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Review Article

Nanotechnology

Ayurveda and Nanotechnology - A Synergistic Approach to Enhance Therapeutic Efficacy

Sharma V[1*], Jindal A[2], Sharma R[3]

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[1*] Vidhi Sharma, Post Graduate Scholar, Dept of Dravyaguna Vigyan, A and U Tibbia College, Karol Bagh, New Delhi, India.

[2] Amrit Jindal, Post Graduate Scholar, Dept of Dravyaguna Vigyan, A and U Tibbia College, Karol Bagh, New Delhi, India.

[3] Rajesh Sharma, Professor and HOD, Dept of Dravyaguna Vigyan, A and U Tibbia College, Karol Bagh, New Delhi, India.

Medicine, materials science, and biotechnology are just a few of the fields that have been transformed by nanotechnology, the research and engineering of materials at the nanoscale (usually 1–100 nanometers). Materials of this scale have distinct physical, chemical, and biological characteristics that set them apart from their bulk counterparts, enabling improved accuracy and functioning. New avenues for therapeutic innovation have recently been made possible by the combination of nanotechnology and conventional medicinal systems like Ayurveda. This has the potential to significantly improve the targeted distribution, bioavailability, and effectiveness of Ayurvedic medicines. Nanoparticles are a necessary component of traditional Ayurvedic procedures, such as making of Bhasmas (metallic or mineral ash), suggesting a long-standing, albeit unrecorded, use of nanoscale materials. The integration of nanotechnology not only strengthens the therapeutic value of Ayurveda but also bridges the gap between traditional knowledge and modern medicine. Applications include nano-carriers for herbal extracts, nano-emulsions, and lipid-based nanoparticles to deliver active phytoconstituents more efficiently. However, comprehensive toxicological studies, standardization protocols, and regulatory frameworks are essential to ensure safety and efficacy. This article examines how Ayurveda and nanotechnology intersect, stressing recent developments, difficulties, and opportunities in this nascent multidisciplinary field.

Keywords: Nanoscience in Ayurveda, Nanotechnology, Herbal drug delivery, Bioavailability enhancement, Ayurvedic Dravyas Nano formulations, Nanocarriers, Targeted drug delivery, Herbal nanomedicine

Corresponding Author

Vidhi Sharma, Post Graduate Scholar, Dept of Dravyaguna Vigyan, A and U Tibbia College, Karol Bagh, New Delhi, India.
Email: modgilvidhi@gmail.com

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Introduction

The integration of nanotechnology into traditional medicine systems, particularly *Ayurveda*, marks a transformative advancement in the field of healthcare. Nanotechnology, which involves the manipulation of materials at the nanoscale (typically 1–100 nm), offers novel approaches to drug delivery, diagnostics, and therapeutic interventions. One of its most significant contributions lies in enhancing the bioavailability of medicinal substances by reducing particle size, thereby improving solubility, permeability, and absorption of active compounds.

In the context of *Ayurveda*, the application of nanotechnology to *Dravyas* (medicinal substances) has opened new dimensions in the optimization of therapeutic efficacy. Traditional formulations often face limitations in terms of bioavailability and pharmacokinetics; however, nanosizing these compounds addresses such challenges effectively. Nano-enhanced herbal formulations exhibit increased surface area, facilitating more efficient interaction with biological systems and enabling lower dosages, fewer side effects, and prolonged therapeutic effects.

A compelling example of this convergence is the integration of nanotechnology in the preparation of *Ayurvedic Bhasmas* - metal or metal oxide-based formulations traditionally used in Ayurvedic therapeutics. These *Bhasmas*, which undergo a complex, multi-stage process involving high-temperature treatments and intense grinding, naturally achieve nano dimensions typically ranging from 1 to 100 nm. Their nanoscale size not only enhances absorption and biocompatibility in the bloodstream but also aligns closely with modern nanotechnological approaches.

Emerging studies suggest that the ancient techniques employed in *Bhasma* preparation mirror contemporary nanosizing methods, exemplifying a remarkable synergy between traditional wisdom and cutting-edge science. This synergy aligns with the growing demand in modern medicine for personalized and precision healthcare, allowing for tailored treatment regimens and real-time monitoring of patient responses.**[1,2]** Notable advancements include nanoencapsulation of herbal extracts and the development of targeted drug delivery systems.

