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Research Article

Advancements In Herbal-Nano Formulations: A Systematic Review

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ARTICLE INFO	ABSTRACT

Plants have historically served as crucial resources for maintaining and safeguarding human health, with medicinal herbs playing a pivotal role in disease prevention. These herbs contain natural compounds utilized for treating various ailments such as bacterial infections, digestive and respiratory disorders, cardiac issues, cancer, and neurological conditions. Despite their therapeutic potential, the limited solubility of phytochemical components in water impedes their bioavailability. To harness their efficacy and circumvent such limitations, innovative strategies have emerged in healthcare, particularly in the realm of medicinal herb utilization. Nanotechnology, with its profound impact on scientific advancements, has given rise to the field of nanomedicine, presenting novel opportunities for drug delivery. Nano-drug delivery, particularly significant in combating life-threatening diseases like cancer and neurological disorders, involves coupling nanoparticles with drugs to effectively traverse physiological barriers such as the blood-brain barrier. This review emphasizes the burgeoning field of herbal-nano formulations, focusing on methods to deliver phytochemical drugs to targeted cells. Nanoformulations have demonstrated promise in research by facilitating the delivery of active herbal components, enhancing bioavailability, and mitigating the toxic effects associated with diseases.

Keywords: herbal medicine, nanotechnology, nanoformulations, drug delivery, therapeutic efficacy, systematic review

INTRODUCTION

The amalgamation of herbal medicine with nanotechnology represents a promising frontier in pharmaceutical research, offering novel approaches to drug delivery, enhanced therapeutic efficacy, and improved patient outcomes. The integration of nanoscale materials with herbal extracts harnesses the synergistic potential of both disciplines, capitalizing on the inherent properties of botanical compounds and the unique characteristics of nanocarriers. This systematic review aims to comprehensively evaluate recent advancements in herbal-nano formulations, encompassing synthesis methods, characterization techniques, and applications across various therapeutic domains [1].

Herbal medicine has been practiced for centuries, with a rich history of traditional remedies derived from plant sources. The utilization of medicinal plants for the treatment and prevention of diseases is deeply rooted in many cultures worldwide. Herbal extracts contain a diverse array of bioactive compounds, including polyphenols, alkaloids, flavonoids, and terpenoids, which exhibit pharmacological activities ranging from anti-inflammatory and antioxidant to antimicrobial and anticancer properties. However, challenges such as poor solubility, limited bioavailability, and non-specific targeting have hindered the clinical translation and efficacy of herbal remedies [2].

Nanotechnology offers innovative solutions to overcome these challenges by providing precise control over particle size, surface properties, and drug release kinetics. Nanoparticles, nanocapsules, and nanoemulsions serve as versatile platforms for the encapsulation, protection, and controlled release of herbal constituents. By engineering nanoscale delivery systems, herbal bioactives can be delivered to target tissues with enhanced bioavailability, prolonged retention, and reduced systemic toxicity. Moreover, nanocarriers can facilitate the

penetration of herbal compounds across biological barriers, such as the blood-brain barrier, enabling the development of therapeutics for neurological disorders [3].
This systematic review systematically examines the current state-of-the-art in herbal-nano formulations, encompassing a wide range of synthesis methodologies employed for their preparation. From conventional bottom-up approaches to innovative green synthesis methods, each technique offers unique advantages and challenges in tailoring the physicochemical properties of herbal-nano formulations. Furthermore, characterization techniques, including spectroscopic analysis, microscopy, and physicochemical assays, provide valuable insights into the structural integrity, stability, and functionality of these nanostructures [4].
In addition to synthesis and characterization, this review explores the diverse applications of herbal-nano formulations in therapeutics, spanning oncology, inflammatory disorders, infectious diseases, and neurodegenerative conditions. Insights into the mechanisms of action, pharmacological interactions, and safety profiles of these formulations are elucidated, providing a comprehensive understanding of their therapeutic potential. Furthermore, current challenges and future directions in the development and translation of herbal-nano formulations are discussed, highlighting opportunities for innovation and collaboration in this burgeoning field [5].

