Nano Herbal Applications for Therapeutic Utilization and Research Enhancement(NATURE): Enhancing Bioavailability and Therapeutic Efficacy

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Abstract:

This review explores how nanotechnology can be applied to herbal extracts to address common limitations like inadequate solubility, limited bioavailability, and instability of phytoconstituents. This approach has led to the development of advanced delivery systems that offer better therapeutic effectiveness and precise targeting. The review covers various nanoformulation techniques, including liposomes, phytosomes, nanoemulsions, solid lipid nanoparticles (SLNs), and nanostructured lipid carriers (NLCs), along with their mechanisms, benefits, and therapeutic uses.The exploration of nanoencapsulation, homogenization, nanofabrication, and nanoemulsion techniques reveals their role in enhancing the delivery of herbal bioactives. These methods improve absorption, enable precise targeting, and allow for controlled release. Extensive research demonstrates that nanoformulations significantly enhance the absorption and therapeutic effects of herbal compounds in various conditions, including cancer, diabetes, inflammation, and skin disorders. Additionally, these systems often result in fewer side effects and reduced toxicity. The study underscores the necessity of ongoing research to ensure patient safety, regulatory compliance, and effective clinical use. Ultimately, nanoformulated herbal medicines bridge the gap between traditional remedies and modern healthcare, offering more effective, safe, and personalized treatment options.

Major findings:

Herbal extract nanoformulations enhance the solubility, stability, and bioavailability of phytochemicals. These delivery systems improve targeted therapeutic effects, reduce toxicity, and allow for prolonged drug release. They hold significant promise for managing chronic diseases, though clinical application still demands thorough validation.

Keywords: Nanotechnology, Herbal Extracts, Nanoformulations, Bioavailability, Drug Delivery, Phytoconstituents

Introduction:

The integration of nanotechnology with herbal extracts has significantly enhanced their bioavailability and therapeutic efficacy, addressing traditional limitations such as poor solubility and low stability. By employing nano formulation techniques, researchers have developed innovative delivery systems that improve the absorption and effectiveness of bioactive compounds found in medicinal plants. This synthesis of ancient herbal wisdom with modern technology opens new avenues for treatment strategies. Herbs have been employed as therapeutic agents for over four millennia, with substantiating evidence identified within the Indian, Persian-Arabic, and European medicinal traditions. Among these, the ancient civilization of India is renowned as one of the most significant repositories of therapeutically valuable herbs, attributable to its highly diverse forest ecosystems. Although various indigenous medical systems, such as Ayurveda, Unani, Siddha, and tribal medicine, have been historically practiced, Unani and Ayurveda emerged as the most widely utilized systems. According to monographs published by the World Health Organization, there are nearly 21,000 species of herbs documented with recognized therapeutic properties, and it is noted that approximately 80% of the global population depends on traditional medicine for their primary healthcare needs. Phytochemical constituents exhibit limited absorption characteristics due to their elevated molecular weight and their inability to traverse lipid membranes. Furthermore, it has been documented that over 40% of novel bioactive compounds demonstrate poor aqueous solubility, resulting in sluggish drug absorption. Consequently, the exploration of nanoformulations for herbal medications has been undertaken to enhance bioavailability, solubility, drug retention time, drug delivery efficiency, and to mitigate the adverse toxicological effects associated with these pharmaceuticals. The integration of nanotechnology with herbal extracts has significantly enhanced their bioavailability and therapeutic efficacy, addressing traditional limitations such as poor solubility and low stability. By employing nanoformulation techniques, researchers have developed innovative delivery systems that improve the absorption and effectiveness of bioactive compounds found in medicinal plants. This synthesis of ancient herbal wisdom with modern technology opens new avenues for treatment strategies. Research rooted in bionanotechnology is anticipated to yield innovative nanoformulations and broaden their applications, facilitating the effective delivery of a greater array of therapeutic agents. Enhanced Bioavailability: Nanoformulation Techniques: Methods like nanoparticles, nanocapsules, and nanoemulsions encapsulate herbal extracts, improving their solubility and stability[1,2]. Improved Absorption: The nanoscale size of these formulations allows for better cellular penetration, enhancing the overall bioavailability of herbal compounds. Therapeutic Efficacy: Targeted Delivery: Nanoparticles can deliver herbal extracts directly to specific sites in the body, increasing their therapeutic effects while minimizing side effects [3]. Despite the promising advancements, challenges such as large-scale production, standardization, and regulatory hurdles remain. Continued research is essential to ensure the long-term safety and efficacy of these nano-herbal formulations in clinical applications. While the potential of nano formulations is vast, it is crucial to balance innovation with thorough safety evaluations to ensure patient well-being. This review elucidates the utilization of herbal medications for pharmaceutical applications, the synthesis of herbonanoformulations, their roles in drug delivery, as well as recent advancements and future perspectives[4].

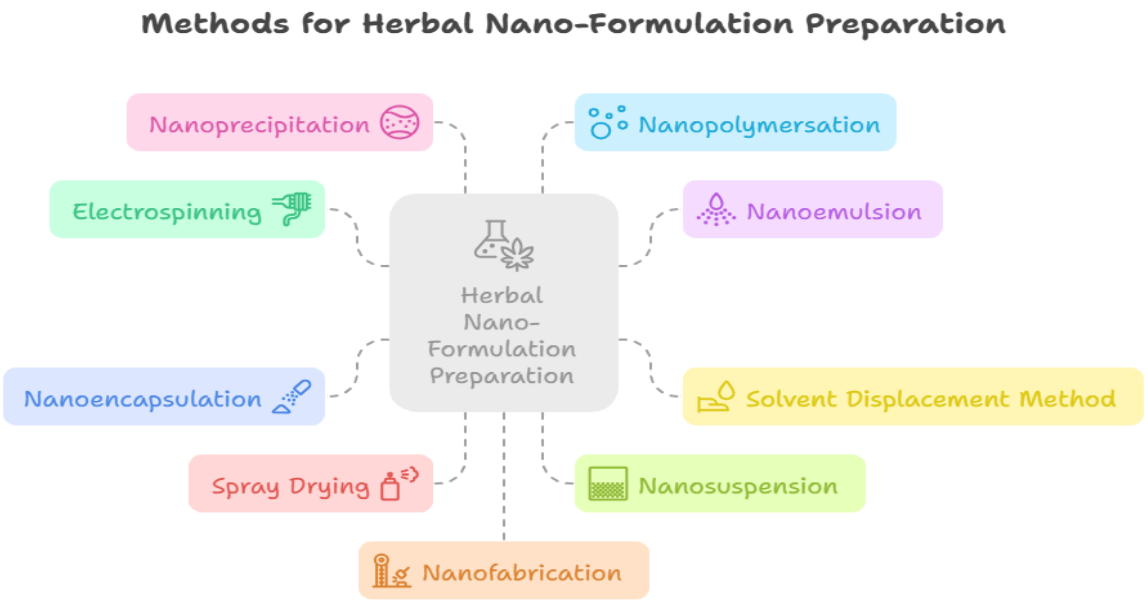

Figure 1. Schematic diagram of the exerting methods for the preparation of herbal nanoformulation[5]

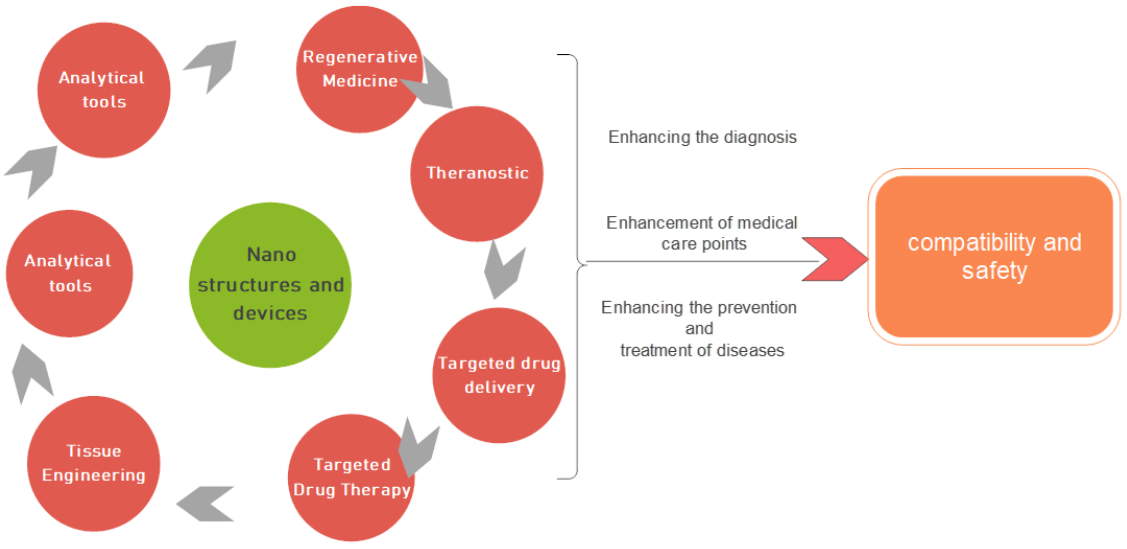

Figure 2. Uses for nanomedicines[6]