Such technologies not only improve antimicrobial and therapeutic properties of *Ayurvedic* remedies but also show promise in managing complex and chronic conditions like cancer, diabetes, and neurodegenerative diseases. **[3,4,5]** Moreover, fusion of *Ayurvedic* principles with modern nanoscience supports holistic treatment approaches by enabling targeted action while preserving systemic balance emphasized in *Ayurveda*.**[6,7]** Despite these promising developments, field faces several challenges. Issues related to standardization, regulatory approval, and long-term safety of nanoparticle-based formulations remain areas of concern.**[8,3,9]** Comprehensive clinical and toxicological evaluations are crucial to ensure these innovative therapies adhere to both modern pharmacological standards and traditional *Ayurvedic* integrity.**[10,11]** As research into *Ayurnano* - interdisciplinary domain merging *Ayurveda* and nanotechnology - continues to evolve, it holds significant promise for reshaping future of integrative medicine. By enhancing bioavailability and therapeutic potential, this fusion may establish *Ayurveda* as a scientifically validated and globally accepted system of medicine in 21st century.

Solubility Enhancement in Ancient *Ayurveda*

The solubility of phytocompounds is often inadequate for their effective therapeutic application. Traditional approaches to improve solubility include *Samskaras*, such as *Bhavana* (trituration), which is the process of treating medications with fluids such as *Kashaya* or *Swarasa* to increase their effectiveness and potency. Different *Bhavana* processes are described in different Ayurvedic scriptures. Its goals include increasing bioavailability, reducing toxicity, and optimizing potency. These goals also involve inducing pharmacological, chemical, and physical modifications to pharmaceutical substances in order to enhance their absorption, assimilation, and overall therapeutic efficacy.**[12]** Other than this, *Ayurveda* has employed concepts such as *Yogavahi*, *Anupana*, *Bhaishajya Kaala*, *Marana* (Incineration or Calcination), *Rasayana*, *Yoga* (formulations), and *Kalpanas* (different dosage forms) like *Sneha Kalpana* (Medicated Ghee and Oil Preparations) which is Lipid-based vehicles that enhance the solubility of lipophilic compounds, improving bioavailability through lymphatic absorption and *Kwatha-Phanta* (Decoctions and Infusions) in which Water-soluble phytoconstituents are effectively extracted,

Thereby enhancing their bioavailability and facilitating easier absorption in the body.; In addition, *Ayurveda* has long used action-enhancing compounds, bio-penetration enhancers, and *Purana Aushadhis* (aged medications) to increase the effectiveness and absorption of medicinal substances. Preparing the body for the best possible medicine absorption also involves ideas like *Samshodhana* (bio-purification). In parallel, new methods like nanocarriers - which encapsulate phytoconstituents that are poorly soluble in water - have been made possible by advancements in nanotechnology. This has improved the solubility, stability, and targeted distribution of these phytoconstituents within biological systems. In particular, nano pharmaceuticals have shown great promise in improving the solubility of active substances, which is directly linked to higher bioavailability and better therapeutic results. Combining these age-old Ayurvedic ideas with cutting-edge nanotechnological advancements provides a viable framework for creating therapeutic interventions that are safer, more efficient, and supported by science, all of which are appropriate for the demands of modern healthcare.

Applications and Benefits

Nanotechnology offers numerous applications in the field of Ayurvedic medicine, particularly in drug delivery systems. These systems are designed to minimize side effects, lower required dosages, and prolong the duration of action of active ingredients. **[3,4]** For instance, nano-drug delivery can facilitate the continuous release of bioactive compounds, ensuring a more consistent therapeutic effect and enhancing the overall activity of herbal medicines. **[8]** One of the primary advantages of using nanotechnology in *Ayurveda* is its ability to enhance the bioavailability profile of herbal formulations. Studies have demonstrated that nanoencapsulation of active compounds can lead to stronger antimicrobial properties and improved efficacy compared to traditional preparations.**[4,8]** This is particularly relevant for chronic conditions such as cancer, arthritis, and neurodegenerative diseases, where enhanced drug delivery can significantly improve treatment outcomes.**[5]**

Mechanisms of Enhancing Bioavailability

Bioavailability refers to the degree and rate at which an active pharmaceutical ingredient or active moiety is absorbed & becomes available at site of action. Enhancing the bioavailability of Ayurvedic *Dravyas*, particularly through nanotechnology, involves several mechanisms that improve solubility, absorption, and overall therapeutic efficacy.

