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Nanotechnology Based Delivery System for Herbal Bioactives

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Abstract: *Nanotechnology-based herbal drug delivery systems have gained significant attention for improving the therapeutic potential of phytochemicals by addressing limitations such as poor solubility, low bioavailability, and non-specific distribution. Herbal extracts serve as natural reducing and stabilizing agents in the green synthesis of nanoparticles, providing an eco-friendly and biocompatible alternative to conventional chemical approaches. A wide range of nanocarriers, including gold nanospheres, gold nanorods, carbon nanotubes, nanogels, polymeric nanoparticles, polymeric micelles, and liposomes, are designed to encapsulate herbal bioactive compounds and enable targeted drug delivery. These nanosystems facilitate active targeting of cancer stem cells (CSCs) through ligand-mediated interactions with specific CSC markers, enhancing therapeutic precision while reducing toxicity to normal tissues. Furthermore, stimuli-responsive drug release systems, activated by internal triggers such as pH, redox conditions, and enzymatic activity, or external stimuli including heat, light, ultrasound, and magnetic fields, allow controlled and site-specific drug release. Overall, nanotechnology-enabled herbal drug delivery represents a promising platform for effective and advanced cancer therapy.*

Keywords: Nanotechnology, Herbal drug delivery, Cancer stem cells, Stimuli-responsive release

I. INTRODUCTION

Herbal medicines have been used for centuries in traditional systems such as Ayurveda, Unani, and Traditional Chinese Medicine for the prevention and treatment of various diseases. These medicines are rich sources of bioactive compounds, including alkaloids, flavonoids, phenolics, terpenoids, glycosides, and saponins, which exhibit a wide range of pharmacological activities such as antioxidant, anti-inflammatory, antimicrobial, and anticancer effects. Due to their natural origin and generally low toxicity, herbal bioactives are considered safer alternatives to synthetic drugs and have gained renewed interest in modern therapeutics. Despite their significant therapeutic potential, the clinical application of many herbal bioactive compounds is limited by several inherent drawbacks. These include poor water solubility, low permeability, instability under physiological conditions, rapid metabolism, and low bioavailability. As a result, conventional herbal formulations often fail to achieve the desired therapeutic concentration at the target site, leading to reduced efficacy and inconsistent clinical outcomes.

To overcome these limitations, nanotechnology has emerged as a promising and innovative approach in the field of drug delivery. Nanotechnology involves the design and development of materials and carrier systems at the nanometer scale (1–100 nm) that can improve drug solubility, stability, absorption, targeted delivery, and controlled release. When applied to herbal bioactives, nanotechnology-based delivery systems significantly enhance their pharmacokinetic and pharmacodynamic profiles. Various nanocarrier systems, such as liposomes, nanoemulsions, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), polymeric nanoparticles, nanogels, phytosomes, and metallic nanoparticles, have been extensively explored for the delivery of herbal compounds. These nanocarriers protect bioactives from degradation, improve their absorption across biological membranes, enable site-specific targeting, and allow controlled or stimuli-responsive drug release.

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The integration of nanotechnology with herbal medicine represents a major advancement in modern pharmaceutics, bridging traditional knowledge with advanced nanoscience. Nanotechnology-based delivery systems for herbal bioactives hold great promise for improving therapeutic efficacy, reducing side effects, and developing safe, effective, and patient-friendly herbal formulations for the treatment of various diseases, including cancer and other chronic disorders.

