

Nano Herbal Therapeutics: A Dual-Edged Sword – Comprehensive Insights into Advantages, Challenges, and Future Prospects

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Abstract:

Nano herbal therapeutics combine nanotechnology with herbal medicine to overcome challenges like poor bioavailability and instability of phytochemicals. These formulations enhance efficacy, safety, and patient compliance compared to conventional herbal and synthetic nanoparticle systems. Plant-derived nanoparticles (PDNPs) offer benefits including improved cellular uptake, low toxicity, eco-friendliness, and cost-effectiveness. Several nano-formulated herbal compounds have shown promising outcomes in preclinical and clinical studies, especially in cancer, inflammation, and metabolic disorders.

This review highlights the pharmacokinetics, pharmacology, and therapeutic potential of nano-herbal systems while comparing PDNPs to synthetic counterparts. We also explore their mechanisms of action, molecular signaling pathways, and roles in targeted delivery. Additionally, the review addresses challenges such as formulation stability, large-scale production, regulatory gaps, and long-term toxicity.

A systematic literature review was conducted using databases like PubMed, Scopus, and Web of Science. Emerging tools such as AI-assisted formulation and biodegradable carriers are discussed as future directions. The integration of nanotechnology and herbal medicine presents a transformative approach to disease treatment. However, regulatory standardization, environmental safety, and ethical commercialization remain critical for clinical translation.

Keywords: Nano herbal therapeutics; Bioavailability; Toxicity; Targeted delivery; Green synthesis

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Introduction

For thousands of years, herbal medicine has been used for medical purposes and healthcare needs with the recommendation of the World Health Organization [1, 2]. These natural remedies are increasingly studied for their significant role in treating various conditions, such as infectious diseases, metabolic syndrome, neurological disorders, and cancers [3, 4].

Herbal products contain a diverse combination of pharmacologically/biologically active phytochemicals including terpenoids, phenolics, and alkaloids [5–7]. The hydrophobic nature of many active compounds in phytomedicine, along with their low solubility and susceptibility to degra-

ation in gastric and colonic environments, can limit their effectiveness in clinical application [8].

Recent studies have focused on innovative approaches based on nanoparticle technologies to enhance the pharmacokinetics of herbal medicinal products and address important concerns such as metabolism, targeted distribution and absorption [9, 10]. Nanotechnology can assist in achieving targeted action, enhancing effectiveness, decreasing first-pass metabolism, and preventing product degradation in the liver, ultimately leading to reduced dosage and improved patient compliance [11]. Various nano-based drug delivery systems, including solid lipid nanoparticles, nanoemulsions, self-emulsifying systems, and nanostructured lipidic carriers, have greatly paved the way for research in this respect

[12, 13]. Consequently, there has been a growing emphasis in the pharmaceutical sector on nano herbal drugs as a promising approach for treating a variety of diseases [14]. This review examines cutting-edge advances in nanotechnology for herbal medicine delivery, in addition to assessing the clinical progress and key challenges facing natural compound-loaded nanocarriers in therapeutic applications. With a comprehensive perspective, we explored the pharmacological properties of phytochemicals from a broad standpoint, their novel mechanisms of action, and associated molecular signaling pathways in diseases therapy, as revealed by recent scientific research.

The synergistic relationship between nanotechnology and herbal medicine, highlighting key advantages (e.g., enhanced solubility, targeted delivery), challenges (e.g., toxicity, regulatory gaps), applications in disease treatment, and future prospects such as AI-driven formulation and personalized medicine illustrate in figure 1.

Advantages of plant-derived nanoparticles [PDNPs] over artificial nanoparticles

PDNPs are garnering expanding interest owing to their exceptional characteristics and promising applications across different fields, especially in medication. In comparison to traditional synthetic nanoparticles, PDNPs offer several advantages, including improved cellular uptake, low toxicity, eco-friendliness, and cost-saving potential [15].

Enhanced intracellular delivery

A major advantage of plant-derived nanoparticles (PDNPs) in biomedical applications lies in their superior cellular uptake efficiency across diverse cell types, including cancer cells, macrophages, and endothelial cells [16]. This enhanced internalization capability stems from the distinct surface properties of PDNPs, where phytochemical coatings and surface charge enable favorable interactions with membranes of cells, stimulating receptor-mediated endocytosis.

The presence of bioactive surface molecules, particularly polyphenols, flavonoids, and proteins, further enhances cellular uptake by mimicking endogenous ligands that bind to cell surface receptors [17]. This intrinsic targeting capability is crucial for optimizing therapeutic outcomes in drug delivery, gene therapy, and other biomedical applications. Notable examples include *Ocimum basilicum* (basil)-synthesized silver nanoparticles demonstrating selective uptake in cancer cells, inducing apoptosis while reducing off-target effects characteristic of conventional chemotherapy [18]. Additionally, nanoparticles derived from *Cocos nucifera* (coconut)-derived exhibit enhanced targeted delivery with minimal cytotoxicity, highlighting their therapeutic potential (figure 2) [19].