Pharmacokinetic Considerations

Pharmacokinetics plays a critical role in understanding how drugs interact with the body post-administration. The process encompasses various phases: liberation, absorption, distribution, metabolism, and excretion (LADME). The liberation phase, which involves the release of the active ingredient from its delivery system, is essential for effective absorption.[8] In many cases, poor solubility of phytocompounds limits their bioavailability. Therefore, optimizing drug formulation through nanotechnology can enhance the solubility and, consequently, the absorption of these compounds in the gastrointestinal tract (GIT). **[8,3]**

Bio-enhancers

Bio-enhancers are substances that increase the bioavailability or biological efficacy of therapeutic agents when co-administered with them. Acting synergistically at low doses, they significantly improve the overall effectiveness of drug formulations, including those in *Ayurveda*.[14] *Ayurveda* has a long-standing tradition of using various herbs and techniques to enhance the absorption and action of medicinal compounds. Notable among these are *Piper longum* (long pepper), *Zingiber officinale* (ginger), and *Glycyrrhiza glabra* (licorice), which have been used as natural bio-enhancers to potentiate the efficacy of co-administered remedies. The earliest recorded observation of this practice dates back to 1929, when Bose reported that the anti-asthmatic activity of *Vasaka* (*Adhatoda vasica*) was significantly improved when used in combination with long pepper (*Piper longum*).**[2,3]**

The concept received formal scientific recognition in 1979, when researchers at the Regional Research Laboratory (RRL) in Jammu - now known as the Indian Institute of Integrative Medicine (IIIM) - coined the term "bioavailability enhancer" after identifying piperine as the world's first natural compound to enhance the bioavailability of drugs. In modern contexts, the integration of bio-enhancers with nanotechnology has further amplified the therapeutic potential of Ayurvedic formulations.

This combination not only improves solubility and stability but also enables targeted delivery and greater clinical efficacy, making traditional medicines more adaptable to contemporary healthcare needs.**[3,14,18]**

Solubility Enhancement Techniques

The solubility of many phytocompounds is often insufficient for effective therapeutic application, posing a significant challenge in herbal drug delivery. Traditional strategies to enhance solubility include particle size reduction, formation of solid dispersions, and use of surfactants or solubilizing agents.**[8,13]** In recent years, nanotechnology has emerged as a transformative solution, significantly improving solubility and bioavailability of poorly water-soluble plant constituents. Nanocarrier systems—such as nanoparticles, nanovesicles, and self-assembled nanoparticles - play a crucial role in enhancing delivery of hydrophobic phytocompounds by improving their stability in biological environments and facilitating better drug dissolution, absorption, and distribution. These systems also help bypass first-pass metabolism, significantly increasing bioavailability of active compounds. As a result, nano pharmaceuticals exhibit enhanced therapeutic efficacy and improved pharmacokinetic profiles, positioning nanotechnology as a pivotal advancement in phytocompound delivery. A notable example of this innovation is valorisation of Ayurvedic industrial waste, as demonstrated in a study utilizing spent materials from traditional *Dashamoola Arishta* formulation. Researchers extracted lignin from waste and processed it into lignin nanoparticles (LNPs), which served as Pickering emulsifiers for encapsulating curcumin and vitamin D3 in a stable nano emulsion.**[19]** This formulation showed excellent encapsulation efficiency, long-term stability, and low cytotoxicity, underscoring its potential as a novel and sustainable drug delivery system. This approach not only advances green nanotechnology but also offers a sustainable pathway for repurposing *Ayurvedic* residues into high-value pharmaceutical and nutraceutical applications. Further advances in nanoparticle technology have led to development of core-shell biopolymer nanoparticles capable of co-delivering curcumin and other active compounds like piperine. This method employs sequential electrostatic deposition techniques, significantly improving stability and bioavailability of both compounds.