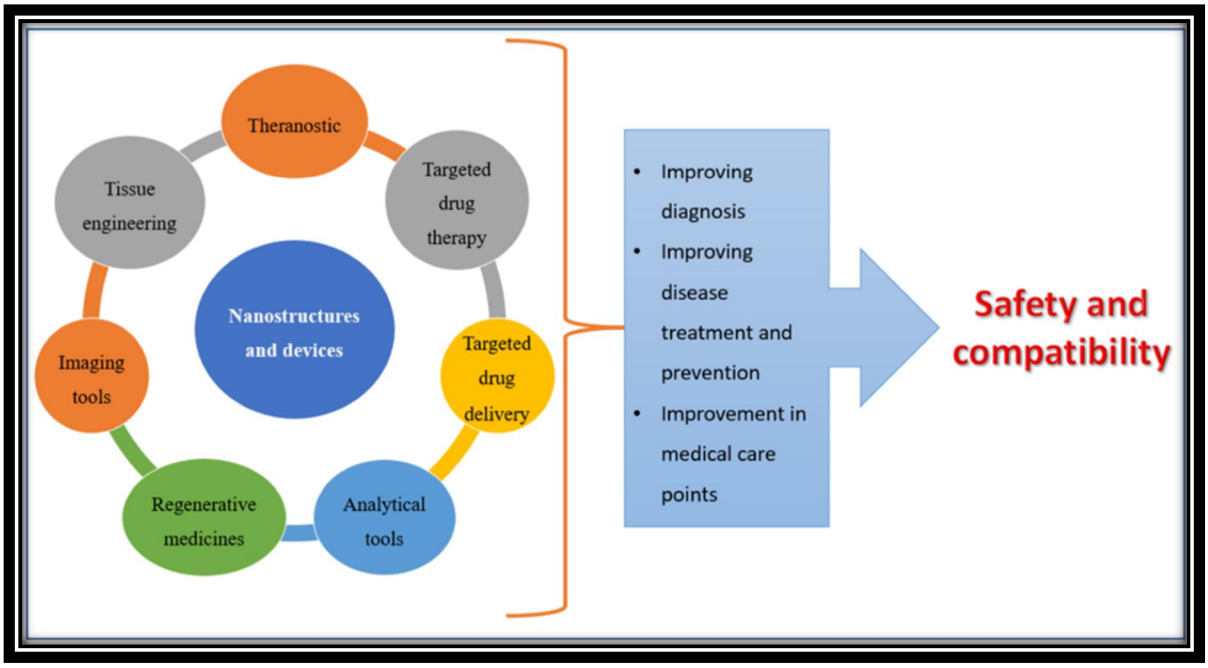

Fig. Applications of nanomedicines.

NANOTECHNOLOGY-BASED DRUG DELIVERY SYSTEMS: A OVERVIEW

Recent advances in nanotechnology have led to the development of nanoscale materials with particle sizes ranging from 1–1000 nm. These nanoparticles offer a large surface area, improved drug stability, better absorption, and targeted delivery. Nanotechnology-based drug delivery systems (DDSs) are widely used to overcome limitations of conventional drugs, especially herbal bioactives, such as poor solubility, low bioavailability, and rapid degradation. Several nano-formulations have been developed for effective drug delivery. Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs) improve drug stability, controlled release, and oral bioavailability. Nanocrystals enhance solubility and dissolution of poorly soluble drugs. Nano-emulsions increase membrane permeability and absorption, while liposomes encapsulate both hydrophilic and lipophilic drugs and enable targeted delivery. Phytosomes improve absorption of plant polyphenols and flavonoids. Ethosomes and niosomes are effective for transdermal delivery with improved stability. Cubosomes provide sustained release and are useful in topical and cancer therapies. Nanotechnology has broad applications in drug delivery, diagnosis, imaging, and cancer treatment. However, concerns related to toxicity, biocompatibility, cost, and ethical issues remain. Overall, nanotechnology-based drug delivery systems offer a promising approach to enhance the therapeutic efficacy and safety of herbal and synthetic drugs, though further clinical studies are needed.