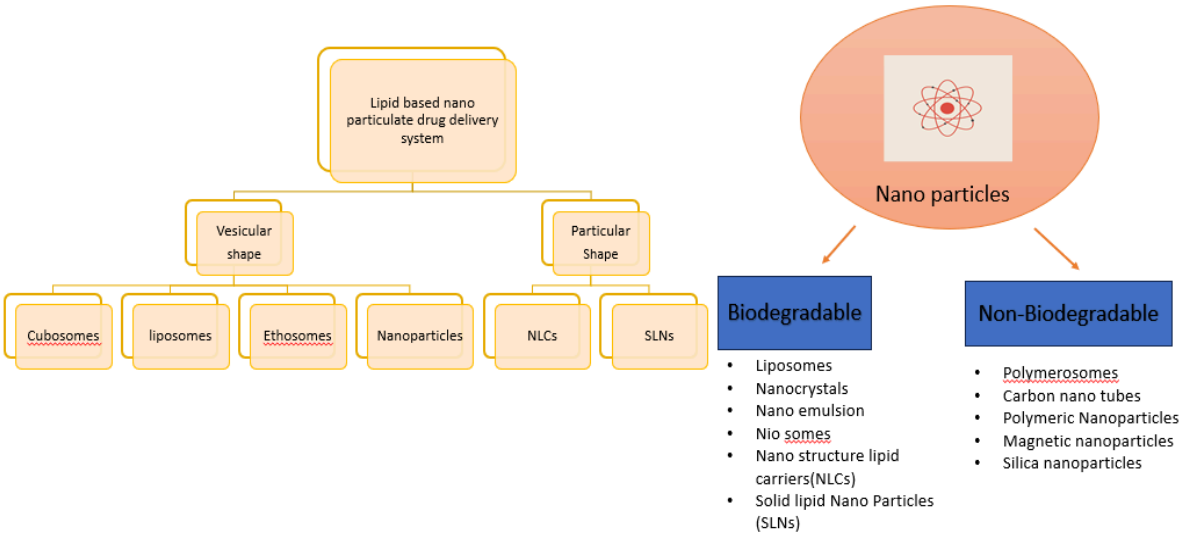

Figure 3. Displaying many kinds of nanoformulations[7]

Methods of Preparation:

Nanoscale materials have been developed with the emergence of nanotechnology, which denotes the synthesis, design, and utilization of materials at the molecular scale[8-10]. Nanoparticles employed for therapeutic applications are solid entities with diameters less than 100 nm, which may exhibit either biodegradable or non-biodegradable characteristics [11-14]. These nanoparticles can exist in two primary forms: nanocapsules and nanospheres. Nanocapsules possess a distinctive polymeric membrane that encapsulates the therapeutic agent, while the active constituents are homogeneously distributed within the matrix of nanospheres [15,16]. The methodologies involved in the formulation of herb-based nano systems are succinctly summarized here, accompanied by a schematic representation depicted in Figure 1.

Electrospinning

Electrofibres with diameters spanning from 10 nm to several micrometers are produced continuously through the application of electrostatic forces via this technique. Numerous research studies have been conducted on the electrospinning process since the year 1999. Essential components required to establish the electrospinning apparatus include a high-voltage power supply, a syringe equipped with a metallic needle, and a collector [17]. The high-voltage power is applied to the active component, facilitating the melting process to produce droplets. Upon the occurrence of electrostatic repulsion within the fluid, this droplet is transformed into a conical shape at the needle's tip to manage the surface tension effectively [18]. The charged polymer solution is expelled from the needle tip as a consequence of the electrostatic force, leading to an interaction between the electric field and the surface tension of the fluid. The solvent subsequently evaporates and accumulates in the grounded collector, resulting in the formation of a uniform fiber[19,20].

Nanoemulsification

Method of solvent evaporation

This approach involves dissolving the medication and the lipid (a compound that resembles fat) in an organic solvent [21-25]. Chloroform and dichloromethane were frequently utilized in early research, but safer solvents like ethyl acetate are now preferred because of their toxicity. Stabilizing agents like poloxamer or polyvinyl alcohol are used to emulsify (blend) this medication, lipid, and solvent mixture into water [26-30]. There are two primary steps in the procedure. To create an emulsion, the drug-lipid solution is first combined with water [31,32]. Second, the medication and lipid combine to create tiny solid particles known as nanospheres when the solvent is eliminated through evaporation. Following centrifugation, these nanospheres are cleaned to get rid of contaminants and then freeze-dried (lyophilized)[33-35] (Figure 4).

Method of solvent displacement

The primary purpose of this technique, which is a modified version of the solvent evaporation process, is to create extremely tiny nanoparticles, often less than 100 nanometers. The medication and lipid are dissolved in this procedure using a somewhat water-miscible solvent, or one that can partially mix with water[36,38]. When this solution is mixed with water, the solvent rapidly enters the aqueous phase due to the differences in solubility, resulting in the formation of nanoparticles from the drug and lipid. Then, typically by filtration or evaporation, these nanoparticles are isolated from the residual solvent [39,40].

Method of Homogenization

This method is commonly used for preparing solid-lipid nanoparticles. It involves high-speed mixing (homogenization) or the use of sound waves (sonication) to form a fine emulsion of the drug and lipid in water. The solvent is then evaporated, leaving behind solid nanoparticles. There are two types of homogenization techniques: hot and cold [41].

Hot Homogenization

which is particularly useful for drugs that dissolve well in fats (lipophilic drugs), involves melting the lipid and mixing the drug into the hot liquid. This mixture is then combined with a hot water-based solution that contains stabilizers. After the mixing is finished, the emulsion is cooled to room temperature, and the lipid solidifies into nanoparticles. However, high temperatures can occasionally affect the stability of certain drugs, and the particle sizes may vary [42].

Cold Homogenization

It is used to prevent heat-related issues. Here, the drug and melted lipid are first cooled rapidly, usually with liquid nitrogen, to form a solid mixture. This solid is then crushed into tiny particles and mixed with cold water. With high-speed stirring, these particles break down into nanoparticles. This method reduces heat damage and offers better control over the particle size and drug distribution [43].

Nano precipitation

Colloidal suspension is created when polymers dissolve in organic solvents like acetone and then diffuse into the aqueous phase. The approach, sometimes known as the solvent displacement technique, was developed. The aqueous medium employed should be soluble in the solvent and insoluble in the polymer. The suspension can be made with or without a surfactant [44,45].

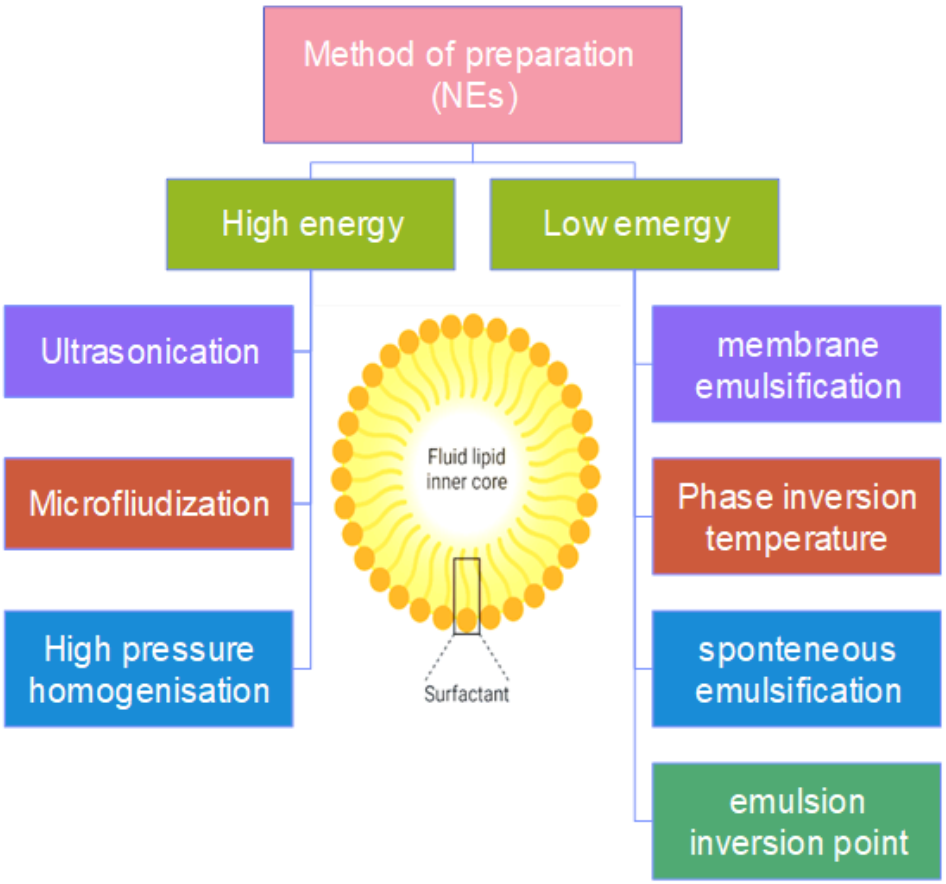

Figure 4. Technique for creating a nanoemulsion (NEs)[46]

Nanoencapsulation

Nanoencapsulation is the process of enclosing solid, liquid, or gas nanoparticles. This method creates nanocapsules by embedding the drug material, also referred to as the core, within a matrix [47]. By encasing many medication molecules in an inert substance, this technique shields them from the stomach's acidic environment as well as other adverse circumstances [48]. It is also in favour of controlled drug release. Due to their fragile and unstable nature, proteins and genes are encapsulated in nanocarriers to preserve their activity [49]. To ensure their stability and protect them from metabolic degradation, these biomolecules are enclosed within the carrier. For effective attachment of proteins to delivery systems, bioconjugation reactions are recommended, as they are highly specific and help maintain protein functionality with minimal structural alterations [50].

Nanofabrication

It is a group of techniques used to create structures with dimensions of 100 nanometers or smaller. One of the key steps involves etching, which selectively removes specific materials to produce either isotropic or anisotropic patterns, depending on the direction in which the material is removed [51]. Hollow mesoporous silica nanoparticles, synthesized using sodium carbonate, have demonstrated excellent biocompatibility and are widely recognized as nanocarriers or nanoreactors for drug delivery applications. crucial to the effectiveness and mechanism of a drug's cell membrane penetration [52,53]. The charges directly impact the stability of drug-particle complexes on the nanoparticle's surface. High-charged complexes repel more quickly and are stabilized by the repulsive force, which stops nanoparticles from aggregating [54,55].
Because positive charges react with anionic mucus and aid in the adherence and retention of nanoparticles within the mucus layer, the degree of absorption also varies depending on the particle's charge. The significance of particle shape and the biological characteristics of nanocomplexes are explained by numerous studies.

