

From Nature to Nanomedicine: AI-Driven Nano-Herbal Innovations Across the Drug Development Lifecycle

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Abstract

Drug development is still a major bottleneck with high attrition rates, long timeframes with increasing cost and requires inventive and integrated solutions. During this period, nano-herbal convergence has emerged as an attractive means of combining the therapeutic richness of plant-derived biomolecules with the functional merits of nanotechnology. We here review the novel, emerging class of plant mediated nano-metallic particles (in which mono-, bi- and tri-metallic systems can be used) that plays pivotal roles in redefining phases of different steps in the life cycle of a drug.

Green synthesis approach using plant extracts is a sustainable and biocompatible method for the preparation of nanoparticles, in which some phytochemicals act as a natural reducing as well as stabilizing agent. Such nanoparticles have been shown to display increased biological activity, better stability and improved compatibility as opposed to their traditionally synthesized equivalents. This platform is doubly potent, with its application of artificial intelligence for predictive modelling, synthesis parameter optimization, target identification by molecular docking and in the early-stage prediction of toxicity.

By taking advantage of synergistic effects and the capability to act against multiple targets, multi-metal nanoparticles are a promising approach for further enhanced therapeutic efficacy in complex diseases. However, there are still significant obstacles preventing their clinical translation such as variations in plant composition a lack of standardization scalability constraints and regulatory uncertainties despite the limited success in clinical research.

In the context of AI-assisted precision nanomedicine and sustainable manufacturing techniques this review outlines recent advancements highlights key obstacles and suggests future prospects. In the broader view, the holistic of AI-powered convergence nano-herbal approach provides a futuristic paradigm to whole drug development with sustainable and targeted lead molecule identification process.

Keywords: Nano-herbal convergence, Plant-mediated nanoparticles, Artificial intelligence, Drug development lifecycle, multi-metal nanoparticles.

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Introduction

Introduction Drug discovery is still one of the most complicated and costly processes in modern science, from drug discovery to clinical application. Conventional drug development is typically characterized by long timelines, increasing costs, and high attrition rates with only a limited fraction of lead molecules eventually finding an on-market trajectory [1]. Failures happen for reasons of insufficient efficacy, unexpected toxicity and unfavorable pharmacokinetic behaviour. All these limitations of solubility, bioavailability, specificity and systemic

side effects in practice reduce the therapeutic benefits and complicate patient adherence [2].

Although the historical and potential therapeutic value of herbal medicine is as significant as that of conventional medicine, the transition from exploratory research to evidence-based clinical practice poses comparable challenges. Although many bioactive compounds from plant sources have high pharmacological properties, their usage is limited due to poor water-solubility [2], chemical instability [3], fast metabolism and inconsistent absorption profiles. Furthermore, the inherent

variability in phytochemical composition due to environmental, geographical and processing factors creates challenges for the standardisation and reproducibility of these studies [4]. These drawbacks emphasize the need for creative methods to increase the therapeutic efficacy of herbal formulations while preserving safety and consistency.

Nanotechnology is a new science which has been merged with herbal medicine in recent years to face these challenges. Nanotechnology also opens up ways to produce nanocarriers that can deliver drugs/therapeutics with higher solubility, permeability, property of control release and site-specific targeting [5]. Scope Hypothetically, the scope of nanotechnology will be wider especially when applied in herbal medicine where it can not only improve the pharmacokinetic profile regarding phytoconstituents but also protect them from degradation which may boost their biological efficacy. It has resulted in the emergence of nano-herbal formulations that integrate safety, characterizing a natural product from modern forms of drug delivery system [6].

One particularly promising new development in this area is exploited plant-mediated metal nanoparticles (also called green-synthesized nanoparticles). In comparison to traditional methods of chemical synthesis, plant-mediated methods provide a greener and more sustainable for offering cost-effective devices that use phytochemicals as reducing and stabilizing agents [7]. These phytochemicals are involved in the formation of nanoparticles, but they also provide extra biological functions leading to additively or synergistically therapeutic effects. Plant-synthesized nanoparticles have diverse pharmacological activities, including anti-bacterial, antioxidant, antitumor, and anti-inflammatory effects [8]. Nanocarriers exhibit a great compatibility with drug and disease diagnosis because of the unique physical and chemical features of nanoparticles, such as nanosized, high surface activity, and controllable shape.