Safety profile

PDNPs exhibit significantly lower toxicity compared to synthetic nanoparticles. The toxicity profiles of nanoparticles are determined by key physicochemical properties including size, shape, surface charge, and composition. Synthetic nanoparticles, especially metal-based variants like silver, gold, and copper, often demonstrate cytotoxicity through the elimination of metal ions. This release is capable of triggering oxidative damage, inflammatory responses, and destruction of cells [20]. In contrast, PDNPs are naturally stabilized by biocompatible phytochemicals such as polyphenols, alkaloids, and flavonoids. These plant metabolites not only provide nanoparticle stability but also contribute intrinsic anti-inflammatory and antioxidant properties that in addition minimize potential negative consequences. For instance, *Neem* (*Azadirachta indica*)-synthesized silver nanoparticles show minimal cytotoxicity in human cells, demonstrating excellent potential for drug delivery [21]. Green tea (*Camellia sinensis*)-derived copper and gold nanoparticles display exceptional biocompatibility and low toxicity, with validated safety profiles in cancer therapeutics [22, 23].

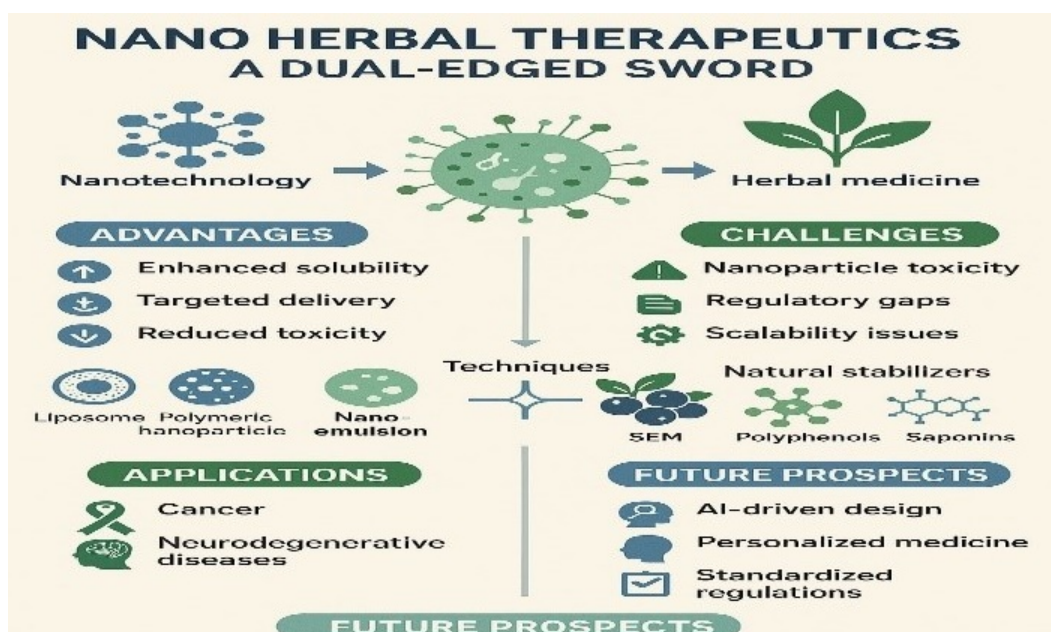


Figure 1. Overview of Nano-herbal therapeutics: A dual-edged approach integrating nanotechnology and herbal medicine.

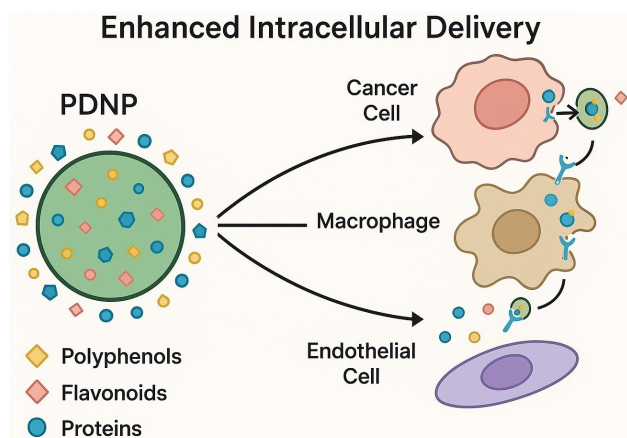


Figure 2. Enhanced intracellular delivery of plant-derived nanoparticles (PDNPs) via receptor-mediated endocytosis.

Eco-friendliness & sustainability

The synthesis of PDNPs provides a sustainable alternate to conventional methods of nanoparticle production. By using plant extracts as natural minimizing and stabilizing factors, PDNP synthesis minimizes harmful byproducts, supporting greener and more sustainable manufacturing practices. Employing plants as a renewable source represent an ideal platform for nanoparticle production. In contrast, synthetic nanoparticle synthesis typically relies on hazardous chemicals and solvents that pose significant environmental risks if improperly disposed of. These processes are also energy-intensive, resulting in a substantial carbon footprint [24]. Green biosynthesis techniques, that use herbal extracts as reducing factors (e.g., silver nanoparticles synthesized using *Cucumis sativus* peel extract), are becoming more popular due to their eco-friendliness and cost-effectiveness (figure 3) [25, 26].

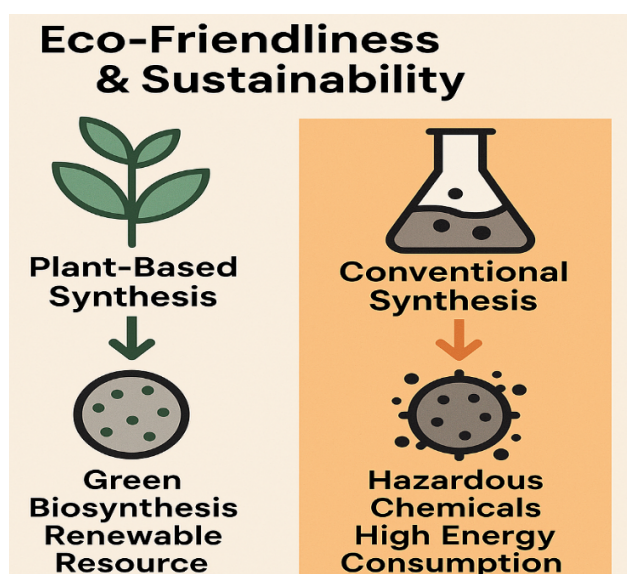


Figure 3. Eco-friendly and sustainable synthesis of plant-derived nanoparticles (PDNPs).