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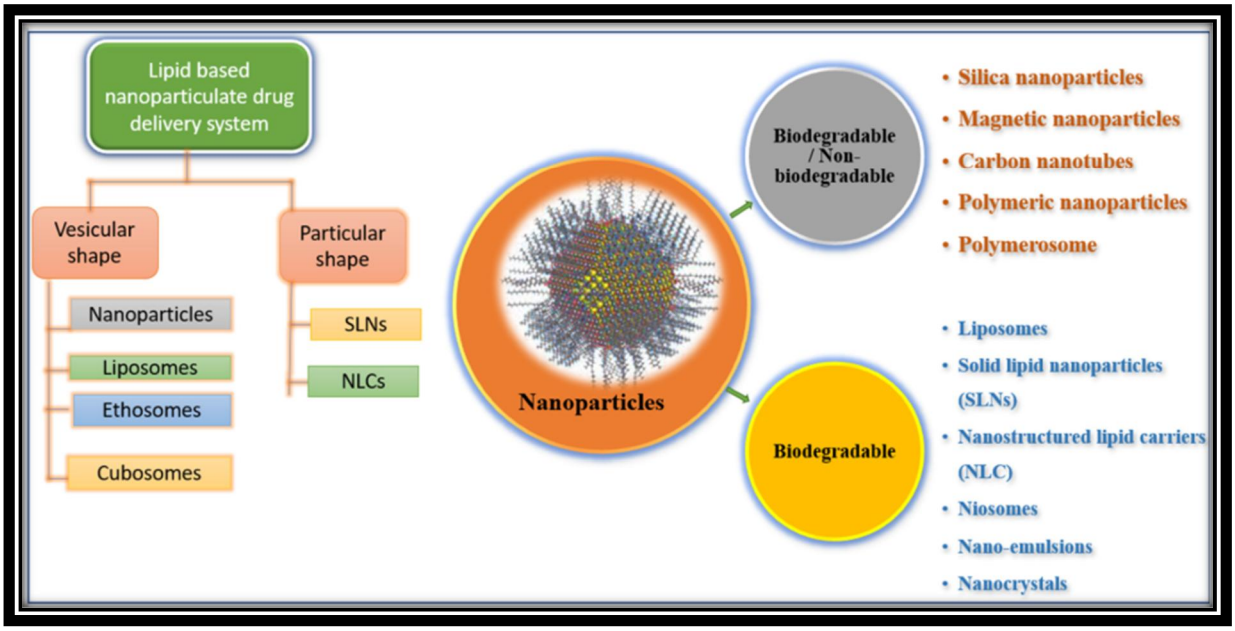
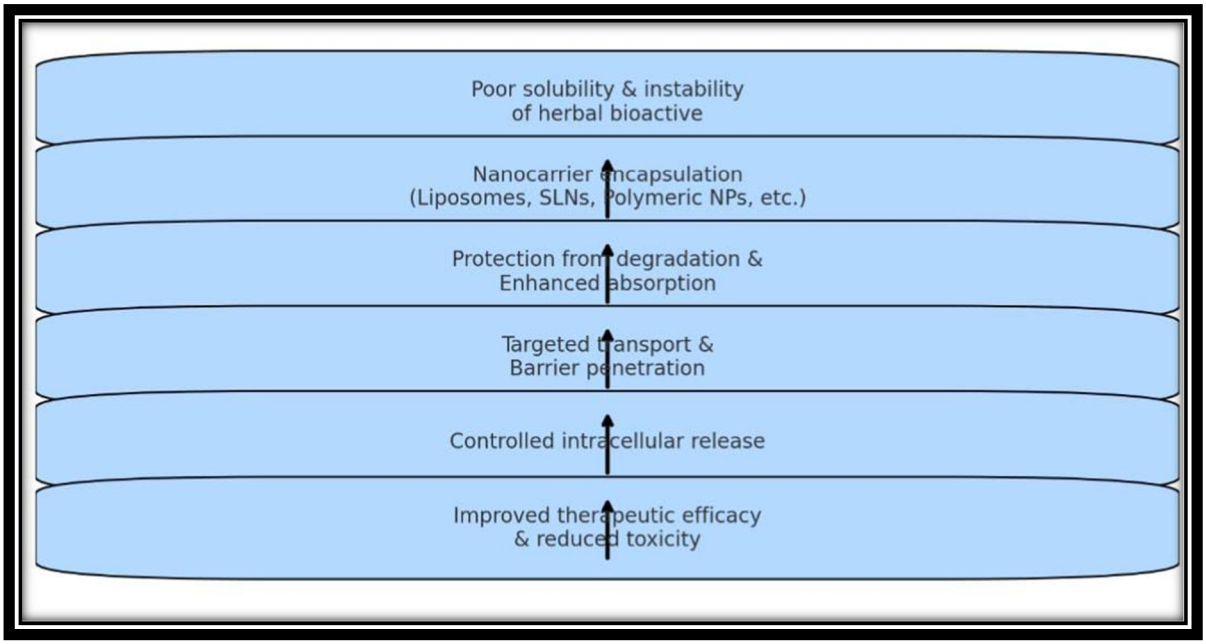