Such innovative delivery systems demonstrate the effectiveness of nanotechnology in optimizing Ayurvedic formulations for better clinical outcomes. **[15,16]** These case studies highlight the promising role of nanotechnology in enhancing the bioavailability and efficacy of Ayurvedic *Dravyas*, illustrating a future path that combines traditional knowledge with cutting-edge scientific advancements.

Case Studies on Herbal and Ayurvedic Nano-particles for Diverse Biomedical Applications

Silver and Gold Nanoparticles

Green nanotechnology aligns closely with Ayurvedic principles, where herbal formulations were traditionally combined with metals like gold and silver. This modern approach enables the precise creation of nanoparticles using herbal extracts and metal precursors.

These green-synthesized nanoparticles encapsulate bioactive *Ayurvedic* phytochemicals, and their size and surface composition can be accurately measured using advanced scientific tools. This innovation enhances the standardization, efficacy, and integration of Ayurveda into precision medicine, offering a scientifically robust pathway for its evolution as a modern therapeutic system.

The green synthesis of multifunctional silver and gold nanoparticles from herbal sources, such as Siberian ginseng, has also shown promise in nanomedicine. These nanoparticles have been functionalized to enhance their therapeutic effects while minimizing toxicity. In particular, research indicates that gold nanoparticles derived from *Curcuma wenyujin* can induce apoptotic effects against cancer cells, showcasing their potential role in targeted cancer therapies.**[15,17]**

Such developments illustrate how nanotechnology can augment the therapeutic profiles of traditional herbal medicines, paving the way for novel treatment modalities in modern healthcare.

Nanotechnology - Enhanced Delivery of Curc-umin

Recent studies have demonstrated the potential of nanotechnology in enhancing the bioavailability of Curcumin, a compound derived from *Turmeric*, which is known for its anti-inflammatory, antioxidant, and anticancer properties.

Curcumin's low water solubility and chemical instability have been significant barriers to its therapeutic application. Innovative strategies such as the use of turmeric nanovesicles, liposomes, and chitosan encapsulation have been employed to improve curcumin's solubility and bioavailability. For instance, turmeric nanovesicles have been shown to effectively exert anti-inflammatory effects by repairing damaged intestinal barriers, modulating gut microbiota, and regulating macrophage phenotypes.**[15,16]**

Wound Healing Enhancement Using Zein Nanoparticles Encapsulating Moringa oleifera Extract

This study highlights the encapsulation of *Moringa oleifera* leaf extract into zein nanoparticles for enhanced wound healing. Using a Quality by Design (QbD) approach, the nanoparticles were developed, optimized, and incorporated into a topical gel. Characterization confirmed suitable physicochemical properties, and animal studies demonstrated significantly improved wound healing compared to both control and non-encapsulated extract gels. The findings suggest that zein nanoparticles offer a promising delivery system for Ayurvedic herbal extracts in topical therapeutic applications.**[20]**

Anti-Inflammatory Potential of AgNPs and ZnONPs Synthesized from Ocimum Species

Silver (AgNPs) and zinc oxide nanoparticles (ZnONPs) synthesized using *Ocimum tenuiflorum* (Indian *Tulsi*) and *Ocimum gratissimum* (African or Black *Tulsi*) have demonstrated notable anti-inflammatory activity. This effect is primarily attributed to their ability to inhibit protein denaturation and stabilize cellular membranes—two key mechanisms in inflammation control. While these findings highlight their potential as novel anti-inflammatory agents, further research is essential to evaluate their clinical efficacy and long-term safety for therapeutic use.**[21]**

Green-Synthesized Iron Nanoparticles from *Punica granatum* for Prostate Cancer Therapy