Cost-saving possibility

Plant-derived nanoparticles provide important financial benefits compared to artificial nanoparticles, mainly due to their cost-effective and sustainable production methods. The synthesis of PDNPs involves green chemistry approaches where Plant extracts serve as biological stabilizing and minimizing factors, eliminating the need for costly chemical reagents and energy-intensive processes [27]. This method not only reduces production costs but also minimizes environmental impact. The scalability of PDNP production is enhanced by the simple and cost-effective cultivation of plant materials in large quantities. For example, nanoparticles derived from *Camellia sinensis* (green tea) and *Moringa oleifera* can be produced using environmentally sustainable and cost-effective water-based extraction methods [28]. These biologically synthesized nanoparticles exhibit superior economic viability for industrial applications compared to traditional synthetic alternatives. In contrast, synthetic nanoparticle production involves expensive precursor materials, hazardous chemical reagents, and energy-intensive processes (e.g., high temperature/pressure conditions). Furthermore, the environmental impact of chemical waste and energy consumption hinders the efficiency and sustainability of large-scale synthetic nanoparticle production.

Comparative analysis: Nano-herbal vs. conventional herbal medicine

Nano-herbal formulations offer significant advantages over conventional herbal medicines in terms of efficacy, safety, and patient compliance (figure 3). Studies have shown that nano-encapsulation improves bioavailability, with nanoparticle-based curcumin resulting in 20 – 40 times higher plasma concentrations compared to conventional forms. Additionally, the therapeutic effects of nano-curcumin can last 24 – 48 hours, as opposed to just 4 – 6 hours [13].

Similarly, nano-formulated berberine has been found to have 3.5 times greater glucose-lowering effects in diabetes management while also reducing gastrointestinal side effects by 60% [29]. Safety profiles are also enhanced, as nano-encapsulation helps minimize hepatotoxicity risks associated with compounds like kava-kava by preventing the formation of reactive metabolites [30].

Despite the higher production costs (30 – 50% more than conventional extracts), nano-herbal medicines offer superior cost-effectiveness in long-term therapy due to reduced dosage requirements (60 – 80% less) and improved therapeutic outcomes [31]. Advances in microfluidic synthesis are steadily lowering manufacturing costs, with projections suggesting price parity by 2028 [32]. However, stringent quality control measures, including advanced analytical techniques like MALDI-TOF mass spectrometry, remain a financial hurdle.

Patient compliance is significantly better with nano-herbal therapies, due to less frequent dosing (weekly vs. daily), minimized unpleasant tastes, and alternative delivery methods such as transdermal patches. Market trends reflect growing acceptance, with nano-herbal prescriptions increasing 40% faster than conventional herbal products in chronic pain

management [33]. However, consumer hesitancy persists, particularly in Europe, where 25% of patients express concerns over nanoparticle safety [34]. Insurance coverage also lags, with only 30% of U.S. health plans including nanoherbal treatments compared to 85% for conventional herbal remedies (figure 4). Clinical adoption faces challenges, including limited physician training (only 15% of primary care providers receive education on nano-medicine), regulatory ambiguities, and a lack of large-scale comparative trials [35]. Storage and stability requirements further complicate distribution, as some lyophilized nanoformulations require $-20\text{ }^{\circ}\text{C}$ conditions. Emerging solutions, such as blockchain-enabled cold chain tracking and AI-assisted clinical decision tools, may help bridge these gaps.



Figure 4. Infographic summarizing key differences in efficacy, safety and dosing frequency.

Pharmacokinetics and pharmacological applications of Nano herbal drugs

Recently, many parameters have been utilized to enhance drug absorption and potency in nano-formulations [36, 37]. Due to their small dimensions and larger surface area relative to volume, nanoparticles in drug carriers aid in the pharmacokinetics and bio-distribution of therapeutically active agents. Instead of having specific site actions, nanoparticles can increase stability, enhance the solubility of hydrophobic nutrients, and bypass blood barriers [38].

Encapsulation technology has advanced significantly in the pharmaceutical industry. Bioactive substances are encapsulated into colloidal particles with micro and nanoscale diameters using specific chemicals and manufacturing techniques [39, 40]. The potential of novel drug delivery systems (NDDS) to get beyond the limitations of conventional drug delivery techniques has attracted plenty of attention [41, 42]. Liposomes, phytosomes, matrix systems, and solid lipid nanoparticles are important technologies applied recently [9, 43–45]. Phospholipids are used in phytosomes, a lipid-based nanocarrier technology, to encapsulate active plant-based substances [46]. This system improves the absorption of compounds with low solubility by creating a vesicle structure that can interact with both nonpolar and polar particles [47]. Because phytosomes may efficiently pass through biological membranes, they can be administered

via different administration routes such as, oral, topical and parenteral treatments [48]. Phytosomes provide numerous benefits compared to traditional systems, such as increased stability, decreased toxicity, minimized absorption variability, improved skin absorption, and regulated release of drugs [47].