NANOFORMULATION OF HERBALDRUGS

Nanoformulations represent multifunctional systems engineered at the nanoscale, possessing distinctive physical and chemical properties suitable for diagnostic and therapeutic applications. These formulations typically consist of carriers with particle sizes ranging from 10 to 100 nanometers, within which therapeutically active agents are dissolved, encapsulated, or attached for delivery purposes. Generally, nanocarriers are constructed with an outer polymer shell and an inner core to accommodate drugs. The outer shell plays a crucial role in determining particle circulation time and interaction with cell surfaces, thereby contributing to the stability of the nanoformulation [6].
Nanocarriers, typically sized between 1 to 300 nanometers, are designed to deliver medicinal drugs to specific targets. In oral administration, nanocarriers facilitate site-specific drug delivery and controlled release. Due to their small size and ability to modify shape and charge, nanocarriers serve as effective agents for transporting active principles to target tissues. Consequently, nanocarriers can be described as entities with at least one dimension within the 1 to 100 nanometer scale. Nanostrategies are particularly valuable in the treatment of neural disorders, where conventional drugs face challenges crossing the blood-brain barrier unaided. Various types of nanoformulations are employed in pharmaceutical applications to enhance drug delivery efficiency and therapeutic outcomes [7].

1. **Inorganic Nanocarriers:** Inorganic nanocarriers, comprising quantum dots and metal nanoparticles, represent a burgeoning field in nanotechnology. These nanoscale materials offer unique properties that make them promising candidates for various applications in biomedicine, electronics, and catalysis. Quantum dots, semiconductor nanoparticles with quantum confinement effects, exhibit tunable optical and electronic properties, making them ideal for bioimaging, sensing, and light-emitting diodes. Similarly, metal nanoparticles, such as gold, silver, and iron oxide nanoparticles, possess distinctive physical and chemical characteristics that enable targeted drug delivery, photothermal therapy, and magnetic resonance imaging. Harnessing the potential of these inorganic nanocarriers opens up new avenues for developing advanced nanomedicines and nanodevices with enhanced performance and functionality [8].

a) Quantum dots: Quantum dots are semiconductor nanoparticles with unique optical and electronic properties due to quantum confinement effects. These nanoscale structures exhibit size-dependent properties, including tunable fluorescence emission, high photostability, and narrow emission spectra. Quantum dots have diverse applications across various fields, including biomedical imaging, solar cells, displays, and sensors. In biomedicine, quantum dots are utilized as fluorescent probes for cellular imaging, tumor targeting, and drug delivery tracking due to their brightness, photostability, and multiplexing capabilities. Moreover, the ability to tune their emission wavelength by controlling particle size makes quantum dots valuable tools in multiplexed imaging and diagnostics. However, concerns regarding their potential toxicity and environmental impact necessitate further research to ensure their safe use in biomedical and environmental applications [9].

b) Metal nanoparticles: Metal nanoparticles are nanoscale particles composed of metals such as gold, silver, platinum, and iron, among others. These nanoparticles exhibit unique physical, chemical, and optical properties due to their small size and high surface-to-volume ratio. Metal nanoparticles find widespread applications in various fields, including medicine, catalysis, electronics, and environmental remediation. In medicine, metal nanoparticles are utilized for drug delivery, imaging, and therapy due to their biocompatibility, surface functionalization capabilities, and tunable optical properties. For example, gold nanoparticles are employed in photothermal therapy for cancer treatment, while silver nanoparticles exhibit antimicrobial activity and are used in wound dressings and antibacterial coatings. In catalysis, metal nanoparticles serve as efficient catalysts due to their large surface area and high catalytic activity. Furthermore, metal nanoparticles play a crucial role in electronics, where they are used in conductive inks, sensors, and optoelectronic devices.

Despite their numerous applications, challenges such as stability, reproducibility, and toxicity need to be addressed to ensure the safe and effective use of metal nanoparticles in various applications [10].

2. Lipid Based Nanocarriers: Lipid-based nanocarriers encompass a diverse group of nanoscale delivery systems composed primarily of lipids or lipid-like materials. These nanocarriers offer several advantages, including biocompatibility, biodegradability, and the ability to encapsulate both hydrophilic and hydrophobic drugs. The main types of lipid-based nanocarriers include liposomes, solid-lipid nanoparticles (SLNs), nanosuspensions, and nanoemulsions [11].

a) Liposomes: Liposomes are spherical vesicles composed of one or more lipid bilayers surrounding an aqueous core. They can encapsulate hydrophilic drugs within the aqueous core and hydrophobic drugs within the lipid bilayers. Liposomes are widely used in drug delivery due to their ability to improve drug solubility, prolong circulation time, and enhance drug targeting to specific tissues or cells [12].

