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Green Synthesized Nanoparticles as Emerging Therapeutic Agents: Mechanisms, Biomedical Applications, and Future Prospects

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ABSTRACT

The concept of green-synthesized nanoparticles (GSNPs) has arisen as a novel, sustainable and biocompatible to traditional methods of nanomaterial production, being less toxic and possessing more functionality by taking advantage of environmentally friendly synthesis pathways. The review gives an in-depth discussion of the biological processes, therapeutic uses and safety analyses of GSNPs, which may prove to be the next generation agents in nanomedicine. Natural reducing and stabilizing agents include plants, microorganisms, algae, enzymes, and biomolecules, as they allow the creation of nanoparticles with a regulated morphology and an enhanced stability in mild conditions. This is the reason why GSNPs have a wide range of therapeutic uses, such as antimicrobial, anticancer, immunomodulatory, and diagnostic, due to their unique physicochemical characteristics. As demonstrated in vitro and in vivo, GSNPs are less cytotoxic and more biodegradable than chemically prepared analogs, which proves their appropriateness in the fields of biomedical and environmental uses. The issues of reproducibility, ability to manufacture on a large scale and limited knowledge of nanoparticle-biomolecule interactions still make clinical translation difficult, though. The integration of artificial intelligence, omics technologies, together with standardized protocols of green synthesis in the future will likely

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accelerate the creation of safe, scalable, and multifunctional GSNP platforms. Together, GSNPs constitute a significant step towards sustainable nanotechnology whose potential for health care around the world and environmental care is immense.

Introduction

The particles that are between 1 and 100 nanometers are called and are predominantly distinguished by distinct physicochemical characteristics that diverge considerably from those in the bulk. With an unusually large surface area-volume ratio, their physical, chemical and biological behaviors are tremendously affected, which makes them useful in a variety of technological and biomedical purposes (Alvarez-Chimal and Arenas-Alatorre, 2023). Green synthesis. The green synthesis involves the use of biological resources to produce nanoparticles in a sustainable and environmentally benign technology. It uses natural substances like plant extracts, algae, fungi and bacteria as reducing agents, capping agents and stabilizing agents. As a result, green synthesis is a safer and more sustainable option to traditional chemical and physical synthesis pathways that frequently require the use of toxic reagents and consume a lot of energy, and generate environmental hazards (Singh et al., 2024; Alvarez-Chimal and Arenas-Alatorre, 2023). The focus of the eco-friendly nanofabrication techniques is to reduce environmental pollution, increase biocompatibility of nanoparticles and lessen human contact with toxic substances (Santhosh et al., 2022; Alvarez-Chimal and Arenas-Alatorre, 2023). GSNPs made in green synthesis have become of great interest in healthcare because of their high biocompatibility coupled with low toxicity and, more importantly, appropriateness in application in my medical field. Such environmentally friendly nanomaterials are widely studied in the framework of their application to in vitro and in vivo systems, specifically, wound healing, antimicrobial, anticancer, and targeted drug delivery (Mikhailova, 2023; Singh et al., 2024). The international movement to sustainable nanotechnology is indicative of a paradigm shift in material science, where integration of bio-compatibility, non-toxicity, and a renewable strategy for the design of nanomaterials is beneficial. GSNPs have their therapeutic effect that might be especially remarkable in the field of oncology. Green-synthesized gold and silver nanoparticles have already shown increased anticancer effects, specific delivery, and reduced systemic toxicity (Bharadwaj et al., 2021; Alharbi et al., 2022). These novelties underline how GSNPs can be transformed into a sustainable and efficacious healthcare provider in the creation of solutions based on nanomedicine (Mikhailova, 2023). Target areas of the scope of this review include: (i) the methodologies and the mechanisms involved in the green synthesis of nanoparticles, (ii) the physicochemical and biological properties of nanoparticles, (iii) various biomedical and environmental uses of nanoparticles and (iv) the benefits of developing and implementing green chemistry principles in sustainable technological development (Gautam et al., 2023; Pan et al., 2024). Mechanisms of underlying synthetic reads and biological response are essential in determining the optimal nanoparticle performance and its effectiveness and safety in targeted

