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Review Article

Green Nanomedicine: Pharmaceutical Horizons with Gold and Silver Nanoparticles

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ABSTRACT

The advent of nanotechnology has revolutionized pharmaceutical sciences, offering innovative solutions for drug delivery, diagnostics, and therapeutics. Among various nanomaterials, gold and silver nanoparticles have attracted significant attention due to their unique physicochemical properties, biocompatibility, and multifunctional applications. Conventional synthesis methods, however, often involve toxic chemicals and energy-intensive processes, raising concerns about sustainability and safety. Green synthesis, employing biological resources such as plant extracts, microbes, and biomolecules, provides an eco-friendly alternative that aligns with the principles of sustainable development. This approach not only reduces environmental impact but also enhances the biological functionality of nanoparticles through natural capping agents. Green-synthesized gold and silver nanoparticles exhibit promising pharmaceutical applications, including antimicrobial, anticancer, anti-inflammatory, and targeted drug delivery activities. Their ability to interact with biomolecules at the cellular and molecular levels opens new horizons in nanomedicine, particularly in precision therapeutics and regenerative medicine. Furthermore, the integration of traditional ecological knowledge with modern nanotechnology fosters a holistic framework for sustainable healthcare innovations. This review highlights the current progress, challenges, and future prospects of green-synthesized gold and silver nanoparticles in pharmaceutical sciences, emphasizing their potential to bridge biological sustainability with advanced medical applications.

1. Introduction

Nanomedicine has emerged as one of the most transformative fields in contemporary pharmaceutical sciences, offering innovative solutions for diagnosis, therapy, and drug delivery. At its core, nanomedicine exploits the unique physicochemical properties of materials at the nanoscale—typically between 1 and 100 nanometers—to achieve functionalities that are unattainable with bulk materials (Dykman & Khlebtsov, 2012). Among the diverse nanostructures investigated, metallic nanoparticles, particularly gold (Au) and silver (Ag), have attracted considerable attention due to their exceptional optical, electronic, and biological properties. Their ability to interact with biological systems at the molecular level has opened new horizons in oncology, infectious disease management, regenerative medicine, and biosensing (Gurunathan et al., 2014). However, conventional methods of nanoparticle synthesis often rely on toxic chemicals, high energy inputs, and environmentally hazardous processes, raising concerns about sustainability and safety. In response, the concept of green nanomedicine has emerged, emphasizing eco friendly synthesis routes that harness biological resources such as plants, microbes, and biopolymers to produce nanoparticles with reduced environmental impact and enhanced biocompatibility (Singh et al., 2016; Ahmad et al., 2024).

The rationale for green synthesis lies in its alignment with global sustainability goals and the increasing demand for safer biomedical materials. Traditional chemical and physical methods of nanoparticle production often involve harsh reducing agents, stabilizers, and solvents that can leave toxic residues, posing risks to both patients and ecosystems (Patil & Kim, 2017; Nath et al., 2024). In contrast, green synthesis employs naturally occurring biomolecules—such as flavonoids, terpenoids, alkaloids, and proteins—as reducing and capping agents. These biomolecules not only facilitate nanoparticle formation but also impart additional biological activity, creating multifunctional nanostructures. For instance, plant extracts rich in polyphenols can reduce metal ions to

nanoparticles while simultaneously coating them with antioxidant compounds, thereby enhancing their therapeutic potential (Ahmed et al., 2016). Similarly, microbial systems, including bacteria, fungi, and algae, can biosynthesize nanoparticles intracellularly or extracellularly, offering scalable and cost effective production platforms (Singh et al., 2016). This convergence of nanotechnology and biotechnology represents a paradigm shift toward sustainable pharmaceutical innovation.
Gold nanoparticles (AuNPs) have long been recognized for their biocompatibility, stability, and tunable surface chemistry. Their strong surface plasmon resonance enables applications in imaging, biosensing, and photothermal therapy (Dykman & Khlebtsov, 2012).

In cancer treatment, AuNPs can be functionalized with targeting ligands to selectively accumulate in tumor tissues, where they convert light energy into heat, destroying malignant cells with minimal damage to surrounding healthy tissue (Patil & Kim, 2017). Furthermore, AuNPs serve as versatile drug carriers, capable of delivering chemotherapeutic agents, nucleic acids, or peptides with controlled release profiles (Singh et al., 2016). Silver nanoparticles (AgNPs), on the other hand, are renowned for their potent antimicrobial properties. They exhibit broad spectrum activity against bacteria, fungi, and viruses, including multidrug resistant strains (Gurunathan et al., 2014). Their mechanisms of action involve disruption of microbial membranes, generation of reactive oxygen species, and interference with DNA replication (Ahmed et al., 2016). Beyond antimicrobial applications, AgNPs have demonstrated cytotoxic effects against cancer cells, making them valuable candidates for oncological therapies (Gurunathan et al., 2014). The dual utility of AuNPs and AgNPs in both therapeutic and diagnostic domains underscores their central role in the pharmaceutical horizons of green nanomedicine.