b) Solid-Lipid Nanoparticles (SLNs): SLNs are colloidal particles composed of lipids that are solid at room temperature. They offer advantages such as high drug loading capacity, controlled drug release, and stability during storage. SLNs can be surface-modified to improve drug targeting and reduce systemic toxicity, making them suitable for various therapeutic applications [13].

c) Nanosuspensions: Nanosuspensions are colloidal dispersions of submicron-sized drug particles stabilized by surfactants or polymers. They are prepared by techniques such as high-pressure homogenization or wet milling. Nanosuspensions are particularly useful for poorly soluble drugs, as they enhance drug dissolution, bioavailability, and therapeutic efficacy [14].

d) Nanoemulsions: Nanoemulsions are thermodynamically stable dispersions of oil and water stabilized by surfactants. They consist of nanoscale droplets with a narrow size distribution. Nanoemulsions offer advantages such as improved drug solubilization, enhanced drug absorption, and ease of administration. They are used in various drug delivery applications, including oral, topical, and parenteral delivery [15].

3. Polymeric Nanocarriers: Polymeric nanocarriers represent a diverse class of nanoparticles composed of synthetic or natural polymers that are widely used for drug delivery and biomedical applications. These nanocarriers offer several advantages, including biocompatibility, controlled drug release, and the ability to encapsulate a wide range of therapeutic agents. The main types of polymeric nanocarriers include dendrimers, nanogels, polymer-drug conjugates, micelles, and polymeric nanoparticles [16].

a) Dendrimers: Dendrimers are highly branched, three-dimensional macromolecules with well-defined structures. They possess a high density of functional groups on their surface, allowing for precise control over drug loading and release kinetics. Dendrimers are used for targeted drug delivery, imaging, and diagnostics due to their uniform size, biocompatibility, and ability to penetrate biological barriers [17].

b) Nanogels: Nanogels are hydrogel nanoparticles with a crosslinked polymer network that can swell in aqueous environments. They offer advantages such as high drug loading capacity, tunable drug release kinetics, and protection of encapsulated drugs from degradation. Nanogels are used for localized drug delivery, wound healing, and tissue engineering applications [18].

c) Polymer-Drug Conjugates: Polymer-drug conjugates are covalent complexes formed by linking drugs to polymeric carriers. They improve drug solubility, stability, and pharmacokinetics while reducing systemic toxicity. Polymer-drug conjugates are employed for targeted drug delivery, chemotherapy, and combination therapy approaches [19].

d) Micelles: Micelles are self-assembled colloidal nanoparticles formed by amphiphilic block copolymers in aqueous solutions. They possess a hydrophobic core and a hydrophilic shell, allowing for the encapsulation of hydrophobic drugs within the core and stabilization of the nanoparticles in biological fluids. Micelles are used for solubilization of poorly soluble drugs, targeted drug delivery, and imaging applications [20].

e) Polymeric Nanoparticles: Polymeric nanoparticles are colloidal particles composed of biodegradable polymers such as poly(lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), or chitosan. They offer advantages such as sustained drug release, protection of encapsulated drugs from degradation, and the ability to target specific tissues or cells. Polymeric nanoparticles are used for a wide range of therapeutic applications, including cancer therapy, gene delivery, and vaccine delivery [21].

METHODS OF PREPARATION OF HERBO-NANO FORMULATION

Nanotechnology has revolutionized material science by enabling the production, design, and application of materials at the molecular level. Nanoparticles, with sizes less than 100 nm in diameter, have emerged as promising agents for therapeutic purposes [22]. These nanoparticles can be categorized into two main systems: nanocapsules and nanospheres. Nanocapsules feature a unique polymeric membrane that encapsulates the drug, whereas nanospheres disperse the active components uniformly within a matrix system. Methods involved in the formulation of herbal-nano formulations are diverse and multifaceted. These methods encompass various techniques aimed at achieving desired particle sizes, shapes, and drug delivery profiles [23]. A schematic representation of these methods is illustrated in **Figure 1**.