Nevertheless, various obstacles exist in translating such developments. One of these major hurdles is ensuring the scalable and reliable production of green synthesis techniques. Variability in the composition of plant extracts (e.g., between batches) may change the characteristics of nanoparticles and thereby influence translatability and effectiveness [9]. A further challenge is that the regulatory framework surrounding nano-herbal drugs remains underdeveloped; existing guidelines regarding safety, efficacy, and quality control of such products are insufficient for translating them successfully into clinics, including problems of toxicity, biodistribution, and environmental impacts [10].

A novel approach to addressing these issues is the incorporation of artificial intelligence (AI). Indeed, the entire process ranging from bioactive compounds to optimal synthesis parameters and interactions can

be revolutionized by using machine learning algorithms to facilitate all steps of this development pipeline [11]. In this case, algorithms enable exploring vast amounts of data to uncover hidden patterns, optimize formulations, and predict the toxicity profile of the nanoparticles being designed. An innovative approach based on machine learning makes the process more efficient by decreasing costs and increasing chances of success.

This emphasizes the need for a comprehensive sustainable-facilitated intelligent framework for nanotechnology in addition to herbal medicine and AI-assisted techniques. This framework has the potential to increase efficacy increase reproducibility and make medications safer and more efficient in drug delivery systems.

With a focus on plant-mediated metal oxide nanoparticles the current review aims to explore AI-based nano-herbal convergence. It covers everything from green synthesis to physicochemical characterization (such as morphology and elemental composition analysis) biological evaluation (such as cytotoxicity and antimicrobial testing) and translational pieces of evidence. It follows a stepwise path throughout the lifecycle. Beyond that this review highlights the power of transdisciplinary approaches in reshaping the co-development strategies for next-generation therapeutic agents by summarizing the most recent developments discussing important challenges and outlining promising future directions [12].

2. Conceptual Framework: Nano-Herbal Convergence

2.1 Definition and Evolution

Nano-herbal convergence is an innovative and emerging concept in pharmaceutical sciences that relates nanotechnology with plant derived systems. Compared with the common nano technology that is highly dependent on used synthetic chemical raw materials and energy-consuming manufacturing processes, nano-herbal system is the biomimetic system which plant metabolites can drive themselves to form and realize their function as intrinsic drivers for nanoparticle synthesis. It is not merely a convergence of technology, rather the move is towards bio Projected nanomedicine where natural principles of molecular interaction inspire materials science and biology.

Traditionally, the production of nanoparticles through both top-down or bottom-up approaches was purely a chemical process, however, the advent of green nanotechnology provides us with the alternative plant-based production approaches. In the last decade, this technique has evolved from being just a green option to becoming technologically and functionally more competent where the nanoparticles would be pre-synthesized as well as pre-functionalized by plant chemicals. Recently reported research highlights the enhanced pharmacological efficacy of nanoparticles made by plants based on

their hybridized structure where metallic cores would be combined with bioactive organic coronas [13].

2.2 Role of Phytochemicals in Nanoparticle Synthesis

Phytochemicals play an essential role as versatile plant molecules participating in the process of nanoparticle synthesis as both a reducing agent, a stabilizer and a functionalization element. Taken together, these phytochemicals (such as flavonoids, phenols, terpenoids, alkaloids, proteins etc.) form a biochemically active system that controls the process of nanoparticle creation at the molecular level.[14]

Reduction Mechanism

Firstly, the reduction of metal ions to zero valence state is involved in the synthesis of nanoparticles. Several polyphenols and flavonoids possess hydroxyl and carbonyl groups that are able to donate electrons to form free radicals within a short duration of time. The biochemical reduction is eco-friendly and controllable for the formation and formation of nanoparticles. Additionally, due to antioxidant properties of the compounds, their kinetic rate increases leading to strong reducing capability in comparison to chemical reducing agents.

Stabilization (Capping)

Because of the high surface energy, nanoparticles usually tend to agglomerate post-nucleation. The phytochemicals have the ability to prevent the agglomeration by surrounding the surface of nanoparticles with a coating which ensures their stabilization. Groups like $-OH$, $-COOH$ and $-NH_2$ chemically bond with the surface of metal to form a protective organic coating on the metal surface. The natural capping method is a great replacement for surfactants and makes these nanoparticles biocompatible [15]. Most importantly, the stabilization method results in a particle size and morphology such that the nanoparticles can overcome the limitations of solvent or magnetic saturation and produce monodispersed nanoparticles.

Functionalization

Phytochemicals not only reduce and stabilize the nanoparticles but provide an inherent biological functionality to them. As such, these bound biomolecules become potent drug molecules interacting selectively with biological targets. This is where the uniqueness of plant-based nanoparticles lies compared to ordinary nanoparticles, which require further functionalization despite being already synthesized – thus named ‘in-built functionalization’. A few recent studies have shown that these nanoparticles exhibit exceptional antibacterial, anti-cancerous, and antioxidant properties owing to combined effects of the metal core and the phytochemical layer [16].