Additionally, phytosome phospholipid structures shield bioactive ingredients from being broken down by gut bacteria and digestive enzymes [49]. The benefits of phytosomes make them promising candidates for a variety of medicinal applications [50].

Another investigation revealed that, in comparison to free curcumin, curcumin phytosomes greatly increase bioavailability. In pancreatic cancer patients, curcumin phytosomes and gemcitabine resulted in a disease control rate of more than 61% and a response rate of 27%, indicating their potential to increase therapy efficacy [51, 52].

Nanoencapsulation offers innovative approaches to overcome the limitations of applying essential oils. Essential oils typically consist of terpenic hydrocarbons and oxygenated derivatives such as ketones, aldehydes, phenols, esters, and alcohols. These compounds are usually chemically unstable and easily volatile in unfavorable environmental conditions like light exposure, oxygen, and heat, which restricts their use [53].

An oily core is encased in a polymeric wall to form polymeric nanocapsules. Essential oils can be employed as a component of the oily core or integrated into the polymer matrix. The polymers utilized might be either natural or artificial, including poly (DL-lactide-co-glycolide) (PLGA) and chitosan. Chitosan nanoparticles with a particle size of 40 – 80 nm have been shown to enhance the biological activities of essential oils, including antioxidant, antimicrobial, and anticancer properties [54]. Other research studies in this field are exploring the application of nanocarriers, such as liposomes, dendrimers, and biopolymer-based carriers, to encapsulate potent plant-based anticancer drugs like resveratrol, quercetin, and curcumin. This approach aims to overcome challenges such as low effectiveness in the body, limited solubility in water, and nonspecific drug delivery to target tissues [55, 56].

Encapsulation of polyphenols in nanocarrier systems, including nanogels, polymeric nanoparticles, liposomes, and micelles, has been shown to improve polyphenol targeting capability, aqueous solubility, and enable combined chemotherapeutic and immunomodulatory effects against cancer [57].

Overall, nanotechnology can enhance the therapeutic effectiveness of traditional herbal remedies by improving solubility and stability, regulating the rates of drug release, and improving permeability and targeting.

Phytochemicals found in herbal extracts serve a dual purpose as therapeutic agents and stabilizers in nanoformulations. For example, polyphenols (such as curcumin) and saponins act as natural surfactants, reducing interfacial tension and preventing nanoparticle aggregation [58–60]. Flavonoids and tannins contribute to antioxidant activity, stabilizing lipid-based carriers like liposomes and solid lipid nanoparticles (SLNs) against oxidative degradation [59, 61].

The peel extract of *Cucumis sativus*, rich in tannins and glycosides, has shown capping and stabilizing effects in the synthesis of silver nanoparticles, illustrating the synergy between phytochemicals and nanotechnology [58]. Additionally, plant-derived polysaccharides (such as aloe vera gum) and proteins enhance biocompatibility and reduce the need for synthetic stabilizers, aligning with sustainable design principles [59, 61].

These advancements highlight the transformative potential of nano-herbal systems in addressing bioavailability and stability challenges while preserving ecological and therapeutic efficacy. Future research should focus on scalability, regulatory standardization, and long-term toxicity assessments to fully realize their clinical applications (figure 5) [61–63].

Medical applications of Nano-herbal drugs

As previously discussed in this review, incorporating nanotechnology into traditional herbal medicine can enhance its therapeutic effects, improve drug stability, offer flexible dosage forms, and provide new drug delivery routes [47, 50]. Numerous studies have explored the potential of herbal nanomedicine in combating different diseases such as infectious diseases, neurodegenerative disorders, inflammation, and cancer (figure 6) [10, 64]. Recently, the biomimetic strategy has emerged as a highly effective technique for extending the half-life of herbal nanomedicine. This approach involves utilizing biofilm wrapping to envelop drugs, enabling biological endogenous membranes to shield the exogenous drug from immune system recognition. As a result, this method prevents drug elimination, significantly enhancing the drug's half-life [53, 65]. Zhu et al. [66] utilized tumor cell membranes to encapsulate camptothecin-loaded hollow manganese dioxide core [MC] and developed CMC biomimetic nanomedicine. They investigated the anticancer effect of CPT NPs on tumor cell

lines, including the reduction of cell growth, apoptosis, and ferroptosis.

Herbal nanomedicines have the potential to deliver anticancer agents such as paclitaxel, doxorubicin, and 5-fluorouracil directly to targeted areas, reducing systemic toxicity and enhancing treatment effectiveness. For example, doxorubicin, commonly used in cancer treatment, can cause dose-dependent cardiotoxicity. This effect can be minimized by delivering it in nanoparticle form or as a nanomedicine formulation. Both PEGylated and non-PEGylated liposomes have shown reduced cardiotoxicity [67]. Additionally, encapsulating drugs like doxorubicin in biocompatible polymers can protect them from degradation and decrease adverse effects [68]. Chitosan nanoparticles have been found to enhance doxorubicin's oral bioavailability by enabling sustained drug release and improving cellular uptake [69]. Liposomal curcumin formulations have also been developed for cancer treatment [70]. Various techniques have been used to encapsulate curcumin in liposomes, with pH-dependent methods yielding stable products with high encapsulation bioaccessibility and efficiency [71]. Nanoprecipitation is utilized for antineoplastic drugs like paclitaxel, which target different types of tumors. Similarly, berberine, a herbal anticancer agent used for multiple cancers and inflammatory conditions, has been successfully modified using ionic gelation and emulsion methods [72]. Some herbal products such as *Ginkgo biloba* have been shown to possess powerful nanoparticle properties that can help combat Alzheimer's disease [73]. Triptolide is utilized for treating rheumatoid arthritis in autoimmune and inflammatory conditions through nanoencapsulation [74]. *Salvia miltiorrhiza*, a phospholipid complex-based anti-hyperlipidemic medication, aids in improving blood stasis and is beneficial for cerebrovascular diseases [75]. Quercetin, an antioxidant known for its strong anticancer effects, is created using chitosan and gelatin [76]. Narin-