This study explores the green synthesis of iron nanoparticles (FeNPs) using aqueous extract of *Punica granatum* (pomegranate), a medicinal plant known for its anticancer properties. The FeNPs, characterized by spherical morphology (10–40 nm) and confirmed through UV–V is spectroscopy and XRD analysis, Were evaluated for antioxidant and anticancer activity. The DPPH assay showed 50% antioxidant activity at 127 µg/mL. FeNPs demonstrated potent cytotoxicity against prostate cancer cell lines (DU 145 and NCI-H660), with IC_{50} values of 117 and 110 µg/mL, respectively, and showed no significant toxicity to normal HUVEC cells. Mechanistically, the nanoparticles induced apoptosis by increasing pro-apoptotic markers (cleaved caspase-8, Bax), reducing anti-apoptotic Bcl-2, inhibiting colony formation, and modulating molecular pathways by upregulating p53 and downregulating total and phosphorylated STAT3. These findings suggest that FeNPs synthesized from *Punica granatum* could serve as a promising nanotherapeutic approach for prostate cancer.**[22]**

Green Synthesis of Silver Nanoparticles from *Swertia Chirata* for Antimicrobial Applications

This study explores the green synthesis of silver nanoparticles (AgNPs) using *Swertia Chirata*. Various plant extracts were prepared using different solvents, and AgNPs were synthesized through the reduction of silver nitrate. These nanoparticles were characterized for their size and morphology using UV–V is spectroscopy, SEM, and EDX. Phytochemical analysis confirmed the presence of bioactive compounds with antioxidant potential. Both the crude extracts and AgNPs exhibited strong antibacterial activity against several human pathogens, surpassing conventional antibiotics in efficacy. These findings underscore the potential of *Swertia Chirata* - derived AgNPs for use in nano-medicine, particularly in drug delivery and antimicrobial therapies.**[23]**

***Nanotriphala*: A Novel Anti-inflammatory Nanoparticle Formulation for COVID-19-Induced Hyperinflammation**

This study developed a nanoparticle-based formulation of *Triphala* - an Ayurvedic blend of *Emblica officinalis*, *Terminalia bellerica*, and *Terminalia chebula* - to enhance its bioavailability and evaluate its anti-inflammatory potential against COVID-19-induced inflammation. The resulting "*Nanotriphala*" was synthesized via solvent displacement and demonstrated high encapsulation efficiency and a sustained release profile. In vitro experiments on lung epithelial cells (A549) showed that *nanotriphala* and its key compounds, chebulagic and chebulinic acids,

Significantly reduced the expression of pro-inflammatory cytokines and genes triggered by the SARS-CoV-2 spike protein. The formulation also downregulated inflammasome-related proteins, suggesting that nanotriphala may serve as a promising supportive therapy for managing chronic inflammation associated with COVID-19.**[24]**

Enhancing Antifungal Therapy: Solid Lipid Nanoparticles Loaded with Holoptelea integrifolia Extract

Fungal infections have become increasingly common and difficult to treat, prompting interest in plant-based remedies like *Holoptelea integrifolia*, known for its antifungal properties due to the presence of friedelin. This study aimed to enhance its therapeutic efficacy by formulating solid lipid nanoparticles (SLNs) loaded with the plant extract. The SLNs, prepared via hot homogenization and ultrasonication, exhibited favourable properties such as spherical shape, good encapsulation efficiency, and sustained drug release. Notably, these nanoparticles showed significantly greater antifungal activity against *Candida albicans* compared to the free extract. The findings support the potential of SLNs as an effective nano-based delivery system for treating fungal infections using herbal extracts.**[25]**

Phospholipid-Encapsulated Polyherbal Nano-carriers for Enhanced Antidiabetic Activity

Managing metabolic disorders like diabetes often requires a multi-herb approach due to associated complications such as hyperlipidaemia and oxidative stress. However, poor lipid solubility of many phytoconstituents limits their in vivo efficacy. This study developed a phospholipid-encapsulated polyherbal formulation containing *Momordica charantia*, *Trigonella foenum-graecum*, and *Withania somnifera* to improve bioavailability and therapeutic efficiency.