2.3 Advantages Over Conventional Nanoparticles

Nano-herbal systems offer distinct advantages over traditional nanoparticles by merging biological properties with physicochemical benefits, resulting in superior overall performance.

Biocompatibility and Reduced Toxicity

Conventional nanoparticles often cause toxicity problems due to artificial surfaces and residual chemicals. On the other hand, because the surfaces of plant-derived nanoparticles are covered in natural biomolecules they are naturally biocompatible. This feature makes them more suitable for biomedical applications by reducing cytotoxicity and enhancing cellular absorption [17].

Eco-Friendly and Sustainable Synthesis

Green chemistry through use of plant extracts does not use toxic chemicals, excessive energy, and complicated purification processes. Not only does this process meet the world's sustainability requirements, but it also ensures that there is a reduction in carbon footprint. Plant-based synthesis utilizes renewable materials, thus making it economically viable.[18]

Intrinsic Bioactivity and Synergistic Effects

In light of the fact that these natural compounds must also be biodegradable, the nanoparticles prepared using plant-based compounds possess inherent biological activity, apart from being carriers of drugs, compared to normal nanoparticles. The process by which the surface of the nanoparticles is coated with phytochemicals resulting in synergistic medicinal activity is explained in this paper, thereby increasing the efficacy without the need for further drug loading. This novel dual approach in nanomedicine is an advance in nanotechnology where the carrier itself is used as a therapeutic tool [13].

Enhanced Functional Performance

These characteristics of hybrid nature of nanocarrier systems from herbal origin have allowed improving the physicochemical properties, such as high surface reactivity, better dispersion stability, and sustained release. Furthermore, biologically active coating provides targeting effectiveness and interactions with the cellular membrane, which confirms the effectiveness of these systems in treating diseases [19].

The nano-herbal convergence, highlighting phytochemical-driven nanoparticle formation and therapeutic applications, is illustrated in Figure 1.

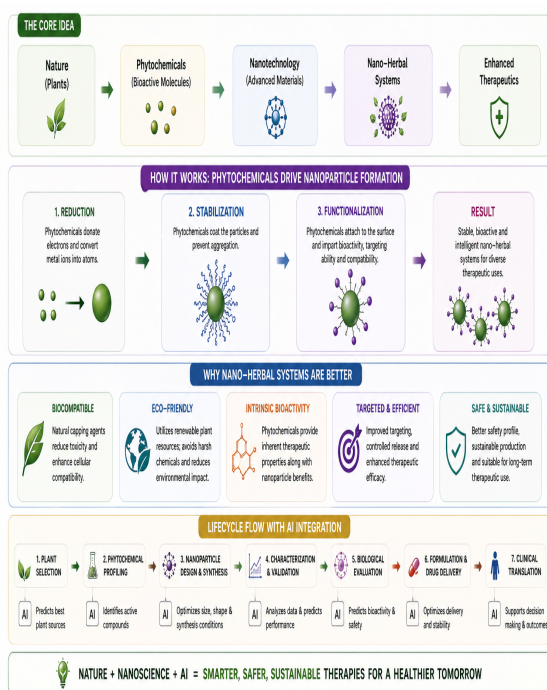


Figure 1: Nano-Herbal Convergence: Phytochemical-Driven Nanoparticle Formation and Therapeutic Applications

3. Classification of Plant-Derived Metal Nanoparticles

Metal nanoparticles can be divided into groups according to the number of kinds of metallic elements which are implanted in their structures and it has been stated that both element kind and its proportion play unique role obtaining great properties. This categorization impacts their physicochemical properties, biological activity, and implementation prospects directly. The increase in the number of metals increases synergistic interactions which provide enhanced function and wider biomedical application [20].

A comparative analysis of plant-derived metal nanoparticles, highlighting their key characteristics and applications, is presented in Table 1.

3.1 Mono-metal Nanoparticles

It can be classified as mono-metal nanoparticles those which contain only a simple metallic element, e.g., silver (Ag), gold (Au) and zinc oxide nanoparticles the first two or copper (Cu). In these methods, nanoparticles are mainly bio-synthesized using plant extracts that serve as reducing and stabilizing agents (phytochemicals). Mono-metal nanoparticles are frequently studied for potential uses as antimicrobial antioxidant or anticancer agents due to their comparatively simple synthesis procedures and documented protocols.[21]

3.2 Bi-metal Nanoparticles

Bimetallic nanoparticles include the composition of two distinct metals which could be alloyed together, core-shell nanoparticles, or heterogeneous structured nanoparticles. The oxide-metals combination improves the interface reactivity, catalysis, and biological efficacy of the metals.