The integration of green synthesis with nanomedicine offers several advantages. First, it reduces reliance on hazardous chemicals, thereby minimizing toxicity risks for patients and healthcare workers (Patil & Kim, 2017). Second, it lowers production costs by utilizing readily available biological resources, such as plant leaves, fruit extracts, or microbial cultures (Singh et al., 2016). Third, it enhances the functional diversity of nanoparticles, as biomolecules from natural sources can impart antioxidant, anti inflammatory, or immunomodulatory properties (Ahmed et al., 2016). Fourth, it aligns with regulatory and ethical imperatives for sustainable healthcare, addressing concerns about environmental pollution and resource depletion (Patil & Kim, 2017). These advantages make green nanomedicine particularly relevant in regions with rich biodiversity and traditional medicinal practices, such as India, where integration of modern nanotechnology with Ayurvedic and herbal knowledge can yield innovative therapeutic solutions.

Despite these promising developments, several challenges remain. The reproducibility of green synthesis is often limited by variability in biological resources, such as seasonal changes in plant phytochemical composition (Singh et al., 2016). Achieving uniform particle size, shape, and distribution is critical for clinical applications but difficult to control in biosynthetic processes (Patil & Kim, 2017). Moreover, the long term biocompatibility and toxicity of nanoparticles must be thoroughly evaluated, as their interactions with biological systems can be complex and unpredictable (Gurunathan et al., 2014). Regulatory frameworks for nanomedicine are still evolving, and standardized protocols for characterization, safety assessment, and clinical translation are urgently needed (Dykman & Khlebtsov, 2012). Addressing these challenges requires interdisciplinary collaboration among chemists, biologists, pharmacologists, and regulatory experts.

The pharmaceutical horizons of gold and silver nanoparticles synthesized via green methods extend beyond conventional applications. Emerging research explores their potential in neurodegenerative diseases, cardiovascular disorders, wound healing, and vaccine adjuvants (Patil & Kim, 2017). For example, AuNPs functionalized with neuroprotective compounds may offer novel strategies for treating Alzheimer's disease, while AgNPs incorporated into wound dressings can accelerate healing by preventing infections and modulating inflammation (Ahmed et al., 2016). In diagnostics, AuNP based biosensors can detect biomarkers with high sensitivity, enabling early disease detection and personalized medicine (Dykman & Khlebtsov, 2012). The convergence of green nanomedicine with fields such as genomics, proteomics, and artificial intelligence further expands its scope, paving the way for precision healthcare solutions (Worakitjaroenphon et al., 2023).

In summary, green nanomedicine represents a dynamic and rapidly evolving field that combines sustainability with cutting edge pharmaceutical innovation. Gold and silver nanoparticles, synthesized through ecofriendly routes, exemplify the potential of this approach to revolutionize drug delivery, cancer therapy, antimicrobial resistance management, and diagnostics. While challenges related to reproducibility, toxicity, and regulation persist, ongoing research and technological advancements continue to push the boundaries of what is possible. The integration of traditional ecological knowledge with modern nanotechnology offers unique opportunities, particularly in biodiversity rich regions, to develop holistic and sustainable healthcare solutions. As the world grapples with pressing issues such as antimicrobial resistance, cancer burden, and environmental sustainability, green nanomedicine stands at the forefront of scientific and societal progress, offering hope for a healthier and more sustainable future.

1. Applications of Green Nanomedicine with Gold and Silver Nanoparticles

2.1. Cancer Therapy

Gold nanoparticles (AuNPs) have been extensively studied for their role in cancer treatment due to their unique optical properties and biocompatibility. Their surface plasmon resonance allows them to absorb and scatter light efficiently, making them suitable for photothermal therapy (Dykman & Khlebtsov, 2012). When functionalized with tumor specific ligands, AuNPs can selectively accumulate in malignant tissues and convert near infrared light into localized heat, thereby inducing apoptosis in cancer cells while sparing healthy tissues (Patil & Kim, 2017). Additionally, AuNPs serve as carriers for chemotherapeutic drugs, nucleic acids, and peptides, enabling controlled release and enhanced therapeutic efficacy (Singh et al., 2016) (Figure-1). Silver nanoparticles (AgNPs) also demonstrate anticancer potential, primarily through the generation of reactive oxygen species (ROS) that trigger oxidative stress and apoptosis in tumor cells (Gurunathan et al., 2014). Their cytotoxicity against breast, lung, and colon cancer cell lines highlights their promise as adjuncts to conventional therapies.