The optimized formulation (HA) was encapsulated in a phosphatidylcholine - cholesterol vesicle system (HAL) and evaluated in diabetic rat models. Compared to the non-encapsulated HA and a marketed formulation, HAL demonstrated superior antidiabetic activity at a lower dose, showing potential equivalent to metformin. These findings suggest phospholipid-based nanocarriers can significantly enhance the efficacy of polyherbal treatments in metabolic disorders.**[26]**

***Moringa oleifera* Nanoparticles Mitigate Breast Cancer Progression and Chemotherapy-Induced Cardiotoxicity**

Moringa oleifera (MO), renowned for its medicinal properties, shows potential in reducing tumour aggressiveness and alleviating side effects of chemotherapy. This study evaluated the effects of MO nanoparticles (MONPs) on breast cancer induced by DMBA in albino rats treated with the chemotherapeutic agent doxorubicin (DOX). Rats were divided into control and cancer-induced groups, with further subdivisions to assess both synergistic and preventive impacts of MONPs. Results demonstrated that treatment with MONPs, alone or combined with DOX, significantly reduced tumour markers and cardiotoxicity indicators. Additionally, antioxidant levels and protein profiles improved, reflecting enhanced oxidative balance. These findings suggest that prophylactic and synergistic use of MONPs can effectively protect against DOX-induced heart damage while inhibiting breast cancer progression and oxidative stress.**[27]**

Challenges and Limitations

The integration of nanotechnology into *Ayurvedic* medicine presents significant challenges, including standardization and quality control of formulations, particularly *Bhasmas*, which require strict adherence to traditional methods. The absence of standardized preparation and evaluation protocols complicates their integration into modern healthcare systems, raising safety and reliability concerns. Additionally, regulatory hurdles, such as lack of clinical trials and scientific validation, contribute to skepticism about the safety and efficacy of *Ayurvedic* nano formulations. Safety concerns about nanoparticles and traditional ingredients, as well as heavy metal contamination, also pose significant limitations. The lack of precise measurement and validation techniques further complicates matters, as inconsistencies in treatment outcomes could undermine confidence in these integrative therapies.

Future Directions

To advance the field of herbal nanoparticles, it is crucial to expand research collaborations with countries with traditional medicine heritage, such as India, Iran, and Arab nations. This will accelerate innovation and global acceptance of herbal nanoparticle research.

Comprehensive bibliometric analyses can guide future research priorities and highlight global contributions, particularly from China. Validation of herbomineral nanoformulations is essential for standardized clinical validation, boosting consumer confidence and medical acceptance.

Integrating modern technologies with traditional *Ayurvedic* knowledge could lead to targeted delivery systems that enhance drug bioavailability and reduce side effects. Personalized medicine, which aligns with modern precision medicine approaches, could improve treatment outcomes and patient satisfaction. Safety concerns must be addressed through long-term toxicological studies, evaluating the biocompatibility and environmental impact of nanomaterials used in *Ayurvedic* formulations.

Conclusion

The integration of nanotechnology into traditional Ayurvedic medicine has revolutionized the treatment of herbal compounds, overcoming limitations such as poor solubility, low bioavailability, and inconsistent therapeutic efficacy. Nano formulations, such as nanoparticles, nanovesicles, and self-assembled systems, improve solubility, stability, and targeted delivery of phytoconstituents, enhancing clinical efficacy with reduced dosages and minimized side effects.

This is particularly beneficial for managing chronic conditions like diabetes, cancer, and neurodegenerative disorders. Green nanotechnology aligns with *Ayurvedic* principles, as seen in the precision formulation of herbal-metal nanoparticle systems that mirror traditional *Bhasma* preparations. These nano-*Bhasmas* offer improved bioavailability and biocompatibility, bridging ancient wisdom with modern scientific validation.

Sustainable practices, such as the valorization of *Ayurvedic* industrial waste, demonstrate how nanotechnology can improve drug delivery and promote eco-friendly pharmaceutical development. The synergy achieved by combining multiple phytochemicals in nano formulations enhances therapeutic outcomes, supporting integrative and personalized healthcare approaches. However, challenges such as regulatory standardization, long-term safety, and thorough clinical evaluation remain critical to the widespread adoption of these technologies.

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