The metal ions used in plant-based nanoparticle synthesis are simultaneously reduced into stable core-shell structures, making them functionally efficient. These biologically active bimetallic nanoparticles owe their high level of efficacy against bacteria, inflammation, and cancer cells to the synergism of the metals involved [22].

3.3 Tri-metal Nanoparticles

The tri-metallic nanoparticles form an even higher level in the hierarchical series of nanoparticles that involve the presence of three different metals within a single structure. Such materials possess enhanced functionalities by combining the advantages of all the metals together.

Although such nanoparticles are difficult to synthesize, natural occurrences in plants provide an eco-friendly and efficient method for their synthesis. Stabilization and reduction of these materials through different types of phytochemicals make them stable and functional. Tri-metallic nanoparticles have gained much interest because of their applications in drug targeting and biosensing [23].

Table 1: Comparative Analysis of Plant-Derived Metal Nanoparticles

Parameter	Mono-metal Nanoparticles	Bi-metal Nanoparticles	Tri-metal Nanoparticles
Synthesis Complexity	Low; simple and reproducible	Moderate; controlled dual-metal reduction	High; precise multi-metal coordination required
Biological Activity	Moderate; dependent on single metal	Enhanced due to synergistic interactions	High; multifunctional and synergistic effects
Stability	Good; may aggregate over time	Improved stability due to metal interaction	High stability with optimized structure

Applications	Antimicrobial, antioxidant, anticancer	Drug delivery, catalysis, anti-inflammatory	Targeted therapy, biosensing, theranostics
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The gradual shift from mono- to tri-metal nanoparticles shows a notable improvement in biological activity stability and potential applications underscoring the significance of multi-metal systems in cutting-edge nano-herbal treatments.

4. AI Integration in Nano-Herbal Drug Development

By enabling data-driven decisions throughout the entire pipeline—from phytochemical selection to nanoparticle design biological evaluation and process optimization—artificial intelligence (AI) is quickly revolutionizing the development of nano-herbal drugs. AI speeds up experiments increases accuracy and facilitates the creation of safer and more efficient nano-herbal systems by fusing big datasets predictive modelling and machine learning (ML) [24,25].

4.1 AI in Phytochemical Screening & Selection

AI-based technologies have the capability to quickly scan through huge libraries of phytochemicals and isolate those with bioactivity and pharmacological characteristics suitable for therapeutic uses. Methods such as QSAR modeling, virtual screening, and deep learning help select compounds based on affinity, physical and chemical properties, and bioactivity predictions.

This helps avoid unnecessary trial-and-error experiments and allows the selection of phytochemicals that have significant therapeutic value. Moreover, AI helps in identifying latent trends in plant metabolomic data, enabling the isolation of new phytochemicals and enhancing plant selection strategies [26].

4.2 AI-Guided Nanoparticle Design

Recently, AI and machine learning models have been used to design nanoparticles with specific physicochemical properties for various biomedical applications.

Size Prediction

Using machine learning algorithms, the size of nanoparticles is predicted based on synthesis conditions and factors such as concentration pH temperature and reaction time. Precise size control is essential since size is one of the most significant physical characteristics that can directly affect cellular uptake and biodistribution [27].

Morphology Optimization

shapes of nanoparticles such as spheres and rods. in turn affects surface reactivity and therapeutic efficacy so AI models can forecast it based on the synthesis conditions.

Surface Charge (Zeta Potential)

The nanoparticles developed have a predictable surface charge which improves stability and interaction with biologically relevant membranes. The particles better targeting with little aggregation, [28].

4.3 Molecular docking and target prediction

Artificial Intelligence (AI) incorporation facilitates quick predictions on phytochemicals with their biological targets through docking. Molecular docking is a tool that helps to predict the probable drug target, binding affinity, and mechanism of action. Docking together with the artificial intelligence score function provides numerous ways of increasing prediction purity and screening the most effective nano-herbal phytocomplexes from inexpensive molecules.

This process helps in accelerating the discovery of new drugs and facilitating the rational drug design process. [29].

4.4 AI-Based ADMET & Toxicity Prediction

AI models prove useful in predicting the ADMET (absorption, distribution, metabolism, excretion and toxicity) profiles of phytochemicals and nano-formulations.