Fig. Illustrating various types of nano-formulations.

PATHOPHYSIOLOGY OF NANOTECHNOLOGY-BASED DELIVERY SYSTEM FOR HERBAL BIOACTIVES

The pathophysiology behind nanotechnology-based delivery systems for herbal bioactives focuses on how these nanoformulations interact with biological barriers, disease conditions, and cellular mechanisms to improve therapeutic outcomes.



Many herbal bioactive compounds suffer from poor water solubility, instability in physiological environments, rapid metabolism, and limited absorption across biological membranes. These limitations result in low bioavailability and reduced therapeutic effectiveness. Nanotechnology-based delivery systems are designed to overcome these pathophysiological barriers by modifying the interaction between herbal drugs and the body. When herbal bioactives are

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encapsulated in nanocarriers (such as liposomes, nanoparticles, nanoemulsions, or lipid carriers), they are protected from enzymatic degradation and harsh conditions of the gastrointestinal tract. The small particle size and large surface area of nanoparticles enhance dissolution, permeability, and absorption across epithelial barriers, including intestinal, skin, and cellular membranes.

At the disease site, especially in conditions like cancer or inflammation, pathological changes such as leaky vasculature, altered pH, increased enzyme activity, and oxidative stress favor the accumulation of nanoparticles. This allows targeted delivery through passive or active targeting mechanisms, increasing drug concentration at the affected tissue while minimizing systemic toxicity. Additionally, stimuli-responsive nanocarriers release herbal bioactives in response to internal triggers (pH, enzymes, redox conditions) or external stimuli (heat, light, magnetic field), ensuring controlled and site-specific drug release. Overall, nanotechnology-based delivery systems modify the pathophysiological interaction of herbal bioactives with the body to enhance efficacy, reduce side effects, and improve clinical outcomes.

TYPES OF HERBAL BIOACTIVE COMPOUNDS

Herbal bioactives are naturally occurring chemical compounds present in medicinal plants that are responsible for their therapeutic effects. Due to limitations such as poor solubility, instability, and low bioavailability, nanotechnology-based delivery systems are widely used to improve their effectiveness. The major types of herbal bioactive compounds are described below:

1. Alkaloids

Alkaloids are nitrogen-containing bioactive compounds with strong pharmacological activities. They exhibit analgesic, anticancer, antimalarial, and antimicrobial properties. Examples include morphine, berberine, quinine, and vincristine. Nanocarriers enhance their solubility, reduce toxicity, and improve targeted delivery.

2. Flavonoids

Flavonoids are polyphenolic compounds known for antioxidant, anti-inflammatory, anticancer, and cardioprotective effects. Common examples include quercetin, kaempferol, rutin, and apigenin. Nanotechnology improves their absorption and stability and protects them from rapid metabolism.

3. Phenolic Compounds

Phenolics possess strong antioxidant and antimicrobial activities. Examples include gallic acid, caffeic acid, and resveratrol. Nanoformulations enhance their bioavailability and sustained release.

4. Terpenoids

Terpenoids are lipid-soluble compounds with anti-inflammatory, anticancer, antiviral, and antimicrobial properties. Examples include artemisinin, menthol, and taxol. Nanocarriers improve solubility and controlled delivery.

5. Glycosides

Glycosides consist of a sugar and a non-sugar moiety and exhibit cardiotonic, laxative, and anticancer activities. Examples include digoxin and sennosides. Nanotechnology enhances their stability and reduces gastrointestinal irritation.