Following an intravenous injection, polymer micelles have been shown to promote efficient blood circulation. Patil's study demonstrated a reversal of the relationship between nanoparticle length and cellular adherence. The first step in the pharmacological action mechanism is the interaction between ligands and intracellular receptors. Complex compounds called nanodrugs target receptors; in this instance, dendrimers and polymer-based nanoparticles were employed for polyanionic receptor-mediated targeting [56].

Nanoformulation Strategies for Herbal Extracts:

Liposomes

Spherical vesicles made up of lipid bilayers are highly biocompatible, featuring a hydrophilic outer surface and a hydrophobic core [57]. This unique structure makes them well-suited for carrying both water-soluble and fat-soluble plant-based compounds. They can encapsulate herbal extracts within their bilayer membranes, shielding the active ingredients from degradation and enhancing their overall stability [58]. Additionally, their adaptable size and ability to be surface-modified allow for controlled drug release and targeted delivery to specific tissues or cells [59,60] (Figure 5).

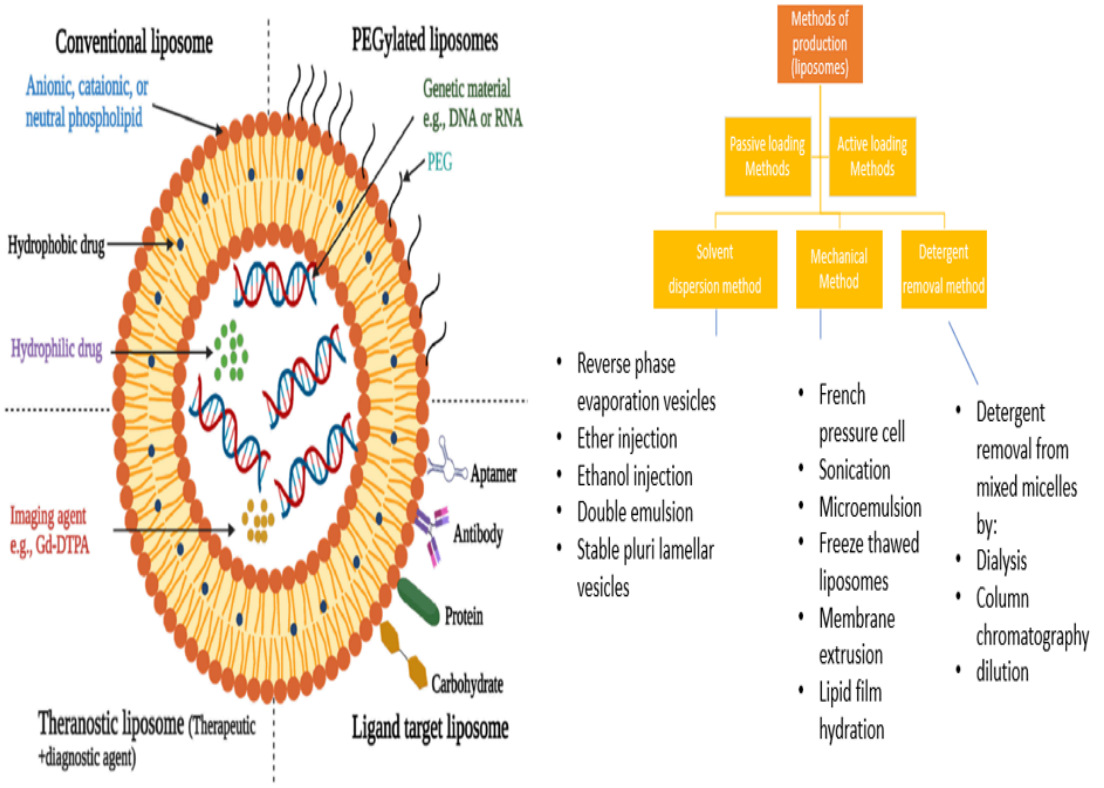

Figure 5. The composition of liposomes and their many preparation techniques [61]

Nanoemulsion

These are mixtures of liquids that do not naturally mix—commonly oil and water (either oil-in-water or water-in-oil)—and are stabilized using an emulsifying agent. They consist of extremely small droplets, typically ranging in size from 20 to 200 nanometers [62].

Polymer nanoparticles

These are nanoparticles composed of either natural or synthetic polymers, where the type of polymer used influences both the rate of drug release and how quickly the particles degrade in the body, ultimately impacting the duration of therapeutic action. They are known for their excellent biocompatibility and stability, and their properties can be tailored or modified based on specific treatment requirements [63].

Nanocrystals

These are submicron-sized crystalline particles that enhance the dissolution rate of herbal compounds, thereby improving their absorption and bioavailability. They are especially beneficial for plant-derived compounds with poor water solubility, addressing a major limitation in herbal drug delivery [64] (Figure 6).

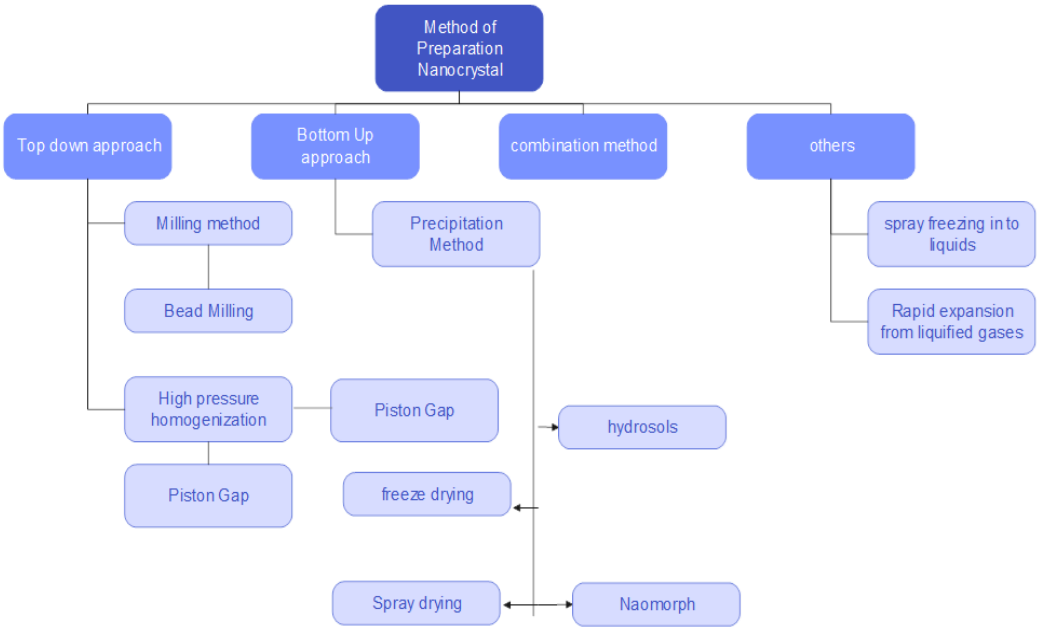

Figure 6. Techniques for creating nanocrystals [65].

Dendrimers

These are structurally defined, compact, and highly branched macromolecules that are well-suited for encapsulating herbal compounds, offering a high capacity for drug loading. Their surfaces can be chemically modified to enhance stability, improve biocompatibility, and enable targeted delivery of herbal therapeutics. Due to their multivalent surface, they can be functionalized with specific ligands, allowing precise targeting and supporting the development of personalized treatment approaches [66].

albumin nanoparticles

These nanoparticles are made from natural albumin protein and are known for their excellent biocompatibility. They can be easily modified for targeted drug delivery and are commonly used to encapsulate plant-derived compounds, enhancing their stability and bioavailability. Due to their ability to accumulate in tumour tissues through the enhanced permeability and retention (EPR) effect, they are particularly useful for delivering herbal compounds in cancer treatment [67].

Metal and inorganic nanoparticles:

These nanoparticles are made from metals or other inorganic materials and exhibit unique physicochemical properties due to their nanoscale size. Common types include metal nanoparticles, quantum dots, silica nanoparticles, magnetic nanoparticles (typically composed of iron, cobalt, or nickel and coated with biocompatible materials), metal oxide nanoparticles, and carbon nanotubes. While they offer various functional

advantages, their potential toxicity, limited stability, and concerns regarding biocompatibility necessitate careful consideration during formulation and application [68].

Polymer micelles

These nanoparticles are made up of polymer chains containing both hydrophobic and hydrophilic segments. They are commonly utilized for their ability to enclose hydrophobic drugs within their hydrophobic core, facilitating targeted and efficient delivery to specific tissues or cells. This enhances the drug's bioavailability and helps minimize unwanted side effects [69].

Phospholipid micelles

These nanoparticles are made from phospholipids, which are amphiphilic molecules containing a water-attracting (hydrophilic) head and a water-repelling (hydrophobic) tail. When placed in an aqueous environment, they naturally assemble into micelles with a hydrophobic core and a hydrophilic outer shell. This structure allows them to encapsulate water-insoluble drugs within the core, enhancing the solubility, stability, and therapeutic effectiveness of poorly water-soluble compounds [70].

Metal-organic frameworks (MOFs) nanoparticles

Metal-organic frameworks (MOFs) are nanoparticles formed by linking metal ions or clusters with organic ligands, resulting in a highly stable crystalline structure. Their porous architecture, along with advantageous features such as a high surface area, adjustable pore size, and strong molecular interactions, makes them well-suited for encapsulating a wide range of drugs and enabling controlled release at targeted sites within the body [71].

hydrogel

Hydrogels are three-dimensional networks of hydrophilic polymers capable of absorbing and retaining large amounts of water, giving them a gel-like texture. Their high-water content, biocompatibility, and adjustable mechanical properties make them effective carriers for herbal medicines, allowing for encapsulation and sustained release of active compounds to provide prolonged therapeutic effects. Each type of nanoparticle offers distinct features that can be customized to match the properties of specific herbal compounds, enhancing bioavailability, targeted delivery, and treatment outcomes. The selection of nanoparticles depends on factors such as the nature of the herbal ingredient, desired release profile, and site of action. Nanoparticles also come in various shapes—such as spherical, rod-like, cubic, star-shaped, and dendritic—each influencing their physical and biological behavior. Researchers continue to develop and optimize nanoparticles of specific shapes and structures to improve their functionality in drug delivery systems [72].