The prediction of toxicity and pharmacokinetics in early stages prevents failure at later stages, thus making it important for the development of safe therapeutics. Artificial intelligence-based models to improve predictions on toxicity (cytotoxicity, genotoxicity and environmental toxicity) have been developed as they become immediate requirements in evaluating nano cure safety [30].

4.5 Process Optimization using Machine learning (Green Synthesis)

Machine learning techniques can be applied to optimize the green synthesis technique and establish relationships between process parameters and properties of the synthesized nanoparticles. With adjustment of parameters such as concentration of plant extracts, ratios of metal ions, and temperature and pH values, the desired properties are acquired.

This ensures optimization from data and thereby ensures that plant-mediated synthesis of nanoparticles becomes predictable and more feasible for industrial applications [31].

4.6 Data Lathes Drug repurposing: Nanocarrier Design, from data

Using AI-driven data-based drug repurposing for finding new potential uses of currently used phytochemicals. AI can help find new uses for known compounds through analysis of pathways, gene expression databases, and disease networks.

AI can also be used in developing innovative nanocarriers, which will involve prediction of drug-carrier interactions, rate of drug delivery, and efficacy of targeting. This approach could lead to the development of customized nano-herbal treatments [32].

Combining AI with nano-herbal medicine is a novel revolution in drug development involving precision-based medicines that are efficient and sustainable.

5. Role Across the Drug Development Lifecycle

All levels of the drug development lifecycle — from early discovery through large scale manufacturing — are shaped by nano-herbal systems, especially when coupled with artificial intelligence. It promotes efficiency, reduces the risk of failure and contributes to the creation of therapeutic systems that are safer and more sustainable in nature.

5.1 Drug Discovery Phase

Finding suitable therapeutic targets and developing lead compounds that exhibit pharmacological effects make up the drug discovery process.

Target Identification

The use of AI-based technology makes it possible to assess genomic, proteomic, and pathway data to quickly find and identify molecular targets that are connected to diseases. By linking the results of this research with existing databases of phytochemicals, researchers can also locate the plant substances that interact with those same molecular targets, and thus may serve as an important source of compounds to be tested as potential drug candidates in the initial stages of drug discovery [33].

Lead Generation by Using Nano-Herbal Systems

Bioavailability increases due to increased phytochemical solubility, stability, and delivery in nanotherapeutic formulations. Encapsulation of biologically active compounds using nanoparticles increases their bioavailability and efficacy, and so these systems can screen better drug leads than natural compounds [34].

5.2 Preclinical Development

Preclinical assessment of drugs includes evaluating their safety, efficacy, and pharmacokinetic characteristics prior to commencing clinical trials.

Evaluation of in vitro & In vivo

Biological activities, toxicological aspects and pharmacological effects of nano-herbal drugs can be assessed using cell-based assays such as cell proliferation assay in tumor cells as well as animal models. Due to their nanometric characteristics, these systems tend to have improved cellular uptake and more effective treatment outcomes [35].

Pharmacokinetics & Biodistribution

Nanoparticles are also known to impact the pharmacokinetics of drugs. Besides the information already present in the databases regarding modeling techniques, AI can further help optimize the features of nanoparticles such as their size and surface charges that influence their effectiveness in targeted drug delivery [36].

5.3 Formulation & Drug Delivery

Nanoherbal systems offer a modern approach to targeted technologies for drug delivery.

Nano-gels

Controlled and sustained release of enhanced phytochemicals with stability and patient compliance.

Nano-emulsions

To increase the solubility and bioavailability of hydrophobic plant active compounds for oral and topical delivery.

Targeted Systems

Functionalization of nanocarriers with targeted ligands allows the delivery of drugs or imaging agents to a specific site while decreasing systemic toxicity [37].

5.4 Clinical Translation

Current state of Clinical Trials

Although nano herbal systems are still under development, there are already some plant-based nanomedicine products that have moved forward for clinical and translational research trials. Clinical studies indicate better efficacy and lesser toxicity compared to traditional drug forms, although more clinical validation is required [38].

Personalized Medicine Potential

AI integration makes it possible to formulate nano herbals through the use of patient-specific information regarding genetics and metabolism. This technique enhances personalized medicine whereby the patient's specific needs are considered when formulating personalized medication [39].

5.5 Regulatory Landscape

Guidelines for Nanomedicine

Utilizing scientific perspective to assess different facets of safety, efficacy, and quality, several guidelines for nanomedicine were recommended by regulatory agencies such as FDA and EMA. However, their complex composition has constrained the emergence of an emerging perspective on nano-herbal systems development [40].