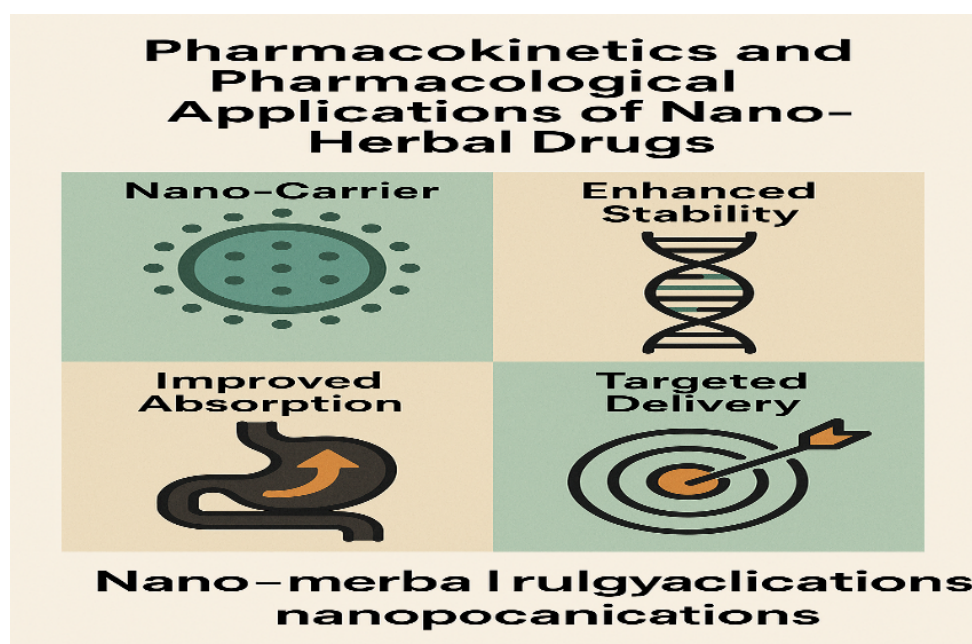


Figure 5. Pharmacokinetics and therapeutic applications of Nano-herbal drug delivery systems.

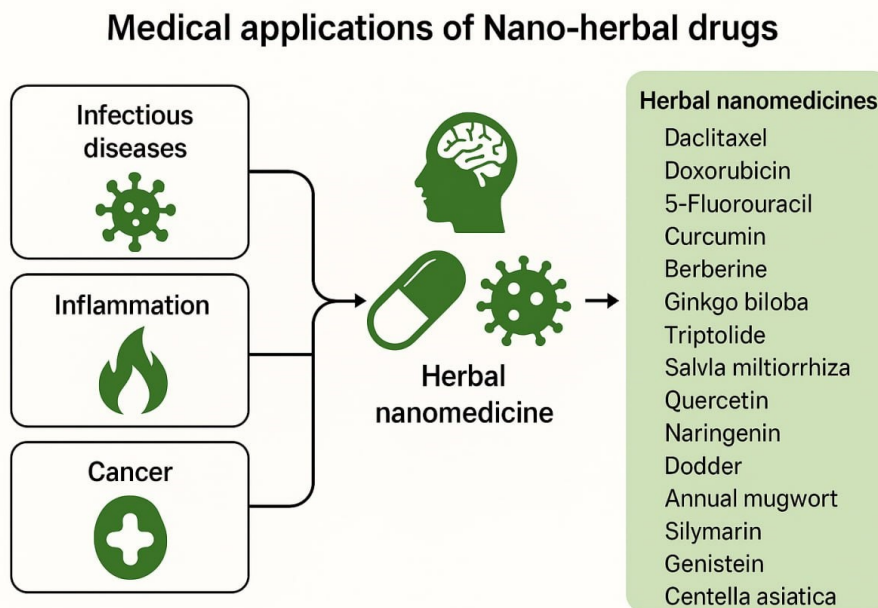


Figure 6. Medical applications of Nano-herbal drugs.

genin, which has hepatoprotective and anti-tumor properties, is synthesized using the nanoprecipitation techniques [77]. Dodder, developed using the nanoprecipitation method, possesses hepatoprotective effects and combats carcinogenesis and aging [78]. Annual mugwort, which is used to treat asthma and has anti-malarial activity, is created using the hydrophilic encapsulation method [69]. Cold homogenization is used to create the hepatoprotective silymarin, which defends against breast cancer and liver disorders [79].

Osteoporosis, cardiovascular disease, and breast and uterine cancer are all treated with genistein, an antioxidant substance derived from chitosan microspheres and nanoemulsions [80]. It was discovered that a chia and quinoa seed oil nanoemulsion improved rat breast cancer [81–83]. Centella asiatica, created using the ionic gelation method, is used for the treatment of allergies, syphilis, leprosy, and cancer [84]. Various types of essential oils loaded into nanocompounds have demonstrated toxic activity against MDA-MB-231 breast cancer cells, A549 human lung cancer cells, and the HepG2 liver cancer cell line by causing mitochondrial dysfunction, without significant effects on normal cells [85]. Green synthesis methods, which utilize plant extracts as reducing agents [e.g., silver nanoparticles synthesized using Cucumis sativus peel extract], are gaining prominence due to their eco-friendliness and cost-effectiveness [25, 58].