Phytosomes

are advanced lipid-compatible complexes that enhance the absorption and bioavailability of water-soluble plant compounds like polyphenols and flavonoids, which otherwise show poor absorption due to their large molecular size. These complexes form stable chemical bonds with phospholipids (typically phosphatidylcholine) in a 1:1

or 1:2 ratio, unlike liposomes, where the drug is merely encapsulated. In phytosomes, the active ingredient integrates into the lipid membrane, facilitating better cellular uptake and protection from degradation in the gastrointestinal tract. Studies have shown their superiority over conventional delivery systems. For example, a flavonosome—combining quercetin, kaempferol, and apigenin—demonstrated strong antioxidant and hepatoprotective effects [73](Figure 7).

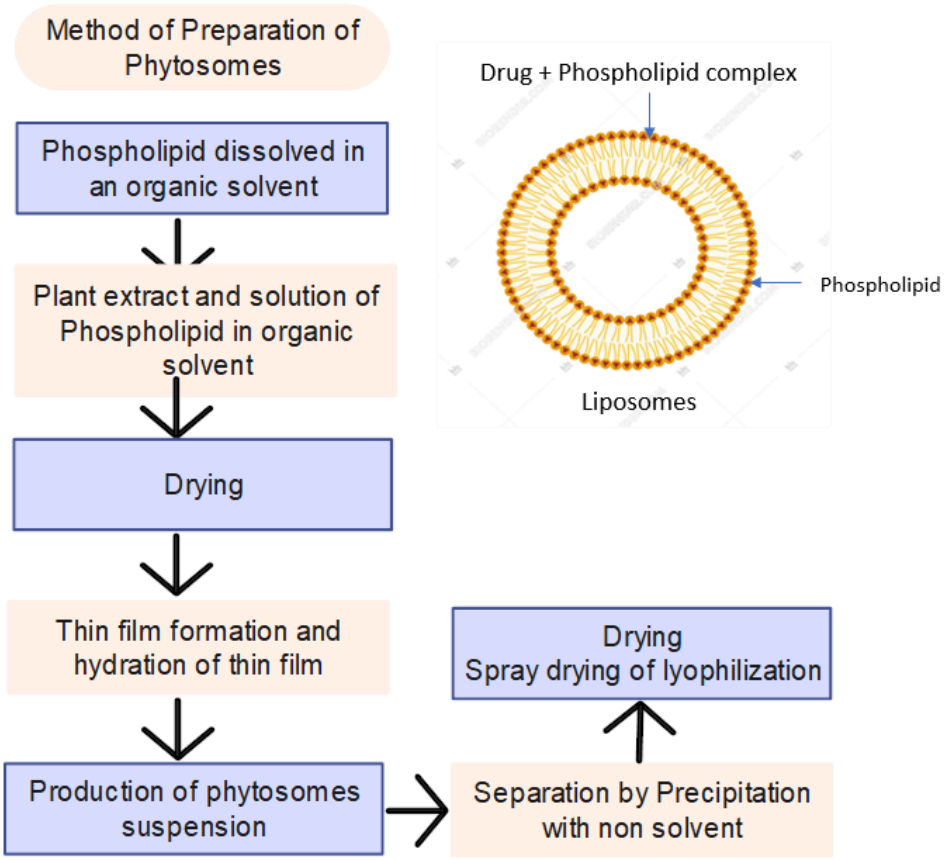

Figure 7. The composition of phytosomes and the various liposome production techniques [74]

Nanostructured lipid carriers (NLCs)

To get around matrix flaws in solid lipid nanoparticles (SLNs), second-generation lipid nanoparticles (NLCs), which are derived from SLNs, blend liquid (like castor oil and olive oil) and solid (like stearic acid and glyceryl monostearate) lipids. NLCs provide better drug loading, stability, and controlled release with less drug loss when stabilized with substances like thiomersal. They facilitate co-delivery of bioactives, increase bioavailability, and extend circulation duration. When encapsulated in NLCs, compounds like silymarin, triptolide, tripterine, and curcumin have demonstrated enhanced absorption. Notably, NLCs loaded with cardamom essential oil and food-grade lipids showed outstanding stability and high loading efficiency (>25%) [75] (Figure 8).

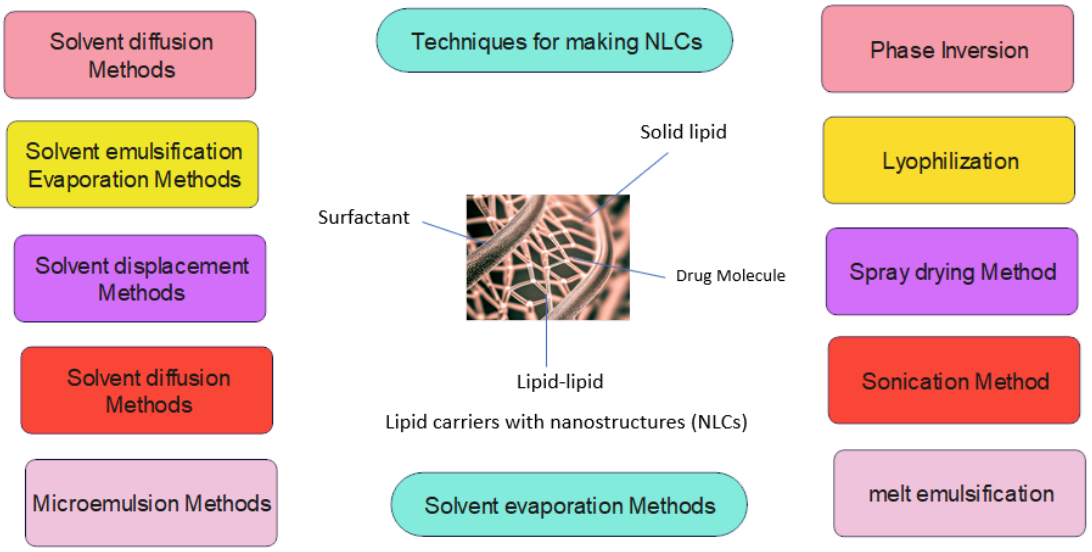

Figure 8. Techniques for making lipid carriers with nanostructures (NLCs) [76]

Solid Lipid Nanoparticles (SLNs)

Solid Lipid Nanoparticles (SLNs), which were created in the early 1990s, are colloidal carriers made of solid lipids stabilized by emulsifiers that range in size from 50 to 1000 nm. SLNs are frequently made by high-pressure homogenization and allow for the targeted administration of a variety of bioactives, such as medications and proteins. They provide decreased toxicity, regulated release, and improved stability both in vivo and in vitro. SLNs contain both liquid and solid lipids, in contrast to nanoemulsions. While triptolide-loaded SLNs showed antioxidant and anti-inflammatory benefits with less GIT irritation and enhanced solubility, puerarin-loaded SLNs revealed greater absorption and organ targeting in rats [77] (Figure 9).

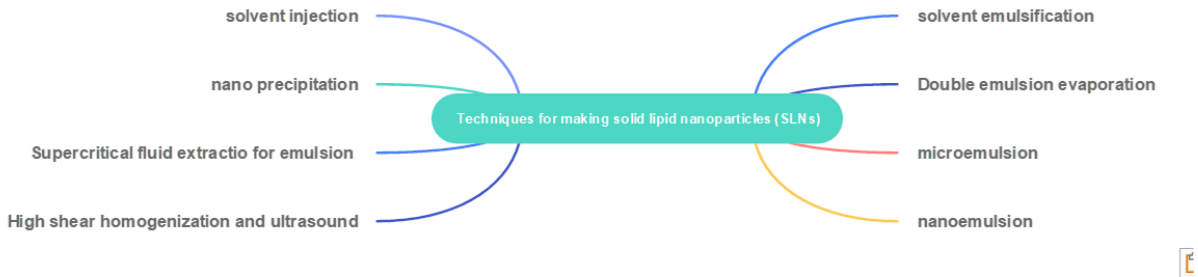

Figure 9. Techniques for making solid lipid nanoparticles (SLNs) [78]

Niosomes

Typically measuring between 100 nm and 2 μm in diameter, niosomes are nano-sized spherical vesicles with a hydrophilic aqueous core surrounded by one or more layers of non-ionic amphiphilic lipids arranged in a lamellar phase. They are structurally similar to liposomes and are electrically neutral, but they have better stability, deeper skin penetration, and better therapeutic efficacy with less toxicity [79].

A number of methods have been used to formulate them, including sonication, reverse-phase evaporation, microfluidization, multiple membrane extrusion, remote loading, thin-film hydration, and the bubble method. Significant benefits of niosomes include enhanced solubility of poorly water-soluble medications, cost-effectiveness, formulation flexibility, and controlled release of encapsulated active ingredients. Because of these characteristics, they can effectively transport hemoglobin, peptides, and targeted delivery systems for anticancer treatment [80].

Additionally, niosomes exhibit improved skin penetration and retention, longer systemic circulation, and sustained drug release at the target region. They are especially well-suited for topical treatments, notably in dermatological conditions like skin cancer, due to their greater stability over liposomes and absence of significant toxicity. Table 8 lists some instances of niosomal systems that use natural remedies or phytoconstituents [81](Figure 10).