6. Saponins

Saponins have immunomodulatory, anticancer, and cholesterol-lowering effects. Examples include ginsenosides and diosgenin. Nano-based delivery improves their permeability and reduces hemolytic toxicity.

7. Tannins

Tannins are polyphenolic compounds with antioxidant, antimicrobial, and anti-inflammatory properties. Nanocarriers help in controlled release and enhanced therapeutic action.

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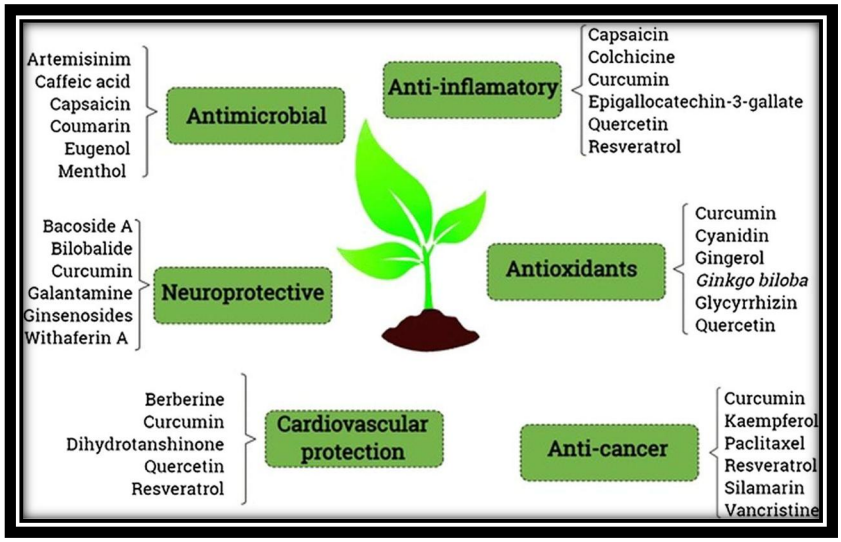

8. Essential Oils

Essential oils are volatile aromatic compounds with antimicrobial, antifungal, and anti-inflammatory effects. Examples include eucalyptus oil, peppermint oil, and clove oil. Nanoemulsions and lipid nanoparticles improve their stability and bioavailability.

9. Polysaccharides

Polysaccharides exhibit immunomodulatory, antioxidant, and wound-healing properties. Examples include aloe vera polysaccharides and beta-glucans. Nanotechnology improves their targeted delivery and biological activity.

No.	Paper Title	Journal/Source	Year	Authors	Conclusion
1	*Development of Herbal-Based Nanoparticles for Enhanced Drug Delivery*	Int. J. Pharmacognosy & Herbal Drug Technology	**2025**	Govind Sharma	Herbal-based nanoparticles synthesized via green methods improved solubility, stability, bioavailability, and targeted delivery of phytochemicals, and hold promise for cancer, microbial and inflammatory therapies with environmental sustainability benefits.
2	*Nanotechnology in Herbal Medicine: A Promising Approach for Enhanced Drug Delivery and Therapeutic Efficacy*	J. Drug Delivery & Therapeutics	**2025**	Tajne PS, Kalamb VS, Girhe PN et al.	Review highlighting how nanoformulations enhance therapeutic efficacy of herbal drugs by improving bioavailability, targeted delivery, and reducing side effects.
3	*Nano technology-based drug delivery systems and herbal medicine*	J. Drug Delivery & Therapeutics	**2025**	Kathole KS, Hatwar PR, Bakal RL et al.	Nanocarriers such as nanoparticles and lipid systems enhance herbal medicine delivery, addressing conventional limitations like low solubility and poor bioavailability.
4	*Exploring nanoformulation drug delivery of herbal*	Intelligent Pharmacy	**2025**	Divyanshi Sharma, Arti Gupta, Reetika Rawat et al.	Comprehensive review showing nanoformulations improve cellular uptake, control release, and therapeutic outcomes of