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applications, e.g., antimicrobial therapy, drug delivery, environmental cleaning up, and energy storage (Rahat et al., 2024; Appiah et al., 2022). Moreover, the current paper emphasizes potential opportunities and difficulties of the GSNP study in the future. The scalability of the green synthesis process, as well as preservation of stability, homogeneity, and therapeutic efficacy of nanoparticles, is just one of the greatest limitations. The interaction of nano-biology also requires a deeper insight to conquer the barriers within biological applications of nanomedicine, especially in cancer nanomedicine. The use of emerging technologies, including machine learning and artificial intelligence, is expected to transform the design of nanoparticles and biosensing with ease of interpretation of complex biological data (Lazaro and Mooney, 2021; Singh et al., 2021).

Moreover, there are still problems of creating nanoparticles of constant quality and functionality that could satisfy certain therapeutic and industrial needs. Future studies need to focus on technological implementation and multidisciplinary teamwork in order to increase the usefulness of GSNPs beyond their present biomedical and environmental uses (Pan et al., 2024; Sungkawati, 2024). The solution to these dilemmas will be needed in order to achieve the full potential of the green synthesized nanoparticles in enhancing sustainable nanotechnology and global healthcare.

Biological Routes for Green Nanoparticle Synthesis

Plant-Mediated Synthesis

Plant-mediated assembly of nanoparticles is one of the most effective and nature-friendly ways of nanomaterial assembly. Plant extracts are used in this process as natural reducing and stabilizing factors that help in transforming metal ions into nanoparticles. Such mechanisms are reduced by a wide variety of phytochemicals, such as phenolic compounds, flavonoids, terpenoids, alkaloids, and an assortment of enzymes, among others, which intervene in the bioreduction of metal precursors to their nanoscale analogs (Singh et al., 2023; Munir et al., 2021). This is a one-step biosynthetic process that has several positive features: it is inexpensive, energy-saving, and produces no toxic substances, thereby minimizing the risks of environmental and health hazards. The natural occurring bioactive compounds in the plant extracts do not require the use of synthetic capping and stabilizing agents. More to the point, such reactions are usually carried out at ambient temperatures, which adds to the sustainability and scalability of the process (Dauthal and Mukhopadhyay, 2016; Parveen et al., 2016). The strategy is, however, not devoid of drawbacks. Unpredictability in plant metabolite composition can affect nanoparticle size, shape and stability, including problems in reproducibility and mass-scale manufacture. The standardization of the extraction process, the optimization of terms of synthesis, as well as knowledge in the field of plant-metal interactions are the aspects requiring further advancement (Singh et al., 2023; Fahim et al., 2024). A number of plant species have been studied in the fabrication of nanoparticles. Turneradiffusa, which contains bioactive compounds including oplopanone, g-eudesmol, among others, has been used in the manufacture of metal nanoparticles. In the same manner, Spinacia oleracea (spinach) has also been employed to

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produce silver nanoparticles that have strong antimicrobial effects (Reyes-Becerril et al., 2021; Miranda et al., 2022). They are secondary metabolite-based systems using plants in order to obtain nanoparticles with a wide range of uses in medicine, agriculture, catalysis, and environmental management (Hembram et al., 2018).

Microbial Synthesis

During microbial synthesis, bacteria, fungi and algae are used to synthesize nanoparticles biologically in vivo or in vitro via reduction processes. Reduction of metal ions may occur through intracellular or extracellular interaction between microorganisms with specific cellular morphologies and chemical composition to produce nanoparticles with different morphologies and compositions. Enzymes, proteins, and polysaccharides are examples of biomolecules that have central roles since they are reducing and capping agents that maintain the stability of nanoparticles and prevent aggregation (Eweis et al., 2024; Shaikh et al., 2024). Its positives are that microbial synthesis is eco-friendly, the cost of production is low, and biocompatible and stable nanoparticles can be obtained. Such biological systems are designed to work with mild physiological parameters, which is especially appealing in the biomedical domain, in the context of which low toxicity and increased functionality are required (Mikhailova, 2023; Eweis et al., 2024).