Challenges in Nano-Herbal Approval

There are complexities surrounding the approval of plant extracts due to their variability, lack of standardized procedures, and insufficient information on toxicity over time. Strategies that could be adopted in solving these problems could include [41].

5.6 Manufacturing & Scale-Up

Green Synthesis Scalability

Plant-mediated synthesis is an economical and environmentally friendly method of producing nanoparticles on a large scale. Replicating and reproducing the results during scale-up is still very difficult though [42].

Quality Control Issues

Control of nanoparticle size, components, and their biological activities is critical for successful implementation into clinical trials. These data are used to optimize analytical methodologies and AI-based quality control systems to increase reproducibility of build [43].

“Integration of nano-herbal systems, enabled by the same AI, into the whole process of drug development

can become a key step towards creation of effective and precise therapeutics.

6. Therapeutic Applications of Nano-Herbal Systems

Due to enhanced bioavailability, target delivery and biological activity, nano-phytomedicine-based systems have proved a promising area for diverse therapeutic uses. The incorporation of phytochemical components into the realm of nanotechnology not only increases efficiency but provides an additional expected therapeutic advantage that makes these systems worth consideration in modern pharmacotherapy. The major therapeutic applications of nano-herbal systems, along with their associated pharmacological effects, are summarized in Table 2 and illustrated in Figure 2.

6.1 Anticancer Applications

Nano-herbal drug formulation is one of the most promising ways to treat cancer because of their enhanced delivery as well as effectiveness. Phytochemicals such as flavonoids, alkaloids, and polyphenols possess anti-cancer activity, however, the use of these drugs has limitations since they have low bioavailability and solubility.

These drugs can be delivered to cells using nanoparticles which increase cellular uptake, targeted delivery to tumors, and decrease toxicity. Moreover, these systems can help induce apoptosis and control tumors growth, and function as signaling pathway regulators. Phytochemicals act as a combination of many components within one particle, therefore, enhancing the efficacy of these drugs through synergy mechanisms. [44].

6.2 Antimicrobial & Antiviral Applications

These nanoparticles are nano-herbal, they show considerable antimicrobial and antiviral activities owing to the combined actions of metal ions and phytochemicals. Such systems operate through the disruption of microbial cell membrane, generation of reactive oxygen species and interference with critical metabolic pathways.

In case of antiviral applications, these nano-herbal systems can block the viral entry and replication as well as protein synthesis. Their small size generates a large surface area for interacting with pathogens, which makes them useful against drug-resistant infections. Similarly, plant-mediated nanoparticles represent a less hazardous tool than traditional antimicrobial agents [45].

6.3 Neurodegenerative Disorders

Blood Brain Barrier (BBB) is considered to be a limiting factor in treating neurodegenerative diseases, like Alzheimer's and Parkinson's disease. The use of nanotechnology techniques for herbal compounds that can be delivered via the BBB in the form of nano-herbal systems may solve this problem.

Nanotechnology-based herbal products have been linked to the protection of nerves, as it prevents the oxidation process, stops protein aggregation, and controls the inflammation pathway. Moreover, the

regulated delivery of active substances improves the efficacy of therapy, significantly reducing side effects, which makes nano-herbal products quite appealing for neurological applications. [46]

6.4 Dermatological & Cosmetic Applications

Amongst the drug delivery methods, nano-based herbal systems owing to their enhanced skin permeability and sustained drug delivery systems have become very common in dermatological and cosmetologically sciences.

The use of nano-emulsions, liposomes or nano-gels with or without plant extracts for purposes such as moisturizing, anti-aging treatments, wound healing, and UV protection is increasingly popular. These natural systems not only contribute to skincare but also reduce any adverse reactions caused by chemical substances used in such products. [47].

6.5 Anti-inflammatory & Antioxidant Therapies

The reason is that they possess excellent antioxidant and anti-inflammatory effects because of the existence of phenolic compounds and flavonoids within nano herbal medicines. This particular class of nanoparticle has scavenging activity against free radicals and reduces acute oxidative stress reaction. In addition, it inhibits inflammatory mediators.

Increased bioavailability and increased efficiency of therapy through selective targeting of receptors increase therapeutic effectiveness in chronic inflammation such as rheumatoid arthritis, heart diseases, and metabolic syndromes. Nanoparticles coupled with phytochemicals increase their therapeutic potential [48].