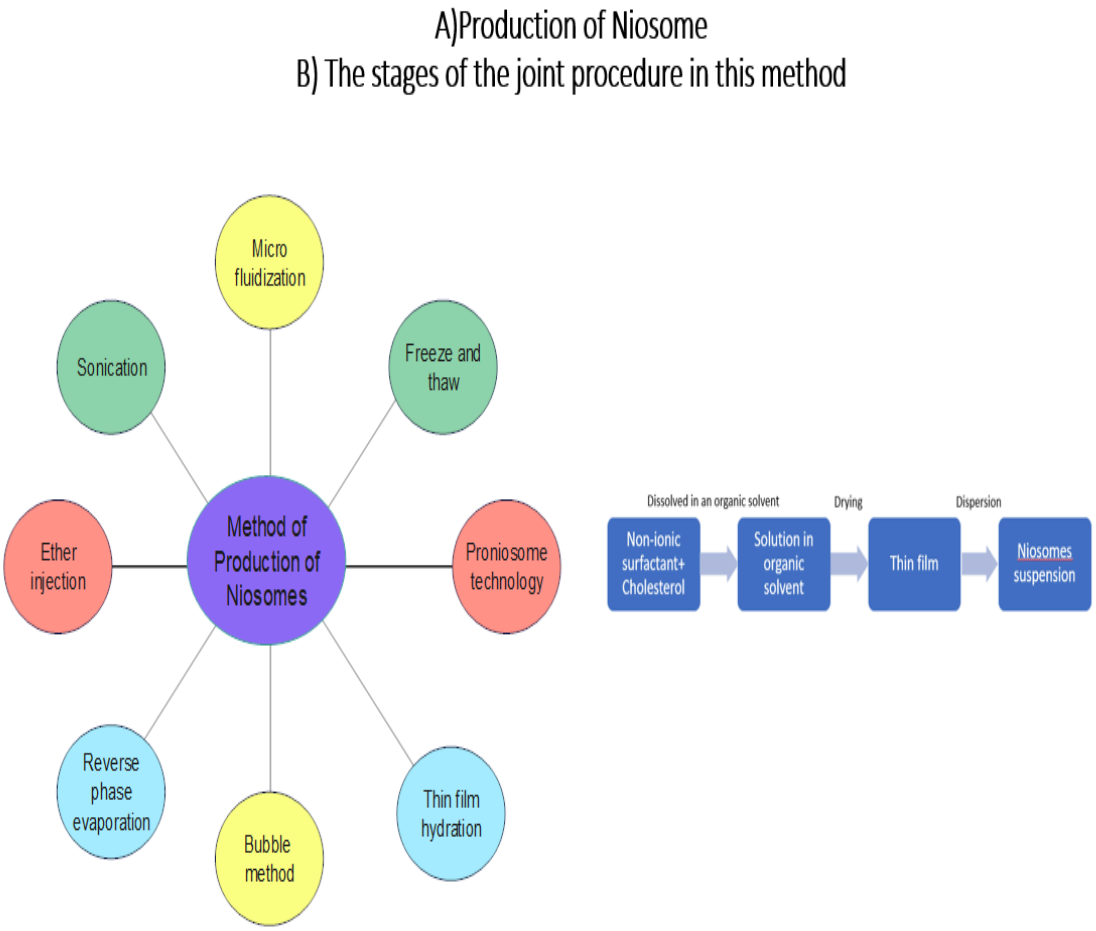

Figure 10. illustrating A) Niosome production B) The steps involved in this method's combined procedure [82]

Cubosomes

Amphiphilic lipids, especially unsaturated monoglycerides, and thermodynamically stable surfactants like poloxamers make up the majority of cubosomes, which are viscous, isotropic nanostructured vesicles. With a high interior surface area (about 400 m^2/g) and a distinctive three-dimensional structure with both hydrophilic and hydrophobic domains, these nanocarriers may efficiently encapsulate hydrophilic, lipophilic, and amphiphilic molecules [83].

The prolonged release of encapsulated medicinal substances is made possible by the numerous diffusion channels provided by the large interfacial area inside cubosomes. Additionally, cubosomes' lipid components are digestible, biodegradable, and bioadhesive, which improves their biocompatibility. Usually, lipid-based cubic phase gels are broken up or dispersed in an aqueous medium to create cubosomes. They are produced using two main methods: the top-down and bottom-up approaches (Figure 10).

Several pharmacologically active substances, such as rifampicin, insulin, somatostatin, and indomethacin, have been effectively encapsulated in cubosomes. They can be used to deliver enzymes, peptides, analgesics, antibiotics, and antimuscarinic drugs. Interestingly, cubosomes can efficiently promote the transdermal distribution of bioactives into the epidermal layers because of their structural similarity to the stratum corneum. Their natural penetrating and adhesive qualities make them even more appropriate for topical treatments, such as the management of melanoma and other types of skin cancer [84].

Polymer-free cubosomal systems with low cytotoxicity to skin tissue have been developed recently for photodynamic treatment and bioimaging of cutaneous cancers. Several instances of cubosomes used to transport herbal bioactives are shown in Table 9 (Figure 11).

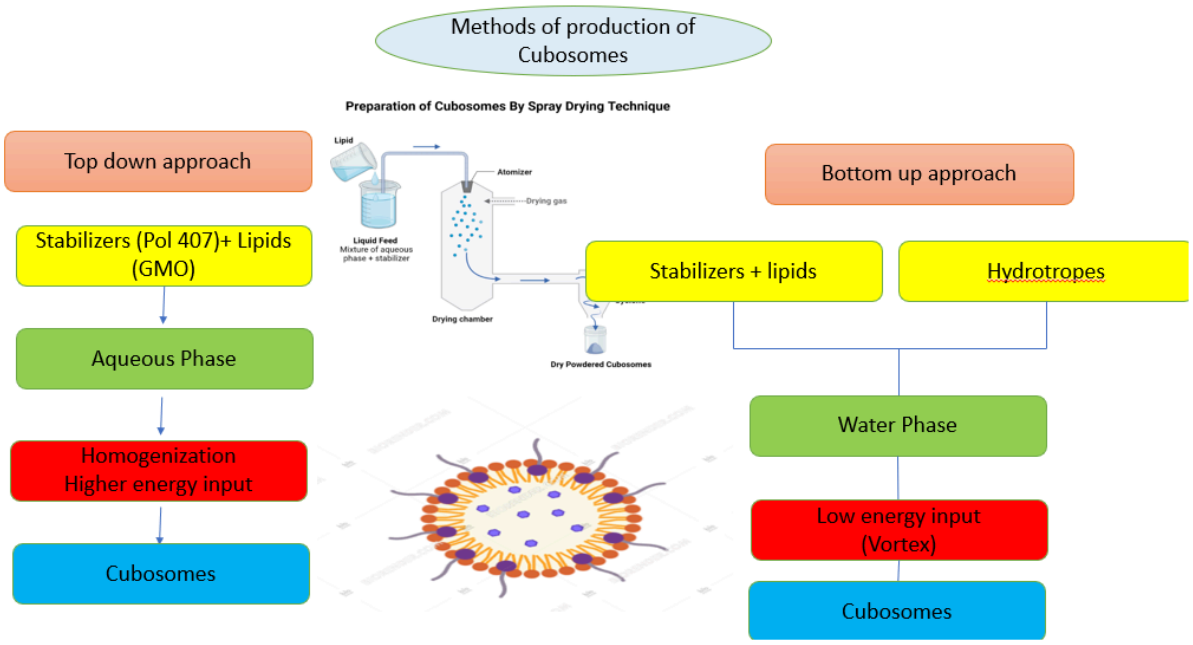

Figure 11. Top-down and bottom-up methods for cubosome preparation [85]

Herbal Extracts and Their Pharmacological Relevance

Bioactive phytochemicals

Traditional medical systems have long utilized phytopharmaceuticals, also known as herbal or botanical medicines, as therapeutic products derived from plants. Their perceived safety and accessibility are influenced by their historical use and natural characteristics, particularly in areas without access to advanced healthcare. These medications contain a variety of bioactive substances that have pharmacological effects, including antibacterial, antioxidant, and anti-inflammatory properties. They are becoming more well-known for their ability to treat long-term conditions like diabetes, heart disease, and some types of cancer. When taken as directed, phytopharmaceuticals may have fewer adverse effects than synthetic medications. They are also a desirable choice in public health because of their price. Additionally, they support sustainable medicinal plant harvesting and biodiversity conservation. Cultural preservation is supported when indigenous information about these treatments is incorporated. Their safety and interactions with other medications, however, need to be

confirmed by science. Their function in contemporary healthcare can be further maximized by increasing their effectiveness with technologies like nanodelivery [86] (Figure 12).

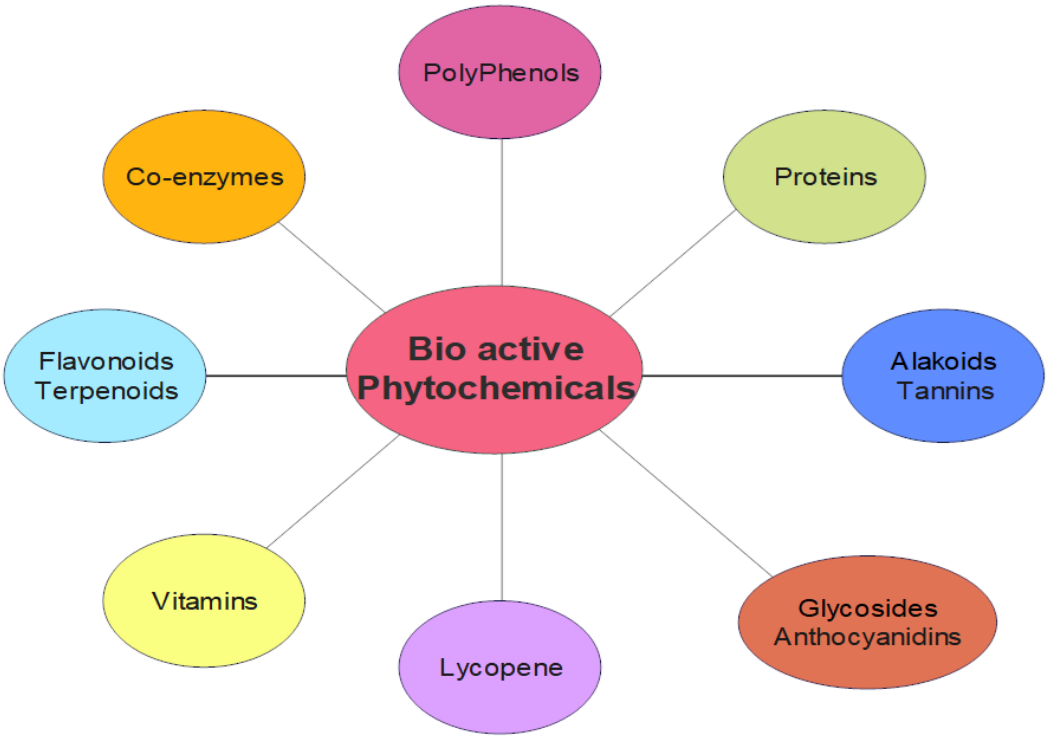

Figure 12. A few instances of phytochemicals or bioactive substances found in herbal remedies or natural items [87]