Furthermore, microbial systems are genetically engineered to regulate the synthesis routes of nanoparticles and provide a possibility of designing nanoparticles in a customized manner. However, there are still a number of challenges. It is not yet easy to achieve consistency in the morphology of nanoparticles and size distribution, and the biosynthetic pathways of nanoparticles in biochemistry are not completely understood. There are logistical, technical and biosafety challenges as well when the small-scale production in the labs is changed to a large-scale production. Also, the overall regulatory regulations on the toxicity and environmental impact of nanoparticles are yet to be established (Campana et al., 2023; Mughal et al., 2021). Irrespective of these challenges, microbial synthesis looks like a good future in eco-friendly nanotechnology. The future of biologically produced nanoparticles is in optimizing the conditions of cultures, learning the interaction of microbes with metals, and increasing yield efficiency (Khan et al., 2018; Olawade et al., 2024).

Other Biological Sources for Green Synthesis

Algae-Mediated Synthesis

The biological agents that are also beneficial in the preparation of nanoparticles are algae due to the presence of bioactive compounds, which contain proteins, polysaccharides, pigments and metabolites that are natural reducing and stabilizing agents. Algae-mediated synthesis is a fast, eco-friendly, and relatively inexpensive method of meticulously producing nanoparticles of varied sizes and shapes. The factors to consider are pH, temperature as well as incubation time. Silver nanoparticles with superb antifungal effects against the pathogenic fungi have been prepared with brown seaweed (Sargassum longifolium) as the

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biomaterial, indicatively (Rajeshkumar et al., 2014). The presence of nanoparticles prepared with the help of algae is valuable in the pollutant removal process, particularly in wastewater purification processes, due to their catalytic capability to address the contaminants (Alprol et al., 2023).

Enzyme-Mediated Synthesis:

Nanoparticles may also be produced through an enzymatic pathway through the reduction and stabilization of metal ions by enzymes. Silver and gold nanoparticles have been produced using b-amylase and sulfite reductase respectively to produce easily stable nanoparticles with shapes and size in control (Mishra and Sardar, 2012; Kumar et al., 2007). Enzymatic method is a better solution due to its specificity, good operating conditions and low concentration of the poisonous by-products. There is also the possibility of biogenic surfaces that result in the enhancement of stability and performance of nanoparticles due to the use of enzymes (Khan et al., 2022).

Biomolecule-Assisted Synthesis:

Other significant ingredients in the fabrication of the nanoparticles are biomolecules which primarily consist of proteins and polysaccharides to be used as reducing agents and capping agents simultaneously. These biomolecules facilitate the stability of formed nanoparticles in terms of morphology and size distribution. As an example, biomimetic production of hydroxyapatitenanoparticles with the use of bovine serum albumin (BSA) facilitates the correct regulation of particle size and shape (Nayar et al., 2006). These bio-molecule-mediated platforms are biocompatible in nature and molecularly specific, rendering them suitable for used in biomedical investigations such as targeted drug delivery, imaging and biosensor construction (Willner and Willner, 2010).

Therapeutic Mechanisms of Green-Synthesized Nanoparticles

Green-synthesized nanoparticles are characterized by exceptional physicochemical and biological properties on which the various therapeutic uses of nanoparticles, specifically as antimicrobials, anticancer, and immunomodulators, are based. They have an eco-friendly synthesis, and this increases their biocompatibility and reduces the possible toxicity, making them a suitable candidate to use in biomedical terms.