Table 2: Summary of Therapeutic Applications of Nano-Herbal Systems

Application Area	Description / Mechanism	Therapeutic Significance	References
Anticancer Applications	Nano formulations derived from plants improve bioavailability and facilitate targeted drug delivery. Phytochemicals such as	Improved efficacy, selective cytotoxicity, reduced systemic toxicity, precision oncology approach	[49,50]

	flavonoids, alkaloids, and polyphenols enhance cellular absorption, promote apoptosis, inhibit angiogenesis, and regulate tumor signaling pathways. Nanoparticles synthesized through green methods produce reactive oxygen species (ROS) and lead to mitochondrial dysfunction.		
Antimicrobial & Antiviral Applications	Nanoparticles engage with microbial membranes, proteins, and nucleic	Broad-spectrum antimicrobial activity, effective against	[51,52]

	acids, resulting in structural damage. The generation of reactive oxygen species (ROS) and the release of metal ions contribute to microbial mortality. Additionally, they impede biofilm formation and quorum sensing, while also obstructing viral replication.	drug-resistant pathogens, antiviral potential	
Neurodegenerative Disorders	Nanoparticles facilitate transport across the blood-brain barrier (BBB). Phytochemicals such as curcumin and resveratrol	Neuroprotection, improved cognitive function, targeted CNS delivery	[53]

	reduce oxidative stress, inhibit protein aggregation , and regulate neuroinflammation.		
Dermatological & Cosmetic Applications	Enhanced skin penetration and controlled release improve delivery of bioactives. Exhibits antioxidant, anti-aging, photoprotective, and melanin-inhibiting effects. Also shows antimicrobial and wound-healing properties.	Improved skin health, anti-aging effects, treatment of acne and infections, enhanced cosmetic performance	[54]
Anti-inflammatory & Antioxidant Therapies	Nanoformulations scavenge free radicals and reduce lipid	Management of inflammation, oxidative stress	[55,56]

	peroxidation. They regulate inflammatory mediators such as cytokines, prostaglandins, and nitric oxide, improving stability and bioavailability.	reduction, prevention of chronic diseases	
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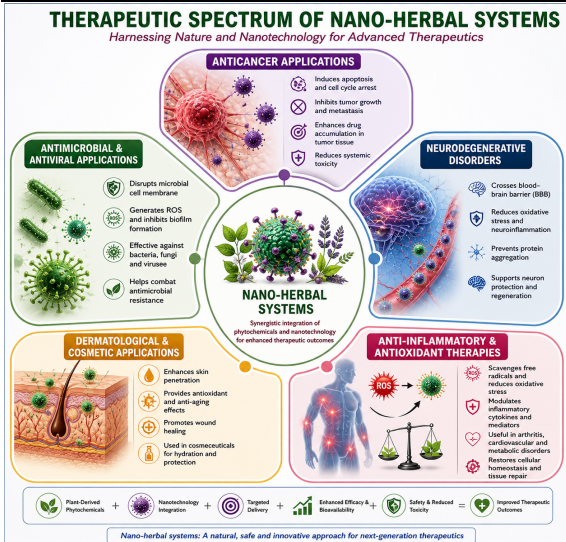


Figure 2: Multifunctional Therapeutic Applications of Nano-Herbal Systems

7. Translational Challenges and Bottlenecks

There are many important obstacles to the clinical use of nano-herbal systems including issues with safety variability reproducibility and current regulatory frameworks. These challenges significantly hinder both their potential therapeutic use and large-scale development.

The comprehensive outline of these challenges is illustrated in Figure 3.

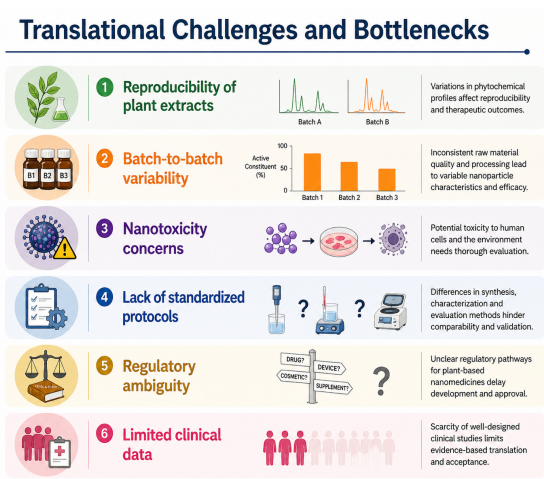


Figure 3 : Translational Challenges and Bottlenecks in Nano-Herbal Systems

8. Opportunities and Future Perspectives

The emerging opportunities and future perspectives in nano-herbal systems are summarized in Table 3.