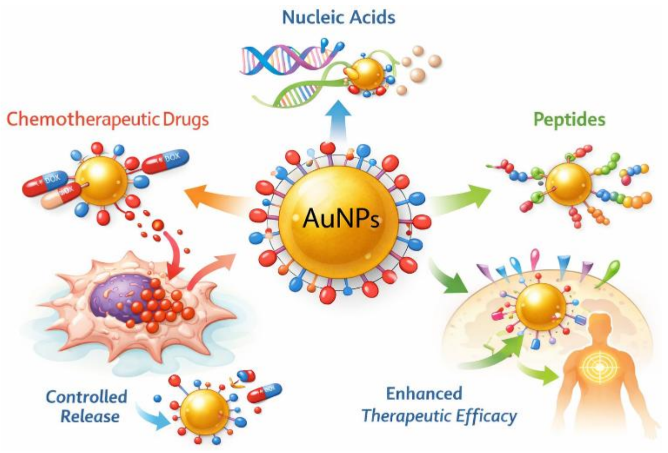

Figure 1. Schematic representation of gold nanoparticles (AuNPs) as multifunctional carriers for therapeutic biomolecules.

AuNPs are shown conjugated with chemotherapeutic drugs, nucleic acids, and peptides, enabling targeted delivery and controlled release. The illustration (Figure-1) highlights their role in enhancing therapeutic efficacy through improved cellular uptake and site-specific release mechanisms.

2.2. Antimicrobial Applications

AgNPs are renowned for their broad spectrum antimicrobial activity. They disrupt microbial membranes, interfere with DNA replication, and induce ROS formation, making them effective against bacteria, fungi, and viruses, including multidrug resistant strains (Ahmed et al., 2016). Their incorporation into wound dressings, coatings, and medical devices has significantly reduced infection rates in clinical settings. AuNPs, while less potent as antimicrobials, can enhance the efficacy of antibiotics when used in combination therapies (Singh et al., 2016). The synergistic effects of AuNPs and AgNPs in antimicrobial formulations represent a promising strategy to combat antimicrobial resistance, a major global health challenge.

2.3. Diagnostics and Imaging

AuNPs are widely used in diagnostics due to their strong optical properties. They serve as contrast agents in imaging modalities such as optical coherence tomography and photoacoustic imaging (Dykman & Khlebtsov, 2012). Their ability to bind biomolecules enables the development of biosensors for detecting disease biomarkers with high sensitivity and specificity. AgNPs, on the other hand, are employed in rapid pathogen detection systems, where their plasmonic properties facilitate colorimetric assays for identifying bacterial and viral infections (Ahmed et al., 2016). These diagnostic applications contribute to early disease detection and personalized medicine.

2.4. Drug Delivery

Both AuNPs and AgNPs can be functionalized with biomolecules to deliver therapeutic agents in a controlled manner. AuNPs are particularly versatile, as their surface chemistry allows conjugation with drugs, peptides, and nucleic acids (Singh et al., 2016). Green synthesis enhances their biocompatibility, reducing risks of adverse reactions. AgNPs, though primarily known for their antimicrobial activity, can also serve as carriers for antibiotics, thereby improving drug penetration and efficacy against resistant pathogens (Gurunathan et al., 2014; Poojari et al., 2014). The integration of green nanomedicine into drug delivery systems offers sustainable and effective solutions for complex diseases.

2.5. Emerging Applications

Beyond conventional uses, AuNPs and AgNPs synthesized via green methods are being explored in wound healing, anti inflammatory therapies, and vaccine development. AgNPs incorporated into wound dressings accelerate healing by preventing infections and modulating inflammatory responses (Ahmed et al., 2016; Kumar et al., 2017; Mamidala et al., 2020). AuNPs functionalized with immunogenic molecules are being investigated as vaccine adjuvants to enhance.