Physicochemical Properties Influencing Therapeutic Effects

Physicochemical properties of nanoparticles (size, shape, surface chemistry, and composition) have a significant impact on their biological activity and therapeutic capability. Smaller nanoparticles tend to be more prone to being picked up by cells and interacting with biological membranes compared to larger nanoparticles due to the higher surface-to-volume percentage ratio (Chung et al., 2016). Besides that, the shape and surface properties determine the reaction of nanoparticles with receptors and biodistribution and clearance rate readings (Singh et al., 2024). Surface modification is linked to green synthesis and tends to enhance the

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stability, dispersibility, and biocompatibility of the nanoparticles, making it easier to apply the nanoparticles to deliver drugs and treat different ailments (Zehra et al., 2025). The chemical composition of the nanoparticles based on the precursor materials used, as well as the biological reducing agents used, is immediately translated into the biological activity of the nanoparticles. In more detail, green-synthesized silver nanoparticles, in particular, the antimicrobial effect is usually linked to the broad range of operation (Banerjee et al., 2017). The capping agents involve natural biomolecules with the help of which the system is stabilized, aggregation is prevented, and the functional stability of the system in the long term is maintained (Chung et al., 2016). The electrostatic attraction and receptor-mediated endocytosis are used to exchange these nanoparticles with the biological systems, assisting in the internalization of the target cells (Roy et al., 2019; Fahim et al., 2024). The sum of these physicochemical attributes defines the effectiveness and safety, and the multi-modality in the therapeutic use of green-synthesized nanoparticles.

Antimicrobial Mechanisms

Nanoparticles produced by green synthesis (especially silver nanoparticles) have strong antimicrobial effects as a result of various mechanisms. They destabilize the cell membranes of bacteria by interacting with phospholipid layers, causing destabilization of the membrane, release of the intracellular elements and subsequent cell death (Kumavat and Mishra, 2024). Moreover, the nanoparticles prevent biofilm formation, a significant immune response of bacteria and can, therefore, avoid chronic and drug-resistant infections (Mousavi-Khattat et al., 2018). The production of reactive oxygen species (ROS) that lead to oxidative stress and cause the destruction of vital biomolecules, such as proteins, lipids, and nucleic acids, is another major antimicrobial effect (Roy et al., 2019). The complex activity of the nanoparticles synthesized using green chemistry ensures that the nanoparticles are very effective against a broad spectrum of pathogenic organisms.

Anticancer Mechanisms

The future of nanoparticles synthesized green in cancer therapy is good due to its ability to provide target therapy and minimal systemic toxicity. Their size is in nanoscale and thus can exploit the enhanced permeability and retention (EPR) effect in the tumor hence, accumulate selectively in tumor sites (Singh et al., 2024). Those nanoparticles can cause apoptotic and malfunctioning cell cycle in the cancer cells; increase intrinsic pathways by biomolecules that are produced on the surface during green synthesis (Boruah et al., 2021). Besides, they also control certain most significant oncogenic signaling pathways of proliferation, survival and metastasis. They are able to suppress tumor growth and development of diseases by altering the expression patterns of genes and prevent angiogenesis (Singh et al., 2024). The above-mentioned properties of the green-synthesized nanoparticle indicate its potential in the use as a multimodal agent in the control of cancer that can be utilized in the delivery of chemotherapeutic agents and also inherently, it has anticancer abilities.

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Immunomodulatory Mechanisms

Green-synthesized nanoparticles are also immunomodulatory in nature which also adds to their application in the process of therapeutic and vaccine. This is attributed to the fact that they are able to interface with the immune cells, control the secretion of the cytokine besides averting the oxidative stress. They are able to interact with the macrophages as well as dendritic cells, lymphocytes and to effect the generation of pro- and anti-inflammatory cytokines. The generation of the nanoparticles of silver by plants has been shown to control the induction of cytokines, thus controlling the immune actions in the instance of the example (Banerjee et al., 2017; Chung et al., 2016). Also of importance are nanoparticles synthesized green which could serve as antigen carriers and adjuvants during vaccine development because of their natural bio-compatibility and the size of the nanoparticles. They enhance the presentation of antigens, immunity activation and preventing the untimely degradation of antigens, and enhances the strength and stability of the vaccine (Goutam et al., 2019; Purohit et al., 2019). Other than this, such nanoparticles have the natural anti-inflammatory and antioxidant properties.. These inhibit pro-inflammatory mediators and eliminate free radicals thereby oxidative stress. Good antioxidative effect of nanoparticles made biologically contains silver and selenium that inhibits oxidative release of cellular components (Zambonino et al., 2021; Begum and Jayawardana, 2023). All these immunomodulatory, antimicrobial and anticancer effects of the green-synthesized nanoparticles indicate that it can have massive potentials as the environmentally friendly multi-purpose tool with the capacity to carry out even greater therapeutic tasks.