Table 3: Emerging Opportunities and Future Perspectives in Nano-Herbal Systems

Future Direction	Concept Overview	Transformative Potential	References
AI + Nanotechnology Synergy	Integration of artificial intelligence and machine learning for design, optimization, and prediction of nano-herbal drug delivery systems	Enables data-driven formulation, predictive modeling, and precision targeting	[57]
Precision Nano-Herbal Medicine	Development of personalized nano formulations based	Facilitates patient-specific therapy with improved	[58,59]

	on genetic, metabolic, and clinical variability	efficacy and reduced adverse effects	
Integration with Omics Technologies	Combination of nanotechnology with genomics, proteomics, and metabolomics for biomarker-driven therapy	Enhances disease prediction, diagnostics, and targeted therapeutic strategies	[60]
Sustainable & Circular Economy Models	Adoption of green synthesis, biodegradable nanomaterials, and plant waste valorization	Promotes eco-friendly production and sustainable healthcare systems	[61]
Smart Nanocarriers & Stimuli-Responsive Systems	Development of nanocarriers responsive to pH, temperature, enzymes, or external	Enables site-specific delivery with improved safety and therapeutic precision	[62]

	stimuli for controlled drug release		
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9. Recent Case Studies in Green Nano-Herbal Systems

Recent case studies highlighting the development and applications of green nano-herbal systems from 2020 to 2025 are summarized in Table 4.

Table 4: Recent Case Studies in Green Nano-Herbal Systems (2020–2025)

Year	Plant Used	Metal Type	Nanomaterial	Application	Key Outcome	Reference
2020	<i>Syzygium aromaticum</i> (Clove)	Bimetallic	Au–Ag NPs	Antioxidant, Catalysis	Enhanced catalytic & antioxidant activity due to synergistic effect	[63]
2021	<i>Annona muricata</i>	Bimetallic	Ag–Cu / Ag–Zn NPs	Biomedical, Catalysis	Ag–Cu showed superior antimicrobial	[64]

					and catalytic efficiency	
2022	<i>Persicaria salicifolia</i>	Bimetallic (Composite)	Ag–ZnO nanocomposite	Waste water treatment	Efficient tetracycline degradation + antibacterial activity	[65]
2024	<i>Eryngium foetidum</i>	Bimetallic	CuO–ZnO NPs	Anticancer, Antimicrobial	~89% inhibition of MCF-7 cancer cells	[66]
2025	<i>Trifolium alexandrinum</i>	Bimetallic	Cu–Zn NPs	Photocatalysis, Biological	Enhanced catalytic degradation and bioactivity	[67]

2026	<i>Cicer arietinum</i> (Chickpea sprout)	Bimetallic Ag–Co NPs	Environmental, Antibacterial, and Environmental	~83% pollutant removal within 180 sec	[68]
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10. Key Innovations of AI-Driven Nano-Herbal Systems

Innovation	Significance
Green & Sustainable Synthesis	Eco-friendly nanoparticle fabrication using plant biomolecules
Multifunctional Therapeutic Platform	Combined antimicrobial, anticancer, antioxidant, and targeting properties
AI-Assisted Precision Targeting	AI-guided optimization of nanoparticle design and drug delivery
Reduced Toxicity	Improved biocompatibility and minimized systemic side effects
Smart Responsive Drug Delivery	Stimuli-responsive and controlled therapeutic release
Personalized Medicine Potential	Patient-specific nano-herbal therapeutic strategies

11. Conclusion

In the same vein, the most pioneering and innovative platform of nanoparticles is that of nano-herbal nanoparticles due to various disciplines like nanotechnology, phytochemistry, and artificial intelligence which can be exploited correctly in the advancement of drug delivery platforms. The enhanced bioavailability, low toxicity, and therapeutic effectiveness are attributed to the green nature of these nanoparticles. Studies show that these nanoparticles have broad uses like being anticancer, antimicrobial, antioxidant, and environmental particles.

Furthermore, the incorporation of artificial intelligence and computational technologies helps in improving the efficiency of nano-herbal nanoparticles using predictive formulation techniques, molecular docking, toxicity predictions, among others. Generally, nano-herbal nanoparticles can be described as a platform that integrates

green technology and intelligent technology to serve as a multifunctional tool for the future.

12. Future Research Directions



The future of precision therapeutics could be completely transformed by combining artificial intelligence green nanotechnology and phytomedicine. This would replace the costly trial-and-error approach to drug development with a more intelligent sustainable and patient-focused innovation ecosystem.

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Author Contributions

All authors contributed to the conception and design of the review, literature search, analysis and interpretation of the available evidence, and preparation and revision of the manuscript. All authors read and approved the final manuscript.

Data

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the preparation of this review.

Ethics

Not applicable.

Consent

Not applicable.

Interests

Approval

Participate

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