food, sensing, and electronics, green nanomaterials have achieved tremendous strides. Green nanoparticles have several applications, including the development of efficient sensors, the improvement of food quality, the reduction of environmental pollution, electrical technology innovation, and medical diagnosis and treatment (Figure 3). Because of their distinctive form, small size, enormous surface area, special physico-chemical properties, nanoparticles thrive in a wide range of industries. Because of their adaptability and potential for broad use, green nanomaterials are an important topic of scientific and engineering research.

Anticancer Treatment

Cancer is a leading cause of death worldwide. Ongoing research aims to identify viable treatments for this cancerous condition. Chemotherapy, surgery, and radiotherapy pose significant hazards for patients. Potential risks include medication instability, damage to healthy cells, and inadequate therapeutic delivery to malignancies. It is essential to find a new treatment approach to deal with these restrictions (Sun *et al.*, 2022; Jena *et al.*, 2024; Garg *et al.*, 2021). Green nanoparticles exhibit strong anticancer capabilities against several cancer cell types. Green nanoparticles showed strong anti-tumor action against a large number of cancer cells without causing any damage. Better treatment choices for

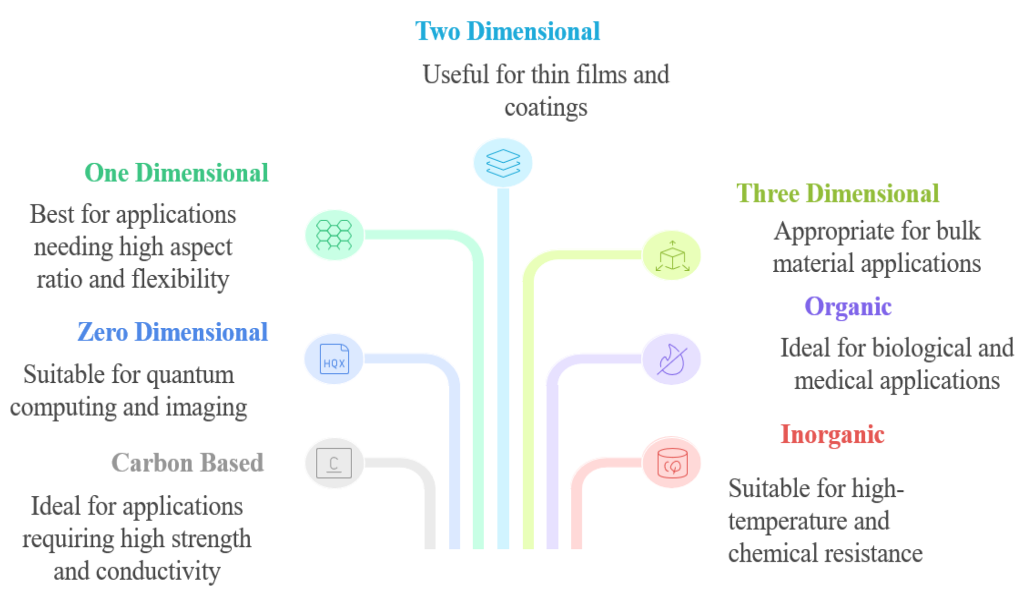

Figure 1: Classification of Nanoparticles.

this debilitating illness may result from this innovative therapy method. Nevertheless, the majority of studies do not contain *in vivo* testing for validation regarding the effectiveness of green nanoparticles as anti-tumor agents.

Antibacterial effects

Due to their ease of entry into the body, harmful microorganisms found in our surroundings pose a serious risk to human health. Drug resistance brought on by overuse of antibiotics has made treating many infections more difficult. The goal of ongoing research is to find antibacterial medications that effectively treat these complicated infections. Green nanoparticles have the potential to have antibacterial effects on both gram-positive and gram-negative bacteria. Nevertheless, it is unknown what mechanisms underlie the bactericidal and growth-inhibiting actions. Nanoparticle parameters, such as shape, size, and surface area, significantly impact their ability to destroy bacterial cells. Nanoparticles may interact with cell walls/membranes or penetrate bacterial cells, causing their demise. Against a wide variety of bacterial species, green nanoparticles have demonstrated potent antibacterial qualities. The shape, size, and surface area of nanoparticles all contribute to the destruction of bacterial cells and greatly influence their antibacterial activity. Membrane rupture, deoxyribonucleic acid damage, and Reactive Oxygen Species (ROS) production are all part of bacterial cell disintegration. The precise interactions between nanoparticles and bacterial cells require further investigation.