Biomedical Applications of Green-Synthesized Nanoparticles

GSNPs have now been regarded as powerful biomedical agents that have a tremendous potential to revolutionize the current biomedicine since their production is eco-friendly and can be programmed to suit the special needs of the physicochemical properties, and they have high biocompatibility. Their applications include antimicrobial treatment, cancer treatment, immunomodulation, diagnostics and imaging..

Antimicrobial Applications

Synthesis of silver nanoparticles (AgNP) by green method has been found to be very effective against the multidrug-resistant (MDR) pathogens. It has been proposed that the anti-microbial activity of AgNPs stems out of their ability to cause damage to bacterial membranes, generate reactive oxygen species (ROS) and anti-b biofilm. In such a way, they are mentioned to be active compounds which have been utilized in antimicrobial resistance (Chung et al., 2016; Roy et al., 2019). Polysaccharide-derived GSNPs have also been reported to possess enormous wound healing abilities because they possess anti-inflammatory, antioxidant and antimicrobial abilities. The nanoparticles support cell growth and tissue development and work against infection of the wound by microbes (Banerjee et al., 2017). Furthermore, the coatings and the biomaterials can be included with the GSNPs to give them prolonged antimicrobial properties. The

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property proves to be helpful at the times when the GSNPs cooperate with medical devices, surgical equipment, and hospitals to mitigate the risks of infection and improve patient safety (Roy et al., 2019).

Cancer Therapy

The gold nanoparticles (AuNPs) produced by green methods are one of the most promising nanocarriers of a cancer therapeutic. This selectivity of the nanoparticles to attack the tumor cells will minimize the systemic toxicity and will help in elevating the level of drugs in the region of the tumor (Bharadwaj et al., 2021; Nisha et al., 2024). Green nanoparticles also have numerous applications in photothermal therapy (PTT) and photodynamic therapy (PDT), where they will convert the absorbed light energy into heat (or reactive species) to kill targeted potentially are destroyed in cancer cells (Santhosh et al., 2022). In addition, GSNPs play a vital role in combination therapy and theranostics where both diagnostics and therapeutic functions can be integrated into the same nanosystem. This versatile nanoparticle can also transport drugs, offer imaging and real-time therapeutic responses during the same time, which is an important step toward customized and precision cancer medicine (Zafar et al., 2020; Selvakesavan and Franklin, 2021).

Immunomodulation and Vaccine Development

GSNPs can play vital immunomodulatory roles, enhancing the immunity and increasing the vaccination development. They increase the recognition of antigens and responsiveness of the immune system as adjuvants and thus, more effective in the production of more effective vaccines (Chung et al., 2016). They also have their power to regulate immune responses which have been used in immunotherapy to treat cancer and treat other conditions of autoimmune disorders. GSNPs can easily control immune signal pathways because of their biocompatibility and the ability to target specific sites providing drugs (Vijayaram et al., 2023). These can also be used to cure chronic inflammatory illnesses which include arthritis as their use is predisposed by their anti-inflammatory usage. GSNPs lower the discharge of tissue inflammation through cytokine release and oxidative stress that divides therapeutic impacts (Altammar, 2023; Zafar et al., 2020). The mentioned abilities highlight the therapeutic versatility of GSNPs and, by extension, their viability as alternatives to the traditional immunomodulatory and anti-inflammatory medications..