Problems with toxicity related to non-herbal remedies

Herbal drug delivery systems based on nanotechnology are developing quickly and have the ability to transport drugs more effectively, but they have also been linked to negative side effects include immunotoxicity, cytotoxicity, and genotoxicity. Cell viability is commonly assessed using well used assays such as MTS, MTT, and WST-1. Usually, comet assays, immunohistochemical biomarkers, and tetrazolium-based reduction assays are used to assess this. Biomarkers like interleukin-8 (IL-8), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α) are used to evaluate the inflammatory response brought on by nanoparticles. These biomarkers are frequently examined using ELISA and lactate dehydrogenase (LDH) tests. Notwithstanding the potential of these nano-formulations, regulatory assessments have demonstrated that medications generated from nanotechnology may be completely safe or even hazardous to human health. As a result, every product based on nanotechnology must pass stringent toxicity testing and adhere to legal requirements [88].

Nano-herbal formulations' benefits

The therapeutic efficiency of herbal medications is typically limited by problems with conventional drug delivery systems, such as low specificity, sensitivity, toxicity, and drug resistance. Due to their large molecular size and high-water solubility, many bioactive plant components, including flavonoids, terpenoids, and tannins,

have low bioavailability. Delivery systems based on nanotechnology provide answers by improving targeted delivery and making it possible to formulate various substances together. The total effectiveness of herbal therapies is increased by nanocarriers because of their high surface area-to-volume ratio, which also improves medication stability, lowers toxicity, and permits controlled release.

The role of nanomedicine in overcoming obstacles in herbal medicine

Traditional herbal medicines offer a wealth of therapeutic benefits; however, their clinical application is limited due to issues such as poor bioavailability, lack of targeted delivery, variable solubility, and inconsistent patient response. Herbal preparations like decoctions, teas, and extracts typically lack the ability to direct active constituents to specific sites in the body, which diminishes their therapeutic efficacy and increases the risk of side effects. Factors such as the complex and variable composition of herbal drugs, poor aqueous solubility of many active phytoconstituents, first-pass metabolism, and individual genetic differences further compromise their clinical utility.

Nanotechnology offers a transformative solution to these limitations by enhancing the pharmacokinetic and pharmacodynamic properties of herbal compounds. Nanoparticle-based drug delivery systems can encapsulate plant-derived bioactives, shielding them from enzymatic degradation and acidic gastric environments, thus improving their stability and systemic absorption. Due to their small size and large surface area, nanoparticles can cross biological barriers such as the blood-brain barrier, enabling delivery to otherwise inaccessible tissues and increasing overall bioavailability [89].

Furthermore, nanoparticles can be engineered with ligands or antibodies for active targeting, selectively delivering herbal compounds to diseased cells or tissues while minimizing exposure to healthy areas. This targeted delivery not only enhances therapeutic efficacy but also reduces systemic toxicity. Additionally, nanoparticles exploit the enhanced permeability and retention (EPR) effect in tumors and inflamed tissues, allowing for passive accumulation at the disease site [90,91].

Controlled and sustained release mechanisms offered by nanocarriers help maintain consistent therapeutic levels, which is particularly valuable in chronic conditions requiring long-term treatment. The potential for polyherbal formulations—combining multiple phytoconstituents within a single nanoparticle system—provides opportunities for synergistic effects, reduced dosing, and decreased risk of resistance. Such strategies also facilitate tailored therapies aligned with individual patient genetics and metabolic profiles, advancing the scope of personalized medicine [92,93].

In conclusion, integrating nanotechnology with herbal medicine offers a scientifically robust and clinically promising approach to overcoming traditional limitations. This convergence enhances the delivery, stability, and efficacy of plant-based therapies, paving the way for safer, more effective, and personalized treatment modalities in modern healthcare.

Nanoparticles' necessity in herbal medicines

- Using nanoparticles to target herbal medications to specific sites improves medication delivery, potency, safety, and selectivity [94].

- Herbal medications can be made more soluble and more effective by using nanoparticles to help localize the medication in a specific area. Because of their special size and high loading capabilities, nanoparticles can transport huge amounts of drugs to disease locations [95].
- The drug's surface area is increased when it is administered in small particles, which speeds up its absorption into the bloodstream. Among other enhanced permeation and retention advantages, it exhibits increased penetration over barriers because of its small size and retention because of inadequate lymphatic drainage [96].
- It exhibits passive targeting to the disease site of action and lessens side effects without the necessity for a particular ligand moiety [97].

Therapeutic Applications of Nano-formulated Herbal Extracts

A variety of nanoformulations have been developed to improve the delivery of both traditional and natural drugs. These formulations help address issues such as instability, low bioavailability, and poor solubility. Nano-based systems enable targeted drug delivery, enhancing therapeutic effectiveness while reducing adverse effects [98-118] (Table 1).

Table 1. Summary of Nanotechnology-Based Drug Delivery Systems [98-118]

Sr. No.	Formulation / Product	Bioactive / Drug	Limitations of Free Drug	Advantages of Nano formulation
1.	Doxil® (liposomal doxorubicin)	Doxorubicin	Cardiotoxicity, instability, non-specific tissue distribution	Improved stability, reduced cardiotoxicity, tumor targeting via EPR effect
2.	Abraxane® (nab®-paclitaxel)	Paclitaxel	Poor solubility, systemic toxicity	Enhanced solubility, targeted tumor delivery, reduced side effects
3.	Nanoemulsion-based formulation	Lipophilic drugs, essential oils	Low absorption and bioavailability	Improved absorption and bioavailability, effective treatment of fungal infections and skin disorders
4.	Curcumin-loaded nanoparticles	Curcumin (fro%m Curcuma longa L)	Poor solubility and stability	Enhanced solubility, stability, targeted delivery, improved therapeutic effects
5.	Resveratrol-loaded nanoparticles	Resveratrol (from grapes, berries, medicinal plants)	Low bioavailability, rapid metabolism, short half-life	Improved dissolution, sustained release, better efficacy and safety in cancer therapy
6.	Phytosome	Sinigrin	Low bioavailability, poor solubility	Enhanced wound-healing activity, minimal cytotoxicity
7.	Phytosome	Taxifolin (from Cedrus deodara)	Poor solubility, large molecular size, low bioavailability	Increased antioxidant and anticancer activity, better membrane permeability
8.	Phytosome-nano suspension	Silybin	Poor water solubility, low GI absorption	Improved hepatoprotection, increased plasma concentration, higher AUC
9.	Phytosome	Apigenin	Poor solubility, rapid metabolism, low oral bioavailability	36-fold increased solubility, higher antioxidant activity, improved oral bioavailability

10.	Phytosome	Quercetin	Poor absorption, low estrogenic efficacy	Enhanced hormone replacement activity, increased GSH, improved lipid profile, reduced inflammatory markers
11.	Phytosome complexed with chitosan	Gingerol	Poor water solubility, low bioavailability	Enhanced antimicrobial and anti-inflammatory activities, sustained drug release
12.	Phytosome	Moringa oleifera extract	High water solubility, poor skin penetration	Enhanced wound-healing, good cell migration and proliferation, non-cytotoxic
13.	Phytosome	Lantana camara extract	Limited antimicrobial activity in crude form	Larger inhibition zones, improved antibacterial and antifungal efficacy
14.	Phytosome	Murraya koenigii extract	Poor membrane permeability, low bioavailability	Sustained release, improved antidiabetic and hypolipidemic activity
15.	Chitosan nanoparticles	Jatropha pelargoniifolia extract	Poor solubility, bioavailability, instability in gastric acid	Higher antioxidant and antimicrobial activity, increased cytotoxicity against cancer cells
16.	Nanocapsule	Piperine	Poor water solubility, rapid metabolism, systemic elimination	3× lower IC_{50}, enhanced antitrypanosomal activity, reduced toxicity to PBMC
17.	Mixed Micelles	Argyreia pierreana extract	Low solubility, weak antidiabetic potential in crude extract	Enhanced antidiabetic and antihyperlipidemic activity, improved pharmacokinetics
18.	Mixed Micelles	Matelea denticulata extract	Similar limitations as above	Greater improvement in activity than Argyreia pierreana, supports dual action
19.	Chitosan/PEG-blended PLGA nanoparticles	Curcumin	Low water solubility, poor stability, low bioavailability	Enhanced anti-migratory, apoptotic, anti-invasive effects in pancreatic cancer
20.	P@FPP nano-micelles (FA-PEG-PTX loaded with PRI)	Pristimerin (PRI) and Paclitaxel (PTX)	- Low tumor targeting - Poor solubility - Rapid drug release - Severe side effects - Chemo-resistance	ul> - Improved tumor-targeting via folic acid - Controlled and sustained release - Enhanced cellular uptake - Synergistic inhibition of NSCLC growth - Reduction in EMT markers and metastasis - Improved in vivo biosafety
21.	SWCNTs (Single-Walled Carbon Nanotubes)	Curcumin	Low solubility, rapid degradation, poor bioavailability	High drug loading, sustained release, enhanced uptake, better cytotoxicity in lung cancer
22.	HA-C60-Tf Fullerene nanoparticles	Artesunate	Low tumor-targeting, poor solubility, systemic toxicity	Improved tumor targeting, reduced toxicity, high loading, dual-drug delivery
23.	PAMAM Dendrimers with EpCAM	Celastrol	Short half-life, poor bioavailability, low specificity	Enhanced targeting, better safety, improved anti-cancer efficacy