2. Challenges in Green Nanomedicine with Gold and Silver Nanoparticles

3.1. Toxicity and Biocompatibility

One of the foremost challenges in the clinical translation of green synthesized nanoparticles is their potential toxicity. Although green synthesis reduces chemical residues, nanoparticles themselves can induce oxidative stress, inflammation, and genotoxicity depending on their size, shape, and surface chemistry (Fratoddi et al., 2015). Silver nanoparticles, in particular, are known to generate reactive oxygen species (ROS), which can damage cellular components and lead to apoptosis (Gurunathan et al., 2014). Long term biodistribution and clearance pathways remain poorly understood, raising concerns about nanoparticle accumulation in vital organs such as the liver, spleen, and kidneys (Patil & Kim, 2017). Establishing standardized toxicological profiles is therefore essential before clinical adoption.

3.2. Reproducibility and Scalability

Green synthesis often relies on biological resources such as plant extracts or microbial cultures, which can vary in composition due to seasonal, geographical, and physiological factors. This variability affects nanoparticle size, morphology, and stability, making reproducibility a significant challenge (Singh et al., 2016). For pharmaceutical applications, uniformity in nanoparticle characteristics is critical to ensure predictable therapeutic outcomes. Scaling up biosynthetic processes from laboratory to industrial levels also poses difficulties, as maintaining consistent reaction conditions and quality control across batches is complex (Iravani, 2011).

3.3. Stability and Shelf Life

Nanoparticles synthesized via green methods may suffer from limited stability due to weak capping by biomolecules. Over time, aggregation or changes in surface chemistry can reduce their efficacy in biomedical applications (Ahmed et al., 2016). Ensuring long shelf life without compromising biocompatibility requires improved stabilization strategies, such as polymer coatings or hybrid nanostructures (Fratoddi et al., 2015).

3.4. Regulatory and Ethical Concerns

The regulatory landscape for nanomedicine remains underdeveloped. There is a lack of standardized protocols for nanoparticle characterization, safety evaluation, and clinical testing (Dykman & Khlebtsov, 2012). Ethical concerns also arise regarding environmental release and disposal of nanoparticles, as their long-term ecological impact is not fully understood (Iravani, 2011). Regulatory agencies must balance innovation with safety, requiring comprehensive risk assessments before approval.

3.5. Environmental Impact

Although green synthesis is more sustainable than chemical methods, nanoparticles themselves may pose environmental risks. Their persistence in soil and water ecosystems can affect microbial communities and aquatic organisms (Kumar et al., 2020). The potential bioaccumulation of silver nanoparticles in food chains is particularly concerning, necessitating environmental monitoring and safe disposal practices.

3.6. Clinical Translation Barriers

Despite promising laboratory results, few green synthesized nanoparticles have advanced to clinical trials. Barriers include insufficient toxicological data, lack of reproducibility, and regulatory uncertainty (Patil & Kim, 2017). Bridging the gap between bench and bedside requires interdisciplinary collaboration, standardized methodologies, and robust clinical validation.

3. Conclusion

Green nanomedicine, particularly through the use of gold (Au) and silver (Ag) nanoparticles, marks a paradigm shift in pharmaceutical sciences by integrating sustainability with biomedical innovation. Eco-friendly synthesis of nanoparticles using plant extracts, microbial cultures, and biopolymers not only minimizes environmental hazards but also enhances biocompatibility and therapeutic potential. These nanoparticles have shown remarkable applications in cancer therapy, antimicrobial resistance management, diagnostics, imaging, and drug delivery, underscoring their versatility and transformative potential in modern healthcare. Despite these advances, several challenges hinder their clinical translation. Issues of toxicity, reproducibility, scalability, and long-term stability remain unresolved, necessitating rigorous toxicological studies and standardized protocols. Regulatory frameworks are still evolving, and ethical concerns regarding environmental impact and nanoparticle disposal must be addressed to ensure safe and responsible use. Bridging the gap between laboratory research and clinical practice requires interdisciplinary collaboration among chemists, biologists, pharmacologists, and policymakers, alongside robust clinical validation and regulatory harmonization. Looking ahead, the pharmaceutical horizons of green nanomedicine extend beyond conventional applications. Emerging research points to their potential in neurodegenerative diseases, cardiovascular disorders, wound healing, and vaccine adjuvants, offering new avenues for personalized and precision medicine. Integrating traditional ecological knowledge with nanotechnology, particularly in biodiversity-rich regions, provides unique opportunities for innovation and sustainable healthcare solutions. In conclusion, gold and silver nanoparticles synthesized via green methods embody the promise of a future where nanomedicine is not only effective but also environmentally responsible. By addressing current challenges and fostering global collaboration, green nanomedicine can evolve into a cornerstone of next-generation pharmaceuticals, contributing to a healthier and more sustainable world.

Competing interests:

The authors declare that they have no competing interests

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