Diagnostic and Imaging Applications

The diagnostics, biomedical imaging products of green synthesis nanoparticles are also a colossal opportunity since there is potential of substituting the conventional materials with materials that are environmentally safe and economical. Nanoparticles of silver and gold produced through green method have broad application in biosensors due to their high optical and electronic characteristics. They can be highly functionalized with a high level of sensitivity and specificity to generate high-quality biosensing systems that are able to detect biomarkers in clinical diagnostics fast and sensitive (Chung et al., 2016;

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Vijayaram et al., 2023). Less surface area GSNPs possess a big surface area that permits them to act as successful contrast agents in medical images since they display optical tunability behavior. Specifically, the manufactured gold nanoparticles in the green colour have been used to enhance the contrast of the image in computed tomography (CT), magnetic resonance imaging (MRI), and photoacoustic imaging and are less toxic when compared to the conventional agents (Santhosh et al., 2022; Khan et al., 2018). To a larger extent, theranostic nanoplatforms, which include diagnostic and therapeutic attendees, are based on GSNPs. The systems permit multiple drug administration, real-time images and therapeutic monitoring. Further functionalization, to which ligands and therapeutic molecules are targeted, makes it possible to obtain more tumor specificity and less off-target effects, which is central to personalized nanomedicine (Rahman et al., 2022; Manikandan and Thomas, 2024).

Toxicology and Safety Considerations

Green synthesized nanoparticles (GSNPs) are one of the most promising, eco-friendly nanoparticles that have undergone new developments in nanotechnology. Nevertheless, their toxicologic profiles and safety issues, however, should be strictly assessed by means of in vitro and in vivo investigation to verify their biocompatibility and safety as well.

In Vitro Toxicity Studies

A number of in vitro toxicity tests have been done to determine cellular interaction properties of GSNPs, including silver and gold nanoparticles and their adverse effects. In such works, a variety of cell lines are usually utilized to quantify such parameters as cell viability, oxidative stress, membrane integrity and apoptosis (Das et al., 2017). As an example, the generation of reactive oxygen species (ROS) can be caused by silver nanoparticles and generates oxidative stress and programmed cell death, which can be evaded by surface modification or capping (Ajdari et al., 2018). Cytotoxicity has been opposed through surface functionalization, e.g., PEGylation, and shown to be much less toxic, improving nanoparticles' biocompatibility and cellular tolerance (Niga et al., 2023).

In vivo Toxicity and Biodistribution.

A requirement of the biodistribution and pharmacokinetics, and possible organ-organism toxicity of GSNPs is in vivo research. Such tests usually entail exposure of animal models to nanoparticles to determine tissue concentration, systemic toxicity, and clearance by the body (Garrigos et al., 2024). Initially, PEG-coated gold nanoparticles have been shown to have insignificant hepatic and renal toxicity, and no histopathological changes in the short-term period (Niga et al., 2023). However, the long-term studies are also essential to assess the risk of bioaccumulation, immunogenicity, and chronicity in different nanoparticle formulations (Ajdari et al., 2018).

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Environment and Ecotoxicology.

These environmental effects of GSNPs should be thoroughly tested using ecotoxicology, as they can be dispersed in the ecological contexts due to the possibility of environmental scattering during synthesis, use, or disposal. GSNPs are safer because their non-toxic solvents, renewable biological reducing agents, and lenient reactive environments make them greener compared to the chemically synthesized nanoparticles (Seabra and Duran, 2015). Nevertheless, they may still be hazardous to the ecology because of their interaction with the microbiota of the soil, as well as aquatic and vegetable life. In this way, the safe implementation of GSNPs in industries and biomedical use must rely on long-term environmental tracking and the benefits and harm assessment (Huang et al., 2024).

Challenges and Future Prospects

Existing Limitations and Challenges.

