

Nanostructured Herbal Formulation for Improved Anti-Inflammatory Efficacy: A Review

B Sibani Patra¹, Suchita Wamankar²

¹M. Pharma., Department of Pharmaceutics, Rungta Institute of Pharmaceutical Sciences, Bhilai

²Department of Pharmaceutics, Rungta Institute of Pharmaceutical Sciences, Bhilai

Abstract—Inflammation is a fundamental biological response involved in the pathogenesis of numerous acute and chronic disorders. Although synthetic anti-inflammatory drugs are widely used, their long-term administration is often associated with adverse effects. Herbal medicines offer a safer alternative; however, poor solubility, instability, and limited bioavailability restrict their therapeutic potential. Recent advances in nanotechnology have enabled the development of nanostructured herbal delivery systems that enhance stability, permeability, and efficacy [4,7]. This review summarizes the role of nanotechnology in improving the anti-inflammatory performance of herbal drugs, discusses various nanocarrier systems, and highlights future prospects for nano-herbal therapeutics.

Index Terms—Nanotechnology, herbal medicines, anti-inflammatory, nanogels, drug delivery

I. INTRODUCTION

Inflammation is a protective physiological response initiated by tissue injury, infection, or chemical irritation. While acute inflammation is beneficial, chronic inflammation contributes to diseases such as arthritis, dermatitis, cardiovascular disorders, and metabolic syndrome. Conventional anti-inflammatory therapies, including non-steroidal anti-inflammatory drugs and corticosteroids, are effective but often produce gastrointestinal, renal, and cardiovascular side effects during prolonged use [3]. Consequently, attention has shifted toward plant-based therapies with improved safety profiles.

Herbal medicines contain bioactive phytochemicals such as polyphenols, flavonoids, terpenoids, and alkaloids that exert anti-inflammatory effects through inhibition of inflammatory mediators, modulation of cytokine signaling, and antioxidant activity. Despite promising pharmacological activity, many herbal

agents exhibit low aqueous solubility, poor membrane permeability, and instability, limiting their clinical translation [9,24].

Key Differences & Synergies

- Speed vs. Safety: Conventional offers rapid relief; plant-based offers gentler, longer-term management.
- Complexity: Herbs are complex mixtures; conventional drugs are pure compounds.
- Integration: Combining them (e.g., nettle with NSAIDs) can enhance effects and reduce doses of conventional drugs, showing promise for managing chronic conditions like arthritis and IBD.

II. LIMITATIONS OF CONVENTIONAL HERBAL FORMULATIONS

Traditional herbal formulations such as extracts, ointments, and gels often fail to achieve adequate therapeutic concentrations at the target site. Poor skin penetration, rapid degradation of phytoconstituents, and inconsistent bioavailability are major challenges [3,9]. These limitations result in reduced efficacy and require frequent dosing, which can compromise patient compliance. Therefore, innovative formulation strategies are necessary to maximize the therapeutic benefits of herbal anti-inflammatory agents.

A. Challenges for Plant-Based Integration

While promising, plant-based therapies face several hurdles for 2025 clinical adoption:

- Bioavailability: Many compounds (like curcumin) are poorly absorbed by the gut, requiring advanced delivery systems like nanoparticles or liposomes to be effective.

- Standardization: The potency of a plant extract can vary based on soil, climate, and harvesting methods, making consistent dosing difficult.
- Drug Interactions: Herbs can interfere with conventional medications (e.g., St. John's Wort can reduce the efficacy of blood thinners).

III. ROLE OF NANOTECHNOLOGY IN HERBAL DRUG DELIVERY

Nanotechnology-based drug delivery systems provide an effective approach to overcome the limitations of conventional herbal formulations. Nanocarriers typically range from 10 to 500 nm in size and offer increased surface area, improved solubility, controlled release, and enhanced interaction with biological membranes [7,13,16]. These systems protect labile phytochemicals from degradation and facilitate their transport across biological barriers.

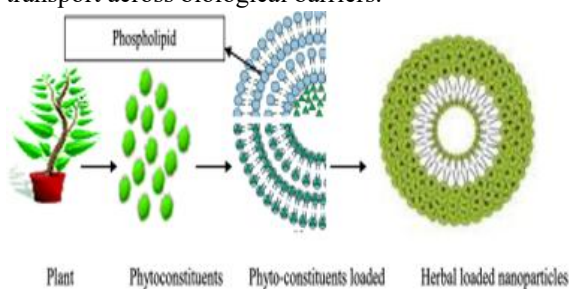


Fig 1 Herbal drug-loaded nanoparticles

- Plant (Herbal Source)
 1. Represents the medicinal plant (e.g., *Helicteres isora*).
 2. The plant contains bioactive compounds responsible for pharmacological activity.