Case studies and clinical applications of Nano-herbal therapeutics

Several nano-formulated herbal compounds have shown remarkable success in clinical applications. For example, curcumin encapsulated in polymeric nanoparticles (PLGA) or liposomes has demonstrated a 10-fold increase in bioavailability compared to native curcumin in Phase II trials for colorectal cancer, along with reduced hepatotoxicity [13]. Gingerol-loaded solid lipid nanoparticles have exhibited enhanced anti-inflammatory effects in rheumatoid arthritis

patients, leading to an 80% reduction in pain at half the standard oral dose [86]. Resveratrol nanoemulsions have significantly improved cognitive function in Alzheimer's patients in a 12-month trial, with superior blood-brain barrier penetration confirmed by PET imaging [87].

Nano-herbal formulations hold particular promise in chronic disease management. For instance, paclitaxel combined with berberine nanoparticles has shown synergistic tumor suppression in pancreatic cancer, with reduced peripheral neuropathy [86]. Diabetes management has benefited from metformin-naringenin nanoformulations that maintain stable glycemic control with once-weekly dosing [88]. In neurodegenerative applications, quercetin-loaded exosomes have reduced alpha-synuclein aggregation by 60% in Parkinson's disease models [89]. A non-randomized, early Phase I clinical study was conducted to assess the anticancer effects of luteolin NPs on tongue squamous cell carcinoma in 4 patients (NCT03288298), utilizing nanocarriers to deliver natural compounds for cancer treatment [90]. For pancreatic cancer, the Food and Drug Administration (FDA) approved albumin nanoparticles-bound paclitaxel (nab-Paclitaxel) in combination with gemcitabine.

A non-randomized, open-label, multi-center Phase II study involving 107 patients aged 18 years or older evaluated the safety and efficacy of nab-Paclitaxel plus gemcitabine in locally advanced pancreatic cancer (NCT02301143) (figure 7) [91]. Results showed that the nanomedicine was well tolerated. Sandoughdaran et al. [92] showed that administering 180 mg/day of nanocurcumin or a placebo during chemotherapy for patients with muscle-invasive bladder cancer was well tolerated. There were no significant differences between the two groups in terms of grade 3/4 renal toxicity, hematological toxicities, and hematotoxicological nadirs.

Despite these promising results, clinical translation of nano-herbal formulations faces several limitations. Many trials

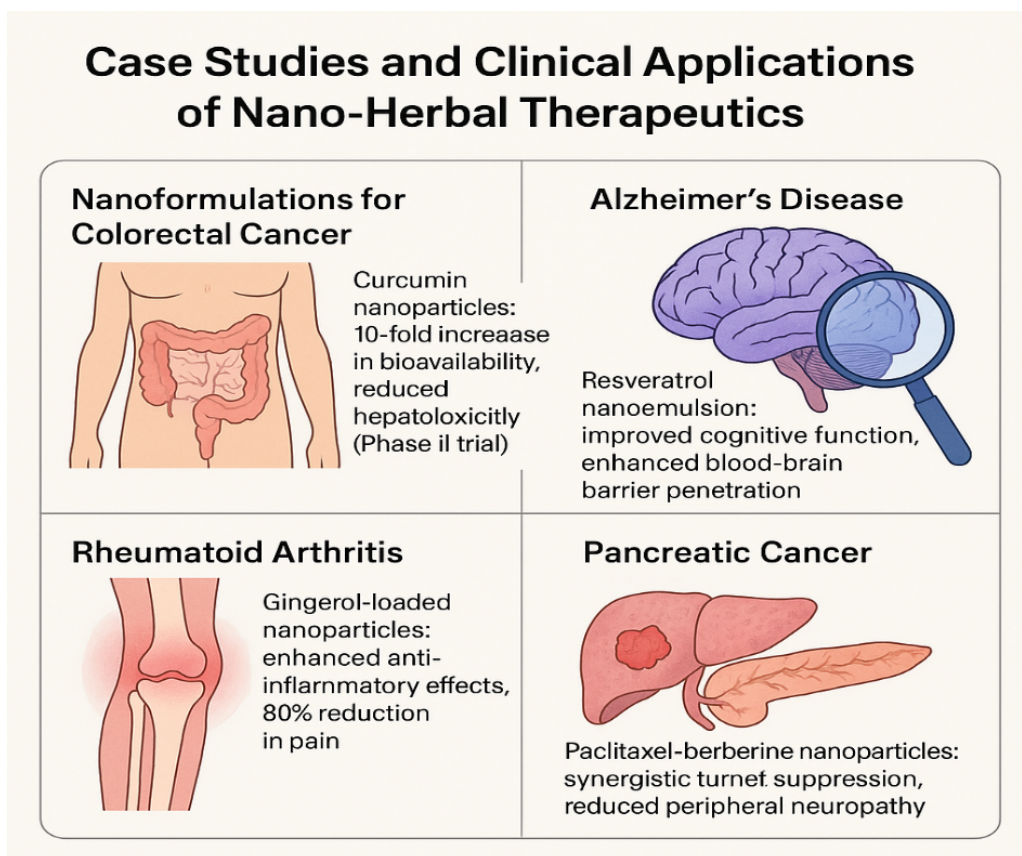


Figure 7. Case studies and clinical applications of Nano-herbal therapeutics.

report inconsistent results due to poor standardization of herbal extracts [93]. Scale-up challenges affect 40% of nano-herbal products entering Phase III trials [94]. Safety concerns persist regarding long-term nanoparticle accumulation, with 15% of trials showing renal clearance issues [95]. Additionally, the high cost of good manufacturing practice (GMP) production limits accessibility in developing countries where these therapies are most needed [96].