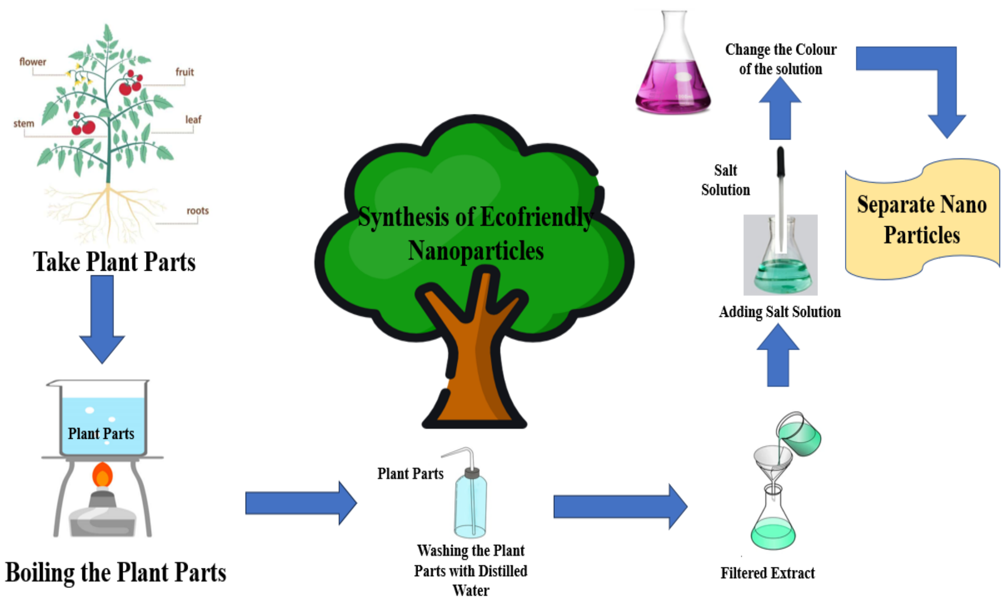

Figure 2: Synthesis of Eco-Friendly Nano Particles.

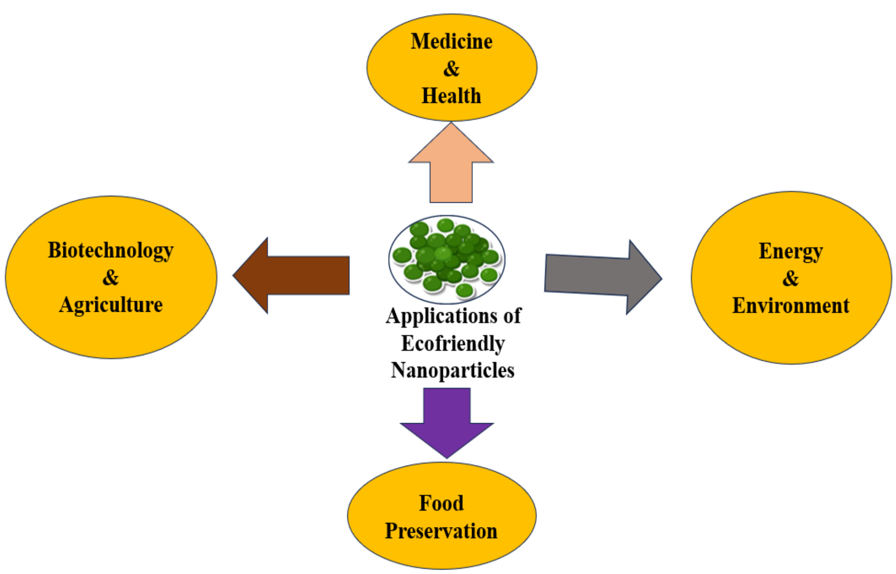

Figure 3: Applications of Ecofriendly Nanoparticles in various fields.