24.	Solid Lipid Nanoparticles	Frankincense and Myrrh Oil	Instability, poor aqueous solubility, light/air sensitivity	Improved stability, bioavailability, enhanced antitumor effect
25.	Nanostructured Lipid Carriers	Sulforaphane	Poor solubility, instability in gastric pH, low bioavailability	Sustained release, potent anti-tumor efficacy in vitro and in vivo
26.	Liposomes	Resveratrol	Low solubility, low bioavailability	Improved pharmacokinetics, tumor uptake, tumor suppression
27.	Phytosomes	Icariin	Rapid metabolism, low oral bioavailability	Improved cytotoxicity and apoptosis in ovarian cancer
28.	Niosomes	Carum Essential Oil	Low solubility, poor bioavailability	Enhanced cytotoxicity, apoptosis, inhibition of migration in MCF-7 cells
29.	Ethosomes	Curcumin	Low solubility and stability	Better solubility, sustained release, improved cytotoxicity against A549 lung cells
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39.	Chitosan/HPMC Blended Patches	Zingiber Cassumunar Oil	Poor stability, low loading, burst release	Improved stability, controlled release, >90% drug content
40.	CMC/PCG Hydrogel with AgNPs	Silver nanoparticles	Unstable silver dispersion, toxicity	Controlled release, antibacterial and wound healing
41.	Whey Protein-Dextran Colloid	Resveratrol	Poor solubility, low stability	Stable emulsions, sustained release, antioxidant activity
42.	Albumin-Shell Oily-Core Nanocapsules	Exemestane & Hesperetin	Hydrophobicity, poor tumor targeting	Tumor accumulation, longer circulation, enhanced cytotoxicity
43.	Nanoemulsion	Paclitaxel & Curcumin	Poor solubility, MDR resistance, P-gp substrate	Enhanced cytotoxicity, NF-kB inhibition, apoptosis in resistant cells

44.	SNEDDS	Naringenin	Poor water solubility, low oral bioavailability	Sustained release, improved bioavailability in rats
45.	Nanogels (TNC-CUR)	Curcumin	Poor stability, limited tumor delivery	2× cell uptake, tumor weight reduction, stable in aqueous medium
46.	Nanosuspensions	Celastrol	Poor solubility, low bioavailability	High drug loading, sustained release, tumor inhibition
47.	Iron Oxide Nanoparticles	Triphalachurna	Low bioavailability, degradation in GI tract	Increased uptake, cytotoxicity in TNBC, non-toxic to normal cells
48.	Gold Nanoparticles	Curcuma wenyujin Extract	Poor bioavailability, therapy resistance	Induced apoptosis in renal cancer cells
49.	Silver Nanoparticles	Berberine	Poor solubility, bioavailability	Induced apoptosis in breast cancer cells, dose-dependent cytotoxicity
50.	Mesoporous Silica Nanoparticles	Paclitaxel & Quercetin	MDR, P-gp expression, low solubility	Dual delivery, downregulation of P-gp, tumor inhibition
51.	Silver Nanoparticles	Berberine	Poor solubility, bioavailability	Induced apoptosis in breast cancer cells, dose-dependent cytotoxicity
52.	Hybrid Liposomal PEGylated Calixarene	Curcumin	Poor solubility and bioavailability	Improved solubility, cell uptake, targeting, therapeutic efficacy
53.	Chitosan-Silica NPs	Echinacea purpurea extract	Low bioavailability, oxidative stress	Reduced ROS, improved antioxidant defense, increased testicular protection
54.	Chitosan-Vitamin B12 NPs	Scutellarin	Low solubility, poor intestinal uptake	5× cellular uptake, enhanced bioavailability, retinal protection
55.	Gold NPs	Cassia fistula extract	Hyperglycemia, poor renal function	Improved lipid profile, reduced glucose & renal markers
56.	Gold NPs	Chamaecostus cuspidatus extract	Hyperglycemia	Reduced plasma glucose, cholesterol
57.	Silver NPs	Cinnamomum cassia extract	Kidney damage, oxidative stress	Improved renal histology, antioxidant activity
58.	Nanoliposome	Momordica spp. fruits	Low bioavailability	Lowered fasting glucose
59.	Gold NPs	Couroupita guianensis extract	Oxidative stress, hyperglycemia	Increased antioxidant enzymes, reduced hepatic/pancreatic injury
60.	PEGylated Liposomes	Elettaria cardamomum extract	Insulin resistance	Increased insulin sensitivity, improved lipid profile
61.	Silver NPs	Eysenhardtia polystachya extract	β-cell damage, oxidative stress	Enhanced insulin secretion, β-cell protection
62.	Silver NPs	Gymnema sylvestre extract	Hyperglycemia	Improved insulin levels, lipid profile
63.	ZnO NPs	Hibiscus sabdariffa extract	Inflammation, poor glucose tolerance	Decreased pro-inflammatory markers, improved glycemic control
64.	Silver/Cerium Oxide NPs	Lawsonia inermis extract	Islet degeneration	Islet regeneration, improved insulin levels
65.	ZnO/CeO2/Ag NPs	Momordica charantia extract	Islet damage	β-cell regeneration, hypoglycemic effect
66.	ZnO NPs	Morus indica extract	Nephropathy	Kidney repair, reduced enzyme levels

67.	Silver NPs	Morus spp. extract	Retinal degeneration	Retinopathy amelioration
68.	Silver NPs	Musa paradisiaca extract	Hyperglycemia	Increased insulin & glycogen, HbA1c reduction
69.	SLN	Plicosepalus spp. extract	Oxidative stress, hyperglycemia	Improved antioxidant enzymes, lowered glucose and HbA1c
70.	Silver NPs	Pouteria sapota extract	Hepatorenal dysfunction	Improved liver/renal markers, antioxidant enzyme elevation
71.	Chitosan-PLGA NPs	Silybin	Poor absorption	Improved glucose, lipid, liver enzymes; β-cell regeneration
72.	Chitosan NPs	Polydatin	Low solubility, rapid clearance	Sustained release, improved insulin & glycogen
73.	Polygalacturonic acid NPs	Oleanolic acid	Low intestinal absorption	Increased absorption, lipid profile improvement
74.	Gold NPs	Resveratrol	Retinopathy	Barrier protection, inflammation reduction
75.	PEG-based NPs	Quercetin	Renal dysfunction	Improved renal function, antioxidant levels
76.	Chitosan-Vit B12 NPs	Scutellarin	Retinal angiogenesis	Downregulated angiogenesis markers
77.	Gold NPs	Curcumin	Cardiomyopathy	Improved heart morphology, reduced TG & enzymes
78.	Solid Lipid Nanoparticles	Resveratrol	Poor bioavailability, low solubility, metabolic instability	Improved antioxidant activity, cellular uptake, and sustained release
79.	Liposomes	Curcumin	Low systemic bioavailability	Improved absorption, distribution, and stability
80.	Polymeric Nanoparticles	Genistein	Low bioavailability, endocrine effects	Better plasma profile, enhanced tumor inhibition
81.	Ethosomes	EGCG	Low skin penetration, photoinstability	Improved skin delivery, antioxidant activity, and photostability
82.	Nanostructured Lipid Carriers	Kaempferol	Low solubility, low tumor specificity	Enhanced cytotoxicity, anti-cancer activity with improved targeting
83.	Nanoemulsions	Naringenin	High hydrophobicity, poor solubility	Enhanced bioavailability, prolonged circulation, anti-inflammatory effects
84.	SLN with Chitosan	Apigenin	Poor solubility and absorption	Enhanced bioavailability, liver targeting, and anti-inflammatory activity
85.	Gelatin Nanoparticles	Theaflavins and Thearubigins	Poor stability and intestinal absorption	Improved antioxidant and antimicrobial activity
86.	Polymeric Nanoparticles	Quercetin	Low solubility, poor bioavailability	Enhanced antioxidant, anti-inflammatory, and chemoprotective effects
87.	Liposomes	Onopordum illyricum extract (phenolic compounds including dicaffeoylquinic acids, luteolin, hispidulin)	Low solubility, poor absorption, chemical instability, limited skin penetration, low antioxidant retention	Small vesicle size (~96 nm), high entrapment efficiency (>90%), enhanced antioxidant activity (DPPH, FRAP), improved ROS reduction in cells, good stability
88.	PG-PEVs (Penetration Enhancer-containing Vesicles)	Onopordum illyricum extract (same bioactives)	Poor permeability, low aqueous solubility, chemical instability	Better homogeneity and storage stability, effective ROS inhibition at lower concentrations, non-toxic profile in skin cells