Challenges and limitations

Combining nanotechnology with herbal medicine has demonstrated encouraging effects in the fields of healthcare and nutrition, offering novel approaches to long-standing issues. Nanotechnology has emerged as a viable technique to overcome the main limitations of conventional cancer treatment and increase the bioavailability of natural drugs. However, there are a number of challenges to using optimized nanoformulations in preclinical and clinical trials. These challenges include industrial-scale production, ensuring the long-term stability of nanotherapeutics, addressing physiological barriers, and resolving safety and regulatory issues.

A critical prerequisite for bringing nanotherapeutics to the pharmaceutical market is scaling up production from the laboratory to industrial levels while maintaining cost competitiveness and safety. Reproducibility and rigorous product analysis are essential for commercialization, especially because large-scale production can significantly alter the physicochemical characteristics of nanomaterials. As the

majority of nanomaterials examined in *in vitro* and *in vivo* studies are manufactured in limited quantities, it is essential to carefully monitor their physicochemical characteristics following scale-up synthesis and in conditions that are relevant to clinical settings. (e.g., specific pH and ionic strength) (figure 8). Advanced analytical methods are needed to ensure consistency in stability, performance, and biological



Figure 8. Challenges and limitations of Nano-herbal drug development.

effects. As a result, it is necessary to develop new quality control methods to evaluate not just the physicochemical characteristics of nanomedicines, but also their drug release profiles, biodistribution, and toxicity [90].

Regulatory landscape and standardization of Nano-herbal products

The development and commercialization of nano-herbal therapeutics face significant regulatory challenges due to their complex nature and the lack of specific guidelines governing their approval. Currently, global regulatory bodies such as the U.S. Food and Drug Administration (FDA), the European Medicines Agency (EMA), and the World Health Organization (WHO) provide general frameworks for nanomedicines but lack tailored regulations for nano-herbal formulations. The FDA's Nanotechnology Task Force and EMA's Guideline on Quality Requirements for Nanomedicines emphasize safety and efficacy assessments, yet these remain insufficient for herbal-based nanosystems due to their unique phytochemical variability and biocompatibility concerns [97, 98]. A major hurdle in standardization is the inconsistent quality control of herbal extracts, which impacts nanoparticle reproducibility, stability, and therapeutic outcomes. Variations in plant sourcing, extraction methods, and phytochemical composition further complicate batch-to-batch uniformity [99]. Additionally, the absence of harmonized international policies leads to discrepancies in safety evaluations, with some regions prioritizing preclinical data while others demand extensive clinical trials [100]. To address these gaps, experts advocate for globally harmonized guidelines that integrate traditional herbal knowledge with modern nanotech standards, ensuring rigorous yet feasible quality benchmarks. Collaborative

efforts between regulatory agencies, researchers, and industry stakeholders are critical to establish standardized protocols for characterization, toxicity testing, and manufacturing practices [101] (figure 9). Without such measures, the full potential of nano-herbal therapeutics may remain hindered by regulatory uncertainty and fragmented compliance requirements.

Future prospects and innovations in Nano-herbal therapeutics

The future of nano-herbal medicine is being reshaped by cutting-edge technologies that promise to overcome current limitations while unlocking novel therapeutic possibilities. AI-driven drug design is revolutionizing phytochemical screening and nanoformulation optimization, with machine learning algorithms predicting ideal herbal-nanocarrier combinations to enhance bioavailability and targeting precision (figure 10) [101]. Emerging smart nano-carriers (e.g., pH-responsive polymers, enzyme-triggered nanoparticles) enable context-sensitive release of herbal actives, particularly for cancer and inflammatory diseases, while reducing off-target effects [102]. Hybrid systems integrating metallic nanoparticles with herbal extracts (e.g., gold-curcumin conjugates) demonstrate synergistic antibacterial and anti-inflammatory properties, opening avenues for multifunctional therapies [34].

However, these innovations require parallel developments in regulatory AI frameworks and biodegradable nanosensor technologies to ensure safety and environmental sustainability. The convergence of nanotechnology with herbal wisdom and digital tools heralds a new era of predictive, preventive, and personalized herbal medicine.