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	actives for enhanced therapeutic efficacy				phytochemicals (flavonoids, triterpenoids).
5	*Herbal Theranostics: Controlled, Targeted Delivery and Imaging of Herbal Molecules*	Nanotheranostics	**2024**	Aseem Setia, Bhaskar Vallamkonda, Randheer	Nanotheranostic platforms combining targeted delivery and imaging enhance tissue penetration and controlled release of herbal compounds.
6	*Advancements in nanotechnology for the delivery of phytochemicals*	Journal of Integrative Medicine	**2024**	Reddy Challa et al.	Review outlining phytosome and other nanocarriers that improve stability & efficacy of herbal bioactives.
7	*Chitosan Nanoparticles: An Approbative System for the Delivery of Herbal Bioactives*	The Natural Products Journal	**2024**	Sapna Saini, Sanju Nanda	Chitosan nanoparticles provide enhanced stability, biocompatibility, and delivery efficiency for a wide range of herbal extracts.
8	*Advances in Phytochemical-Based Nanocarrier Approaches for Rheumatoid Arthritis*	PubMed Review	**2024**	Anju Dhiman	Nanocarrier systems significantly increase solubility, bioavailability and sustained delivery of herbal bioactives for RA treatment.

II. RESULTS AND DISCUSSION

The collected literature clearly demonstrates that nanotechnology-based delivery systems significantly enhance the therapeutic performance of herbal bioactive compounds. Results from recent studies (2024–2025) indicate that nanoformulations effectively overcome major limitations of conventional herbal medicines, including poor solubility, low bioavailability, instability, and non-specific distribution. Various nanocarriers such as solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), polymeric nanoparticles, liposomes, nanoemulsions, phytosomes, and metallic nanoparticles have shown remarkable improvements in drug solubility, stability, absorption, and controlled release. Green synthesis approaches using herbal extracts as reducing and stabilizing agents have further contributed to eco-friendly and biocompatible nanoparticle development.

The reviewed studies highlight enhanced targeting efficiency, particularly in cancer therapy, where nano-based systems improve accumulation at tumor sites through passive and active targeting mechanisms. Ligand-functionalized nanoparticles demonstrated selective targeting of cancer stem cells (CSCs), leading to improved therapeutic precision and reduced toxicity to healthy tissues. Stimuli-responsive nanocarriers responded effectively to internal triggers such as pH, enzymes, and redox conditions, as well as external stimuli like heat and light, enabling site-specific drug release. Chitosan-based nanoparticles, phytosomes, and lipid-based carriers showed superior biocompatibility and sustained release profiles, improving pharmacokinetic behavior and therapeutic outcomes. Overall, the results confirm that nanotechnology-based delivery systems markedly enhance the efficacy, safety, and clinical potential of herbal bioactives across multiple therapeutic applications.

III. CONCLUSION

Nanotechnology-based delivery systems represent a transformative advancement in the field of herbal drug delivery. By addressing critical challenges such as poor solubility, low bioavailability, instability, and rapid metabolism, nanoformulations significantly enhance the therapeutic potential of herbal bioactive compounds. The integration of nanocarriers—including lipid-based systems, polymeric nanoparticles, phytosomes, and metallic nanoparticles—has enabled improved drug protection, targeted delivery, controlled release, and reduced systemic toxicity.Recent studies

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demonstrate promising outcomes in cancer therapy, inflammatory disorders, and chronic diseases, with particular emphasis on cancer stem cell targeting and stimuli-responsive drug release. Green synthesis approaches further enhance the sustainability and biocompatibility of herbal nanomedicines.

Despite these advancements, challenges related to large-scale production, long-term toxicity, regulatory approval, and clinical translation remain. Future research should focus on detailed pharmacokinetic, pharmacodynamic, and clinical studies to ensure safety and efficacy in human applications. Overall, nanotechnology-based delivery systems offer a highly promising platform for the development of effective, safe, and patient-friendly herbal therapeutics, bridging traditional medicine with modern pharmaceutical science.

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