• Phytoconstituents

These are the active chemical compounds extracted from the plant, such as:

- Flavonoids
- Phenolics
- Alkaloids
- Tannins

On their own, these compounds often suffer from poor solubility, instability, and low bioavailability.

• Phospholipid (Carrier System)

Phospholipids (like soy lecithin) act as biocompatible carriers.

They have both hydrophilic (water-loving) and lipophilic (fat-loving) regions, making them ideal for drug delivery.

• Phyto-constituents Loaded into Phospholipids

The phytoconstituents are incorporated into the phospholipid structure. This forms a phyto-phospholipid complex (often called a phytosome).

The interaction improves:

- Stability
- Skin penetration
- Controlled drug release
- Herbal-Loaded Nanoparticles

Final nano-structured system with a well-organized spherical architecture.

Results in:

- Enhanced bioavailability
- Improved anti-inflammatory efficacy
- Reduced dose requirement
- Better patient compliance

Overall significance:

This image visually explains how traditional herbal extracts are transformed into modern nanostructured drug delivery systems, bridging herbal medicine and nanotechnology. It is especially relevant for nanogels, phytosomes, and lipid-based nano formulations used in anti-inflammatory and topical drug delivery research.

Nanostructured delivery systems also enable site-specific targeting and sustained drug release, reducing dosing frequency and improving therapeutic outcomes. Their application in herbal medicine has gained significant interest due to their biocompatibility and ability to accommodate complex phytochemical mixtures.

Helicteres isora (H. isora) – Active Ingredient

Helicteres isora fruit extract is the therapeutically active component of the formulation. It is rich in phenolic compounds, flavonoids, tannins, and glycosides, which are responsible for its anti-inflammatory, antioxidant, analgesic, and wound-healing properties [5,12,15].



Fig 2 Helicteres isora

Role in formulation:

- Acts as the bioactive agent providing anti-inflammatory activity
- Helps inhibit inflammatory mediators such as prostaglandins, cytokines, and free radicals
- Encapsulation in nanostructures improves its solubility, stability, and bioavailability, overcoming limitations of conventional herbal gels

Soy Lecithin – Lipid Carrier

Soy lecithin is a natural phospholipid mixture, mainly composed of phosphatidylcholine. It is widely used in nano-delivery systems due to its biocompatibility and amphiphilic nature [1,11,14].



Fig 3 Soy Lecithin

Role in formulation:

- Forms the lipid bilayer of nanostructures (liposomes / phytosomes)
- Encapsulates both hydrophilic and lipophilic constituents of H. isora
- Enhances drug stability and controlled release
- Improves skin penetration by interacting with stratum corneum lipids

Carbopol 934 – Gelling Agent

Carbopol 934 is a high-molecular-weight cross-linked polyacrylic acid polymer, commonly used in topical formulations.

Role in formulation:

- Converts the nanosuspension into a stable semisolid nanogel

- Provides desirable viscosity, spreadability, and consistency
- Ensures uniform distribution of nanostructures throughout the gel
- Enhances patient compliance by improving texture and ease of application



Fig 4 Carbopol 934 & Tween 80

Tween 80 (Polysorbate 80) – Surfactant

Tween 80 is a non-ionic surfactant with excellent emulsifying and stabilizing properties.

Role in formulation:

- Reduces interfacial tension during nanoparticle formation
- Prevents aggregation and coalescence of lipid vesicles
- Improves physical stability of the nanogel
- Enhances solubilization of herbal constituents

Glycerin – Humectant

Glycerin is a widely used hydrophilic moisturizing agent in topical formulations.

Role in formulation:

- Retains moisture by attracting water into the skin
- Prevents dryness and irritation caused by polymers
- Improves skin hydration and smoothness
- Enhances overall cosmetic acceptability of the formulation



Fig 5 Glycerin & Triethanolamine

Triethanolamine (AR Grade) – pH Adjuster

Triethanolamine is an organic base used to neutralize acidic polymers such as Carbopol.

Role in formulation:

- Adjusts pH to skin-friendly range (5.5–7.0)
- Activates Carbopol, enabling proper gel formation
- Improves chemical stability of the formulation
- Minimizes skin irritation due to improper pH

Propylene Glycol – Permeation Enhancer

Propylene glycol is a hydrophilic solvent and penetration enhancer commonly used in dermatological preparations.

Role in formulation:

- Enhances transdermal penetration of active constituents
- Disrupts lipid structure of stratum corneum, allowing deeper drug diffusion
- Acts as a co-solvent for preservatives and plant extract
- Improves drug retention in skin layers



Fig 6 Propylene glycol & Methyl paraben

Methyl Paraben – Preservative

Methyl paraben is a broad-spectrum antimicrobial agent effective against bacteria.