Future Directions and Emerging Trends

Nanomedicine is one of the most exciting study fields nowadays. Over the past 20 years, extensive research in this subject has resulted in 1500 patents and numerous clinical trials. Nonmedical technology has greatly aided in the diagnosis and treatment of cancer, as it was discussed in previous sections. In nanomedicine and nano-drug delivery systems, nanoparticles are utilized to precisely deliver drugs to tumorous or malignant cells without interfering with normal cell physiology. It is anticipated that this trend will last for decades. Even though they are widely acknowledged, nanomedicine and nano-drug delivery technologies still only slightly affect healthcare, especially the detection and treatment of cancer. The field is still in its early stages, with barely two decades of research and numerous unknown fundamentals. Future research should focus on identifying disease-specific biological markers that can be targeted without disrupting normal cell function.

CONCLUSION

Green nanotechnology has enormous potential for changing cancer therapy. Green nanotechnology integrates sustainable concepts into nanomaterial design, production, and application, providing creative solutions to overcome obstacles in traditional cancer therapies. Green nanotechnology-based drug delivery offers a sustainable and effective solution for cancer treatment due to its accurate targeting, regulated delivery, and low environmental impact. Nanotheranostics, stimuli-responsive nanomaterials, and nanoparticle-mediated immunomodulation signal a shift towards customized and complex cancer therapy techniques.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ABBREVIATIONS

PDNPs: Plant-derived nanoparticles.

REFERENCES

Arayne, M. S., Sultana, N., & Qureshi, F. (2007). Review: Nanoparticles in delivery of cardiovascular drugs. Pakistan Journal of Pharmaceutical Sciences, 20(4), 340–348.

Bhardwaj, B., Singh, P., Kumar, A. *et al.* (2020). Eco-friendly greener synthesisof nanoparticles. Advanced Pharmaceutical Bulletin, 10(4), 566–576.

Bilal, M., Khaliq, N., Ashraf, M., Hussain, N., Baqar, Z., Zdarta, J., Jesionowski, T., & Iqbal, H. M. N. (2023). Enzyme mimic nanomaterials as nanozymes with catalytic attributes. Colloids and Surfaces. B, Biointerfaces, 221, Article 112950. https://doi.org/10.1016/j.colsurfb.2022.112950

Bishnoi, S., Kumar, A., & Selvaraj, R. (2018). Facile synthesis of magnetic iron oxide nanoparticles using inedible *Cynometra ramiflora* fruit extract waste and their photocatalytic degradation of methylene blue dye. Materials Research Bulletin, 97, 121–127. https://doi.org/10.1016/j.materresbull.2017.08.040

Blanco, E., Shen, H., & Ferrari, M. (2015). Principles of nanoparticle design for overcoming biological barriers to drug delivery. Nature Biotechnology, 33(9), 941–951. https://doi.org/10.1038/nbt.3330

Bonifácio, B. V., Silva, P. B., Ramos, M. A. D. S., Negri, K. M. S., Bauab, T. M., & Chorilli, M. (2014). Nanotechnology-based drug delivery systems and herbal medicines: A review. International Journal of Nanomedicine, 9, 1–15. https://doi.org/10.2147/IJN.S52634

Bouafia, A., Laouini, S. E., Ahmed, A. S. A., Soldatov, A. V., Algarni, H., Feng Chong, K. F., & Ali, G. A. M. (2021). The recent progress on silver nanoparticles: Synthesis and electronic applications. Nanomaterials, 11(9), 2318. https://doi.org/10.3390/nano11092318

Cerbu, C., & Trif, E. (2025). Advantages and drawbacks of eco-friendly nano-delivery systems. Therapeutic Delivery, 11, 1–3.

Chapman, R., & Stenzel, M. H. (2019). All wrapped up: Stabilization of enzymes within single enzyme nanoparticles. Journal of the American Chemical Society, 141(7), 2754–2769. https://doi.org/10.1021/jacs.8b10338

Chen, G., Roy, I., Yang, C., & Prasad, P. N. (2016). Nanochemistry and nanomedicine for nanoparticle-based diagnostics and therapy. Chemical Reviews, 116(5), 2826–2885. https://doi.org/10.1021/acs.chemrev.5b00148

De Jong, W. H., & Borm, P. J. A. (2008). Drug delivery and nanoparticles: Applications and hazards. International Journal of Nanomedicine, 3(2), 133–149. https://doi.org/10.2147/ijn.s596

Dhingra, R., Naidu, S., Upreti, G., & Sawhney, R. (2010). Sustainable nanotechnology: Through green methods and life-cycle thinking. Sustainability, 2(10), 3323–3338. https://doi.org/10.3390/su2103323