Even though the green synthesized nanoparticles (GSNPs) can be used as an alternative to traditional nanomaterials because it is eco-friendly, there are numerous challenges to the implementation of these nanoparticles on a large scale. One of the biggest challenges is the possibility of scaling up and repeating the synthesis. Biological variability, including that of plant extracts, cultured microorganisms, and biomolecules, can greatly affect the particle shape, productivity, and stability, making it hard to attain a reproducible quality of nanoparticles (Fahim et al., 2024). Agglomeration of nanoparticles is another issue that is very critical and that can alter surface characteristics, decrease stability, and render biological action. Thus, the necessity of the more advanced and eco-friendly methods of stabilization (capping with the help of biomolecules, coating with natural polymers, etc.) is increasing to ensure the homogeneity of nanoparticles (Singh et al., 2024). Also, seasonal variability, biodiversity of regions, and the effectiveness of extraction can restrict the generalizability of some green synthesis methods due to limited access to biological materials, making them seasonal and location-specific (Banerjee et al., 2017). The solution to these constraints lies in the interdisciplinary approach of the combination of biotechnology, material science and process engineering.

New Trends and Future Outlook.

Green nanotechnology Recent developments in green nanotechnology focus on incorporating the ideas of green chemistry into nanomaterial engineering in pursuit of scalable, sustainable and high-yield synthesis pathways. New methods that utilize plant-based phytochemicals, microbial enzymes and biopolymers as reducing and stabilizing agents have shown better use of nanoparticle morphology and surface functionality (Kandav and Sharma, 2023). Its uses in GSNPs are on the rise in environment remediation, biomedicine and agriculture. GSNPs, as an example, have proven themselves to be outstanding in the purification of wastewater, which promotes the process of adsorption and catalytic breakdown of heavy metals, dyes, and organic pollutants (Goutam et al., 2019; Rodriguez-Rasero et al., 2024). Additionally, the integration of GSNPs and the new

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technological interventions like biosensors, targeted drug delivery programs, and intelligent farming equations is a new destination. Thanks to such hybrid systems, the precise diagnosis of diseases, management of therapeutics, and crop productivity increase can be obtained without breaking the ecological balance and sustainability (Sundararajan et al., 2023).

Society and Economic Repercussions.

Substitutes to the traditional chemical synthesis techniques are green synthesis pathways, which are cheaper and less energetic; they do not need reactive molecules that are highly toxic, and they do not require tedious purification procedures. This economic feasibility will be capable of accelerating the industrial revolution of GSNPs, decreasing spending on such spheres as healthcare, environmental control, and sustainable farming (Vijayaram et al., 2023). GSNP technology is based on the principles of encouraging the utilization of renewable resources and environment-friendly manufacturing, and multiagency aims to maintain the environment, human health, and social welfare in accordance with the United Nations Sustainable Development Goals (SDGs) (Dhumal et al., 2024). However, social perception and regulatory issues on the safety and environmental persistence of nanoparticles are still major concerns. It is crucial to form clear risk evaluations, standardized test platforms, and international safety standards to instill confidence in the population as well as promote responsible usage of GSNPs (Garg et al., 2021).

Conclusion

GSNPs and green-synthesized nanoparticles represent an academic nexus of nanotechnology and green chemistry, and are viable alternatives to non-sustainable synthesized nanoparticles in offering bio-compatible, multifunctional, and green nanomaterials. This review highlights their broad-based therapeutic opportunity, including the presence of antimicrobial and anticancer performance as well as the administration of drugs and tissue repairing, but points out their lower cytotoxicity and eco-footprint. Although significant advances have taken place, several issues, such as reproducibility, scalability and poor comprehension of the nanoparticle-biomolecule interactions, remain, which should be dealt with using standardized synthesis profiles and extensive long-term toxicological analyses. Optimization, clinical translation and regulatory acceptance of GSNPs can be achieved faster through the application of artificial intelligence, omics technologies and interdisciplinary collaboration. In the end, the development of green nanotechnology will not only increase the innovation in biomedicine but also build a more sustainable and ethical science and industry in the future.

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