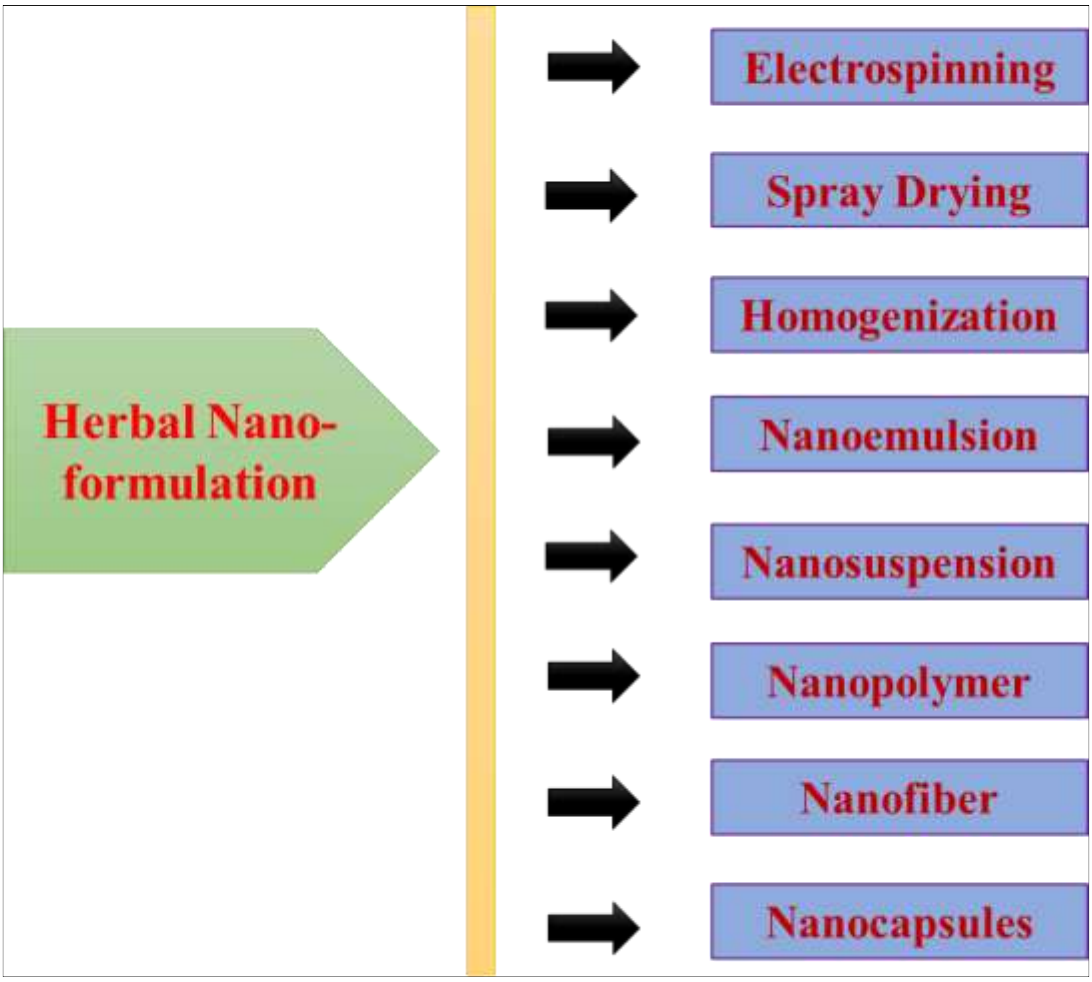

Figure 1: Schematic representation of herbal nanoformulation methods

Electrospinning: Electrospinning is a versatile and widely used technique for the preparation of herbo-nano formulations, offering precise control over the morphology, size, and composition of the resulting nanofibers. In this method, a polymeric solution containing herbal extracts or active compounds is subjected to a high voltage electric field, causing the formation of a charged jet of polymer solution. As the jet travels towards a grounded collector, solvent evaporation leads to the solidification of the polymer fibers, resulting in the formation of nanofibrous mats or scaffolds embedded with herbal constituents [24]. Electrospun nanofibers offer several advantages for herbo-nano formulations, including high surface area-to-volume ratio, interconnected porous structure, and the ability to encapsulate hydrophilic and hydrophobic compounds simultaneously. Moreover, the electrospinning process can be easily scaled up for industrial production, making it an attractive method for the development of herbal-based nanofibrous materials for applications in drug delivery, tissue engineering, and wound healing [25,26].