Eichhorn, S. J., Etale, A., Wang, J., Berglund, L. A., Li, Y., Cai, Y., Chen, C., Cranston, E. D., Johns, M. A., Fang, Z., Li, G., Hu, L., Khandelwal, M., Lee, K.-Y., Oksman, K., Pinitsoontorn, S., Quero, F., Sebastian, A., Titirici, M. M., Frka-Petesic, B. (2022). Current international research into cellulose as a functional nanomaterial for advanced applications. Journal of Materials Science, 57(10), 5697–5767. https://doi.org/10.1007/s10853-022-06903-8

García-Quintero, A., & Palencia, M. (2021). A critical analysis of environmental sustainability metrics applied to green synthesis of nanomaterials and the assessment of environmental risks associated with the nanotechnology. The Science of the Total Environment, 793, Article 148524. https://doi.org/10.1016/j.scitotenv.2021.148524

Garg, R., Rani, P., Garg, R., & Eddy, N. O. (2021). Study on potential applications and toxicity analysis of green synthesized nanoparticles. Turkish Journal of Chemistry, 45(6), 1690–1706. https://doi.org/10.3906/kim-2106-59

Golovin, Y. I., Gribanovsky, S. L., Golovin, D. Y., Klyachko, N. L., Majouga, A. G., Master, A. M., Sokolsky, M., & Kabanov, A. V. (2015). Towards nanomedicines of the future: Remote magneto-mechanical actuation of nanomedicines by alternating magnetic fields. Journal of Controlled Release, 219, 43–60. https://doi.org/10.1016/j.jconrel.2015.09.038

Gupta, D., Boora, A., Thakur, A., & Gupta, T. K. (2023). Green and sustainable synthesis of nanomaterials: Recent advancements and limitations. Environmental Research, 231(3), Article 116316. https://doi.org/10.1016/j.envres.2023.116316

Hassan, S., Khurshid, Z., Sabreena, R. A., & Bhat, R. A. (2023). Green synthesized nanomaterials for biosensors. In Synthesis of bionanomaterials for biomedical applications (pp. 339–355). The Netherlands. https://doi.org/10.1016/B978-0-323-91195-5.00024-6

Hersh, A. M., Alomari, S., & Tyler, B. M. (2022). Crossing the blood–brain barrier: Advances in nanoparticle technology for drug delivery inneuro-oncology. International Journal of Molecular Sciences, 23(8), 4153. https://doi.org/10.3390/ijms23084153

Holzinger, M., Le Goff, A., & Cosnier, S. (2014). Nanomaterials for biosensing applications: AReview. Frontiers in Chemistry, 2, 63. https://doi.org/10.3389/fchem.2014.00063

Jahangirian, H., Lemraski, E. G., Webster, T. J., Rafiee-Moghaddam, R., & Abdollahi, Y. (2017). A review of drug delivery systems based on nanotechnology and green chemistry: Green nanomedicine. International Journal of Nanomedicine, 12, 2957–2978. https://doi.org/10.2147/IJN.S127683

Jena, D., & Mishra, K. (2024). Unlocking nature's pharmacy: A comprehensive review of pharmacological properties in the Cucurbitaceae Family. Research Journal of Pharmacy and Life Sciences, 5(2), 6–22.

Joseph, R. R., & Venkatraman, S. S. (2017). Drug delivery to the eye: What benefits do nanocarriers offer? Nanomedicine, 12(6), 683–702. https://doi.org/10.2217/nnm-2016-0379

Kolahalam, L. A., Kasi Viswanath, I. V. K., Diwakar, B. S., Govindh, B., Reddy, V., & Murthy, Y. L. N. (2019). Review on nanomaterials: Synthesis and applications. Materials Today: Proceedings, 18, 2182–2190. https://doi.org/10.1016/j.matpr.2019.07.371

Kulkarni, D., Sherkar, R., Shirsathe, C., Sonwane, R., Varpe, N., Shelke, S., More, M. P., Pardeshi, S. R., Dhaneshwar, G., Junnuthula, V., & Dyawanapelly, S. (2023). Biofabrication of nanoparticles: Sources, synthesis, and biomedical applications. Frontiers in Bioengineering and Biotechnology, 11, Article 1159193. https://doi.org/10.3389/fbioe.2023.1159193