Role in formulation:

- Prevents microbial contamination in aqueous systems
- Extends shelf life of the nanogel
- Works synergistically with propyl paraben
- Effective at low concentrations with minimal toxicity

Propyl Paraben – Preservative

Propyl paraben is more effective against fungi and molds compared to methyl paraben.

Role in formulation:

- Complements methyl paraben to provide broad antimicrobial protection
- Ensures formulation safety during storage and repeated use
- Maintains product quality and stability

Distilled Water – Vehicle

Distilled water is used as the continuous phase of the formulation.

Role in formulation:

- Acts as a solvent and dispersion medium
- Facilitates hydration of Carbopol
- Ensures uniform distribution of ingredients
- Free from ions and impurities that could affect formulation stability

Table 1 Material and Its Purpose

Sr No	Material Name	Purpose
1	H. isora	Active ingredient
2	Soy lecithin	Lipid Carrier
3	Carbopol 934	Gelling agent
4	Tween 80	Surfactant
5	Glycerin	Humectant
6	Triethanolamine AR grade	PH Adjustment
7	Propylene glycol	Permeation enhancer
8	Methyl paraben	Preservative
9	Propyl paraben	Preservative
10	Distilled water	Vehicle

IV. TYPES OF NANOSTRUCTURED HERBAL DELIVERY SYSTEMS

Several nanocarrier systems have been explored for anti-inflammatory herbal delivery. Nanogels are three-dimensional polymeric networks capable of holding large amounts of water while encapsulating bioactive compounds. They offer excellent spreadability, skin adhesion, and controlled release properties, making them suitable for topical anti-inflammatory therapy [17,19].

Liposomes and phytosomes are phospholipid-based vesicular systems that enhance the bioavailability of both hydrophilic and lipophilic phytoconstituents. Solid lipid nanoparticles and nanostructured lipid carriers provide improved stability and sustained release, while polymeric nanoparticles offer precise control over particle size and drug release kinetics.

V. MECHANISMS OF ENHANCED ANTI-INFLAMMATORY ACTIVITY

Nanocarriers enhance anti-inflammatory efficacy through multiple mechanisms. Reduced particle size improves penetration across the stratum corneum and cellular membranes [6,8,19]. Phospholipid-based

systems integrate with biological membranes, increasing permeability and retention at the target site. Sustained release maintains therapeutic drug levels over extended periods, minimizing fluctuations in drug concentration.

Additionally, nanocarriers protect phytochemicals from oxidative and enzymatic degradation, preserving their biological activity. These combined effects result in enhanced inhibition of inflammatory mediators and improved pharmacological outcomes.

VI. RECENT ADVANCES IN NANO-HERBAL ANTI-INFLAMMATORY SYSTEMS

Recent studies have demonstrated improved anti-inflammatory efficacy of herbal nanogels, liposomal formulations, and lipid-based nanoparticles.

Emerging Trends & Advantages

- **Nano-Herbal Nanozymes:** Synthesized hydrothermally or via microwaves, these mimic enzymes, scavenging free radicals and reducing inflammation (e.g., from garlic, honeyberry).
- **Targeted Delivery:** Nanocarriers improve drug concentration at the disease site, reducing systemic side effects.
- **Improved Pharmacokinetics:** Nanotechnology enhances stability, prolongs circulation time, and increases uptake of phytochemicals.
- **Advanced Formulations:** Development of sprayable nanofibers and biomaterial scaffolds for wound healing, alongside nano-hydrogels for controlled release.

Nanoformulations of plant extracts have shown superior in-vitro and in-vivo performance compared with conventional formulations, including enhanced membrane stabilization, reduced edema, and prolonged therapeutic action. Such findings highlight the translational potential of nanostructured herbal systems for inflammatory conditions.

VII. CHALLENGES AND FUTURE PERSPECTIVES

Despite promising results, challenges remain in the development of nano-herbal formulations. Scale-up, long-term stability, regulatory approval, and comprehensive toxicity evaluation require further investigation. Standardization of herbal extracts and

reproducibility of nanocarrier systems are also critical considerations [4,24]. Future research should focus on advanced characterization, pharmacokinetic evaluation, and clinical validation of nano-herbal systems. Integration of green synthesis approaches and regulatory harmonization will further facilitate the commercialization of nano-enabled herbal therapeutics.

VIII. CONCLUSION

Nanostructured herbal delivery systems represent a promising strategy to enhance the anti-inflammatory efficacy of plant-based medicines. By improving solubility, stability, permeability, and sustained release, nanocarriers address the major limitations of conventional herbal formulations. Continued research and clinical validation may establish nano-herbal systems as effective and safe alternatives for the management of inflammatory disorders.

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