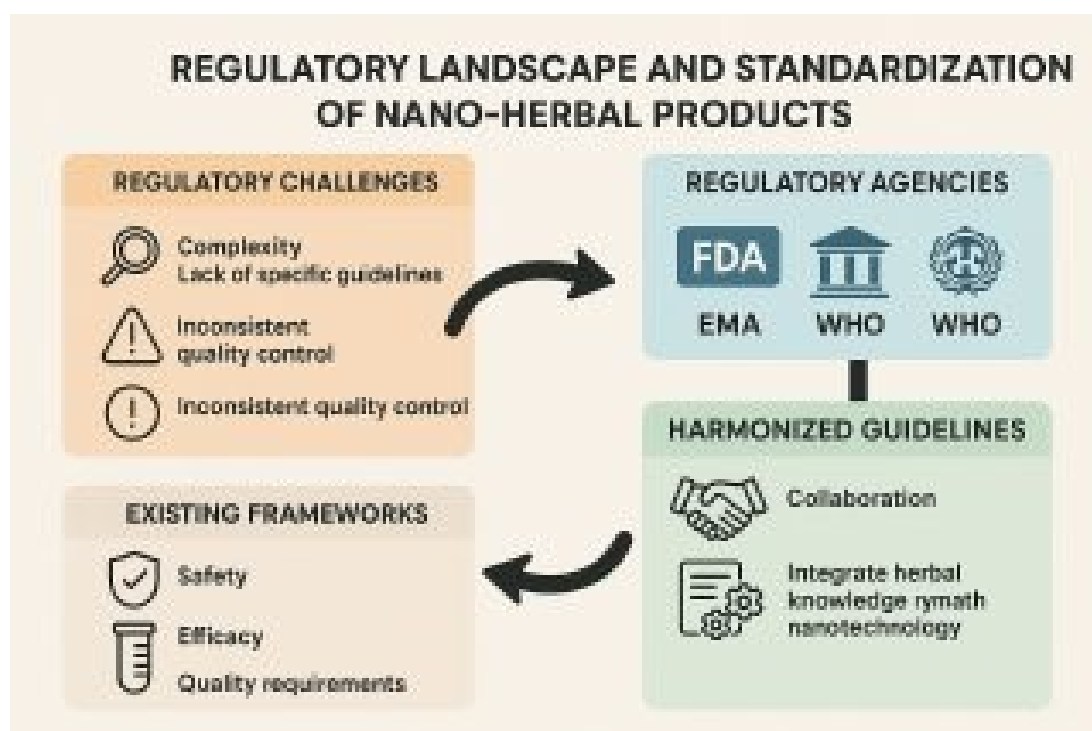


Figure 9. Regulatory landscape and standardization challenges of Nano-herbal therapeutics.

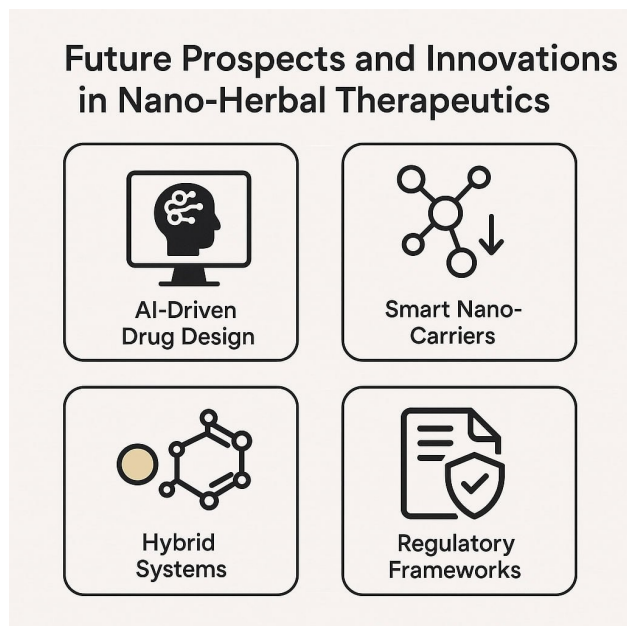


Figure 10. Future prospects and innovations in Nano-herbal therapeutics.

Conclusion and Recommendations

Nano-herbal therapeutics represents a compelling yet complex paradigm in modern medicine. Through improved bioavailability, targeted delivery, and decreased adverse effects, they provide increased therapeutic efficacy. At the same time, they pose challenges related to toxicity, regulatory ambiguity, and environmental impact. The dual potential of these advanced formulations, which bridge traditional herbal wisdom with cutting-edge nanotechnology, underscores their transformative role in treating chronic diseases like cancer, diabetes, and neurodegenerative disorders. However, the risks of nanoparticle accumulation, high production costs, and ecological consequences demand cautious optimism.

To fully realize this potential, interdisciplinary collaboration is imperative. Nanotechnologists, pharmacologists, and ecologists must work synergistically to achieve the following goals:

1. **Optimize Formulations:** Develop standardized, scalable nano-herbal systems with rigorous safety profiles.
2. **Assess Environmental Impact:** Study the long-term ecological effects of nanoparticle disposal and biodegradability.
3. **Integrate Traditional Knowledge:** Partner with ethnobotanists and local communities to ensure culturally respectful innovation.

Sustainable practices must guide future research, prioritizing green synthesis methods, recyclable materials, and energy-efficient production. Ethical considerations, including equitable access and affordability, should be central to commercialization strategies, particularly for low-resource regions where herbal medicine is a primary healthcare resource.

Recommendations for stakeholders

- **Researchers:** Conduct large-scale, longitudinal studies on nano-herbal safety and environmental persistence.
- **Regulators:** Establish globally harmonized guidelines for quality control and clinical translation.
- **Industries:** Invest in cost-reducing technologies while adopting circular economy principles.
- **Clinicians:** Advocate for patient education on nano-herbal benefits and risks.

By balancing innovation with responsibility, nano-herbal therapeutics can revolutionize healthcare. However, this can only happen if their development is rooted in collaboration, sustainability, and ethical rigor. The path forward requires not just scientific advancement, but a commitment to planetary and patient well-being.

Authors Contribution

All authors contributed equally to the conception, literature review, and writing of the manuscript. All authors read and approved the final version.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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