Kumari, A., Kumar, V., & Yadav, S. K. (2012). Nanotechnology: A tool to enhance therapeutic values of natural plant products. Trends in Medical Research, 7(2), 34–42. https://doi.org/10.3923/tmr.2012.34.42

Lam, P.-L., Wong, W.-Y., Bian, Z., Chui, C.-H., & Gambari, R. (2017). Recent advances in green nanoparticulate systems for drug delivery: Efficient delivery and safety concern. Nanomedicine, 12(4), 357–385. https://doi.org/10.2217/nnm-2016-0305

Liu, Q., Wang, H., Shi, X., Wang, Z.-G., & Ding, B. (2017). Self-assembled DNA/peptide-based nanoparticle exhibiting synergistic enzymatic activity. ACS Nano, 11(7), 7251–7258. https://doi.org/10.1021/acsnano.7b03195

Liu, Z., Tabakman, S., Welsher, K., & Dai, H. (2009). Carbon nanotubes in biology and medicine: *In vitro* and *in vivo* detection, imaging and drug delivery. Nano Research, 2(2), 85–120. https://doi.org/10.1007/s12274-009-9009-8

Lu, H., Wang, J., Wang, T., Zhong, J., Bao, Y., & Hao, H. (2016). Recent progress on nanostructures for drug delivery applications. Journal of Nanomaterials, 2016, 20.

Majeed, S., Danish, M., Mohamad Ibrahim, M. N., Sekeri, S. H., Ansari, M. T., Nanda, A., & Ahmad, G. (2021). Bacteria mediated synthesis of iron oxide nanoparticles and their antibacterial, antioxidant, cytocompatibility properties. Journal of Cluster Science, 32(4), 1083–1094. https://doi.org/10.1007/s10876-020-01876-7

McNamara, K., & Tofail, S. A. M. (2015). Nanosystems: The use of nanoalloys, metallic, bimetallic, and magnetic nanoparticles in biomedical applications. Physical Chemistry Chemical Physics, 17(42), 27981–27995. https://doi.org/10.1039/c5cp00831j

Mirza, A. Z., & Siddiqui, F. A. (2014). Nanomedicine and drug delivery: A mini review. International Nano Letters, 4(1), 94. https://doi.org/10.1007/s40089-014-0094-7

Mishra, D., Hubenak, J. R., & Mathur, A. B. (2013). Nanoparticle systems as tools toimprove drug delivery and therapeutic efficacy. Journal of Biomedical Materials Research. Part A, 101(12), 3646–3660. https://doi.org/10.1002/jbm.a.34642

Mishra, K., Jena, D., & Goswami, S. (2024). Deciphering thePharmacological realm of ranibizumab in ophthalmology: Present insights and Future Prospects. Journal of Young Pharmacists, 16(4), 681–686. https://doi.org/10.5530/jyp.2024.16.87

Miu, B. A., & Dinischiotu, A. (2022). New green approaches in nanoparticlessynthesis: An overview. Molecules, 27(19), 6472. https://doi.org/10.3390/molecules27196472

Mohanty, S. K., Swamy, M. K., Sinniah, U. R., & Anuradha, M. (2017). *Leptadenia reticulata* (Retz.) Wight andArn. Molecules, 22(6), 1019. https://doi.org/10.3390/molecules22061019

Monga, Y., Kumar, P., Sharma, R. K., Filip, J., Varma, R. S., Zbořil, R., & Gawande, M. B. (2020). Sustainable synthesis of nanoscale zerovalent iron particles for environmental remediation. ChemSusChem, 13(13), 3288–3305. https://doi.org/10.1002/cssc.202000290

Oliveira, O. N., Jr., Iost, R. M., Siqueira, J. R., Jr., Crespilho, F. N., & Caseli, L. (2014). Nanomaterials for diagnosis: Challenges and applications in smart devices based on molecular recognition. ACS Applied Materials and Interfaces, 6(17), 14745–14766. https://doi.org/10.1021/am5015056

Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., Eltaweil, A. S., Abd El-Monaem, E. M., Mohamed, I. M. A., Badr, M. M., Ihara, I., Rooney, D. W., & Yap, P.-S. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. Environmental Chemistry Letters, 22(2), 841–887. https://doi.org/10.1007/s10311-023-01682-3

Parashar, S., Sharma, M. K., Garg, C., & Garg, M. (2022). Green synthesized silver nanoparticles as silver lining in antimicrobial resistance: AReview. Current Drug Delivery, 19(2), 170–181. https://doi.org/10.2174/1567201818666210331123022