89.	Liposomes (LIPs)	Astaxanthin	Low water solubility	Enhanced solubility and bioavailability; STAT3 and NF-κB inhibition
90.	Nanofibers (NFs)	β-Carotene	Poor bioavailability, instability	Slow degradability; controlled release
91.	Solid Lipid Nanoparticles (SLNs)	Capsaicin	Poor bioavailability; potential irritation	Targeted delivery, high EE (99%), reduced systemic absorption
92.	SLNs (gel)	Tetrahydrocurcumin	Poor penetration, low solubility	↑ Healing, ↓ TNF-α, IL-6; improved redox status
93.	Zein–Silk Sericin NPs	Curcumin	Low solubility, low stability	Deep skin penetration, ↓ NF-κB & cytokines
94.	Hydrogels	Cynaroside	Poor solubility, bioavailability	↓ Inflammation, ↓ T & mast cells; anti-IgE
95.	PLGA-Nanocarriers	Dictamnine	Low penetration, rapid degradation	↑ Skin deposition, ↓ TNF-α, IL-1β, TSLP
96.	Gelatin NPs	EGCG	Instability, low absorption	↓ IL-6/IL-8; non-toxic, good skin absorbance
97.	PEG-PLGA-EGCG NPs	EGCG	Poor skin absorption, instability	Restored redox status, ↓ Th1/Th2/Th17 cytokines
98.	Transfersomes (TRAs)	Glycyrrhizic Acid	Poor skin deposition	↑ Skin retention, ↓ erythema, scratching
99.	Guar Gum NPs	Guar gum	Limited bioavailability	Wound healing, ↓ IgE, ↓ inflammation
100.	NPs	Hederagenin	Poor solubility, low efficacy	Dose-dependent ↓ cytokines, mast cells
101.	Ethosome-based Cream	Piperine	Irritating, low solubility	↓ Skin thickness, IgE; ↑ skin deposition
102.	Nanostructured Lipid Carriers (NLCs)	Quercetin	Poor dermal penetration	↑ Permeability, retention in dermis/epidermis
103.	SLNs	Resveratrol	Low solubility and stability	↓ IL-6 & MCP-1; non-toxic
104.	Nanocapsule-based Bilayer Film	Silibinin	Low permeability, oxidation	Controlled release, ↑ hydration, ↓ scratching
105.	Nanoemulsion Gel	Triptolide	Toxicity, poor solubility	↓ IFN-γ, IL-4; ↑ skin penetration
106.	Nanoparticle of Bay Leaf Extract	Flavonoids (mainly quercetin), tannins	Poor solubility, low bioavailability	↑ Solubility and bioavailability, ↓ blood glucose at lower doses, average particle size 549.2 nm, zeta potential -40.2 mV
107.	Piper nigrum Nanosuspension	Piperine	Poor water solubility, low bioavailability	3.65× higher dissolution, 2.7× higher oral bioavailability, reduced particle size (172.5 nm), enhanced absorption, sustained release
108.	Glycerosomes (with hyaluronate/chitosan)	Curcumin	Poor lung deposition, instability	Enhanced pulmonary delivery, ↑ deposition in deep lung, ↓ IL-6, IL-8
109.	Hyalurosomes	Curcumin	Poor skin retention	↑ Storage stability, ↑ wound healing, ↓ MPO activity, improved keratinocyte protection
110.	Hyaluronic acid–modified ethosomes	Curcumin	Barrier to deep skin penetration	↑ Dermal delivery, ↑ CD44 binding, targeted psoriasis therapy
111.	EGF–Chitosan NPs (spray solution)	Curcumin	Low wound healing efficacy	Almost complete dermal wound healing in rats

112.	Curcumin-alginate nanomicelles	Curcumin	Poor intestinal retention	Enhanced colonic healing, ↑ TGF-β1, ↓ NF-κB
113.	Nanostructured Lipid Carriers (NLC)	Curcumin	Poor dermal delivery	↑ Skin hydration, drug delivery vs. emulsion
114.	Hyalurosomes (topical)	Curcumin	Poor RA bioavailability	↓ IL-6, IL-15, ↑ IL-10; ↓ ROS, NF-κB
115.	Cholesterol-enriched liposomes	Curcumin	Poor osteoarthritis efficacy	↑ Osteoblast survival, ↓ COX-2, TRAP, MMP-3
116.	Wheat germ agglutinin–liposomes	Curcumin	Poor brain targeting	↓ Amyloid-β, ↑ neuronal protection (Alzheimer model)
117.	Nanomicellar curcumin	Curcumin	Poor systemic bioavailability	↓ IL-1β, IL-6, CRP, VCAM; effective in migraine & CVD
118.	Nutriosomes	Curcumin	Degradation in GI tract	Stable in GIT, ↑ Caco-2 protection, ↓ colitis inflammation
119.	Eudragit-coated liposomes	Curcumin	Instability in GIT	pH-sensitive release, preserved antioxidant activity
120.	Solid Lipid Nanoparticles (HSLNs) with Beeswax or GMS	Hibiscus rosa sinensis methanolic extract	Poor oral bioavailability, variability in effect, unstable crude form	Particle size ~175 nm, ↑ antidepressant effect at lower doses (as low as 10–50 mg/kg vs 200 mg/kg crude), sustained release, improved brain bioavailability
121.	Liquid SMEDDS (Self-Microemulsifying Drug Delivery System)	Andrographolide	Poor water solubility, low absorption, fast metabolism	↑ AUC (15×), ↑ Cmax (800 ng/mL), ↓ dose needed
122.	SMEDDS Pellets	Andrographolide	Same as above	↑ Bioavailability (13×), stable pellet form
123.	Herbosome	Andrographolide	Low bioavailability, instability	↑ AUC (3.3×), sustained effect, enhanced hepatoprotective activity
124.	Nanoemulsion	Andrographolide	Poor systemic exposure, degradation	↑ AUC (3.9×), ↑ intestinal permeability, stable nanoform
125.	SNEDDS (Self-Nanoemulsifying Drug Delivery System)	Ethanolic extract of Tempuyung (Sonchus arvensis L.)	Poor water solubility, low bioavailability	Clear nanoemulsion, particle size 16.2 ± 1.06 nm, zeta potential −37.48 ± 0.74 mV, ↑ solubility & potential oral bioavailability
126.	CTNE (Combined Tinospora smilacina Water Extract + Calophyllum Seed Oil Nanoemulsion)	Flavonoids (kaempferol-C-glucoside, diosmetin glucosides), fatty acids, coumarins	Poor bioavailability, low stability, poor skin penetration	Particle size ~24 ± 5 nm, PDI 0.21; ↑ antioxidant activity, ↑ cell viability, enhanced wound healing (90% closure in 24 h), stable for 4 weeks at 4 °C
127.	Nanoemulsion containing *Centella asiatica* methanol extract	Asiatic acid, phytol, rutin, luteolin, chlorogenic acid, PUFA (e.g., α-linolenic acid)	Poor water solubility, poor BBB permeability, low oral bioavailability	Droplet size ~57.6 nm, PDI 0.40, Zeta potential –26.5 mV, pH 8.3; ↑ stability (90 days), non-toxic (IC50 > 500 µg/ml), enhanced brain delivery, sustained release, ideal for epilepsy treatment

128.	NPHEV-10 (Nanoparticles with HEV)	Chlorogenic acid (CGA), Rutin (RU)	Poor water solubility, inadequate molecular size, instability, limited absorption, and reduced oral bioavailability; non-encapsulated extract showed limited or no effect in behavioral tests.	Improved solubility and bioavailability; higher encapsulation efficiency (RU ~95%, CGA ~60%); enhanced antioxidant (DPPH, ORAC) and antidepressant-like activity in vivo; comparable to fluoxetine and imipramine in behavioral tests.

Prospects for the future or advancements in nanoformulation:

Using nanotechnology to deliver herbal active components has demonstrated promise in improving their biological activity and resolving typical problems associated with herbal remedies. The development of nanoformulations has advanced significantly, but there are still a number of obstacles to overcome before they can be used in therapeutic settings. Identifying and controlling interactions between biological components and nano-herbal complexes are challenges. Other challenges include achieving therapeutic objectives, guaranteeing the viability of creating and implementing novel therapeutic strategies, reducing toxicity, abiding by global safety regulations, and precisely evaluating the targeting effectiveness of nanomedicines.

DISCUSSION:

The paper emphasizes the increased interest in using nanotechnology in herbal extracts to address significant limitations such as poor solubility, low bioavailability, and phytoconstituent instability. The combination of old herbal wisdom with advanced drug delivery technologies represents a dramatic shift in therapeutic approaches, allowing for more precise and efficient treatment outcomes. A comparative analysis of various nanoformulations—liposomes, phytosomes, SLNs, NLCs, nanoemulsions, and dendrimers—reveals that each has distinct traits, benefits, and application scopes. Liposomes and phytosomes improve hydrophilic and lipophilic drug loading, but SLNs and NLCs allow greater control over release and stability. Novel carriers, such as cubosomes and metal-organic frameworks, increase diversity, yet each system presents formulation and scalability issues. Studies demonstrating improved efficacy in cancer, diabetes, neurological illnesses, and inflammatory conditions provide credence to nano-herbal compositions' medicinal value. These methods improve target specificity, reduce systemic toxicity, and allow for continuous release, making them ideal for chronic illness management.However, there are ongoing questions about safety, biocompatibility, and long-term toxicity. Nanoparticle accumulation, immunological responses, and regulatory hurdles are all important factors. Toxicological testing and extensive clinical validation are critical for risk reduction and widespread implementation.

Despite breakthroughs, research shortages remain in areas like as standardization, repeatability, patient-specific delivery, and large-scale production. The necessity for standardized methodologies and integrated research remains critical.

Future study should look into green manufacturing methods, functionalization for precision targeting, and combination therapy utilizing polyherbal nanosystems. Collaborative efforts in pharmacognosy, nanoscience,

and clinical sectors will hasten translational outcomes.To summarize, nanoformulations of herbal medications are changing the landscape of phytopharmaceutical delivery. They bridge the gap between ancient treatments and current medicinal uses by increasing efficacy, lowering toxicity, and allowing for controlled release. With adequate validation, these technologies can lead to safer, more targeted, and patient-specific medicines.

Conclusion:

The amalgamation of nanotechnology and herbal medicine signifies a groundbreaking progression in the domain of drug delivery systems. By surmounting the intrinsic constraints associated with conventional herbal formulations—such as inadequate solubility, instability, and suboptimal bioavailability—nanoformulations markedly augment the therapeutic efficacy of phytochemical constituents. Methodologies such as encapsulation, targeted delivery, and controlled release not only safeguard phytochemicals from degradation but also facilitate precise and sustained therapeutic action at the pathological site. Notwithstanding the encouraging outcomes, the clinical application of these systems remains in its nascent stages. The establishment of regulatory standardization, the accumulation of long-term safety data, and the execution of rigorously designed clinical trials are imperative to ascertain their efficacy and safety. Through continuous innovation and interdisciplinary collaboration, nanoformulated herbal therapeutics possess substantial potential to reconcile traditional knowledge with contemporary medical practices.

Conflict of interest:

The author discloses no conflicts of interest.

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