Patra, J. K., & Baek, K.-H. (2014). Green nanobiotechnology: Factors affecting synthesis and characterization techniques. Journal of Nanomaterials, 2014(1), 219. https://doi.org/10.1155/2014/417305

Rodrigues, T., Reker, D., Schneider, P., & Schneider, G. (2016). Counting on natural products for drug design. Nature Chemistry, 8(6), 531–541. https://doi.org/10.1038/nchem.2479

Rudramurthy, G. R., Swamy, M. K., Sinniah, U. R., & Ghasemzadeh, A. (2016). Nano particles: Alternatives against drug-resistant pathogenic microbes. Molecules, 21(7), 836. https://doi.org/10.3390/molecules21070836

Saadeh, Y., & Vyas, D. (2014). Nanorobotic applications in medicine: Current proposals and designs. American Journal of Robotic Surgery, 1(1), 4–11. https://doi.org/10.1166/ajrs.2014.1010

Sahoo, S. R., Behera, S. K., Choudhury, D. K., Majhi, B., Jani, H., & Jena, D. (2022). A review on the antifungal activity of some traditional medicinal plants. European Journal of Pharmaceutical and Medical Research, 10(2), 135–139.

Shin, S. W., Song, I. H., & Um, S. H. (2015). Role of physicochemical properties innanoparticle toxicity. Nanomaterials, 5(3), 1351–1365. https://doi.org/10.3390/nano5031351

Sun, H., Wu, H., Teng, Q., Liu, Y., Wang, H., & Wang, Z.-G. (2022). Enzyme mimicking materials from designed self-assembly of lysine-rich peptides and G-quadruplex DNA/Hemin DNAzyme: Charge effect of the key residues on the catalytic functions. Biomacromolecules, 23(8), 3469–3476. https://doi.org/10.1021/acs.biomac.2c00620

Swamy, M. K., & Sinniah, U. R. (2016). Patchouli (*Pogostemoncablin Benth*.): Botany, agrotechnology and biotechnological aspects. Industrial Crops and Products, 87, 161–176. https://doi.org/10.1016/j.indcrop.2016.04.032

Teli, A., Jena, D., Saikia, L., Mondal, N. S., Sen, S., Mishra, K., & Gautam, M. K. (2025). Ethnobotanical use, Phytochemistry and Pharmacological Activities of *Clerodendrum colebrookianium* (Lamiaceae). Current Nutrition and Food Science, 21(2), 148–155. https://doi.org/10.2174/0115734013306525240321064009

Thilakarathna, S. H., & Rupasinghe, H. P. V. (2013). Flavonoid bioavailability and attempts for bioavailability enhancement. Nutrients, 5(9), 3367–3387. https://doi.org/10.3390/nu5093367

Wang, G., Gao, S., Tian, R., Miller-Kleinhenz, J., Qin, Z., Liu, T., Li, L., Zhang, F., Ma, Q., & Zhu, L. (2018). Theranostic hyaluronic acid-iron micellar nanoparticles for magnetic-field-enhanced *in vivo* cancer chemotherapy. ChemMedChem, 13(1), 78–86. https://doi.org/10.1002/cmdc.201700515

Watkins, R., Wu, L., Zhang, C., Davis, R. M., & Xu, B. (2015). Natural product-based nanomedicine: Recent advances and issues. International Journal of Nanomedicine, 10, 6055–6074. https://doi.org/10.2147/IJN.S92162

Wong, P. T., & Choi, S. K. (2015). Mechanisms of drug release in nanotherapeutic delivery systems. Chemical Reviews, 115(9), 3388–3432. https://doi.org/10.1021/cr5004634

Wu, J., Lin, M., Weng, X., Owens, G., & Chen, Z. (2021). Pre-adsorption and Fenton-like oxidation of mitoxantrone using hybrid green synthesized rGO/Fe nanoparticles. Chemical Engineering Journal, 408, Article 127273. https://doi.org/10.1016/j.cej.2020.127273

Zaheer, Y., Vorup-Jensen, T., Webster, T. J., Ahmed, M., Khan, W. S., & Ihsan, A. (2022). Protein based nano-medicine: Promising therapeutic modalities against inflammatorydisorders. Nano Select, 3(4), 733–750. https://doi.org/10.1002/nano.202100214

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