Nano emulsification: Nano emulsification is a widely employed method for preparing herbo-nano formulations, leveraging the thermodynamic instability of emulsions at the nanoscale to produce finely dispersed droplets. Typically, this process involves the use of high-energy methods such as high-pressure homogenization, sonication, or microfluidization to reduce the size of emulsion droplets to the nanometer range. In this method, a mixture of herbal extracts or active compounds, surfactants, and co-surfactants is emulsified in an aqueous phase or an organic solvent. The high shear forces applied during emulsification break down larger droplets into smaller ones, leading to the formation of a stable nanoemulsion. Control over parameters such as surfactant concentration, emulsification time, and processing conditions allows for the optimization of droplet size and distribution, thereby influencing the encapsulation efficiency and stability of the resulting herbo-nano formulation. Nanoemulsification offers several advantages for herbal drug delivery, including enhanced solubility, bioavailability, and targeted delivery, making it a promising method for formulating herbal medicines with improved therapeutic efficacy [27,28].

a) Solvent Evaporation Method

In the solvent evaporation method, lipids and drug components are dissolved in an organic solvent. Historically, volatile solvents like chloroform and dichloromethane were utilized, but contemporary researchers opt for less toxic alternatives such as ethyl acetate. The solution, comprising lipid, solvent, and drug, is emulsified with stabilizers such as poloxamer or polyvinyl alcohol. The process unfolds in two distinct stages. Initially, the polymer solution is emulsified in an aqueous phase. Subsequently, solvent evaporation and polymer precipitation take place. The resulting precipitate, often referred to as nanospheres, is harvested post-centrifugation and washing. Finally, the nanospheres are stored after lyophilization [29].

b) Solvent displacement method

The method of producing nanoparticles with sizes below 100 nm involves an emulsification technique. This approach is derived from the solvent evaporation method but with slight modifications. Initially, a partially hydromiscible solvent is utilized to dissolve both the drug and lipid components. This solution is then allowed to reach a state of saturation. As a consequence of the thermodynamic equilibrium within the solution, the solvent gradually diffuses into the surrounding aqueous phase, leading to the precipitation of nanoparticles. Subsequently, any remaining solvent is eliminated through either filtration or evaporation methods. This process enables the controlled synthesis of nanoparticles with precise dimensions, making it a valuable technique in various scientific applications, including drug delivery systems and Nanomedicine [30].

c) Homogenization

In the preparation of solid-lipid nanoparticles for drug delivery, homogenization or sonication is employed. Initially, an emulsion with fine droplets is formed, and subsequent solvent removal by evaporation induces the precipitation of lipid nanoparticles. Two methods, hot and cold homogenization, are utilized in this process. Hot homogenization involves operating at temperatures surpassing the melting point, making it suitable for lipophilic drugs. Lipid and drug are combined, and the mixture is loaded with an aqueous solvent. Emulsion congeals at room temperature, yielding lipid nanoparticles. However, drawbacks associated with this method are detailed in Table 1. To address these challenges, the cold homogenization approach was devised. In cold homogenization, lipid and the drug are melted together, followed by rapid solidification in the presence of liquid nitrogen. Subsequent homogenization at below-room temperature, accompanied by vigorous stirring, yields nanoparticles from microparticles. This method offers a solution to the limitations encountered with hot homogenization [31].

d) Nanoprecipitation

The solvent evaporation method, also known as the solvent displacement technique, involves precipitating polymers by dissolving them in organic solvents like acetone. These dissolved polymers then diffuse into an aqueous phase, forming a colloidal suspension. This technique, pioneered by Nagavarma et al., requires the presence or absence of a surfactant, and the aqueous medium must be soluble with the solvent but non-soluble for the polymer [32].

e) Nanoencapsulation

The process of enclosing solid, liquid, and gas nanoparticles is termed nanoencapsulation. Within the encapsulating material, termed a matrix, the drug core forms nanocapsules. This method facilitates the encapsulation of multiple drug molecules within an inert material, shielding them from stomach acid and harsh environments, while enabling controlled drug release. Proteins and genes, being delicate and less stable, are encapsulated within nanocarriers to maintain their activity through conjugation reactions, which involve minimal structural alterations. Given the fragility of proteins and genes, encapsulation within nanocarriers preserves their stability and shields them from metabolic processes. Utilizing bioconjugate reactions for linking proteins to delivery molecules is highly recommended, as these reactions are highly specific and entail minimal risk of structural changes in proteins [33].

f) Nanofabrication

Nanofabrication encompasses a suite of techniques aimed at producing elements at scales as small as 100 nm or less. Among these methods is etching, a process that selectively removes specific materials to form either isotropic or anisotropic features, depending on the direction of material removal. One notable application of nanofabrication is in the creation of hollow mesoporous silica nanoparticles. These nanoparticles have been successfully fabricated using sodium carbonate and are renowned for their excellent biological compatibility.

They serve as effective nanoreactors or carriers for drugs, showcasing their potential in biomedical applications [34].

Table 1: Advantages and disadvantages of different methods of herbal nanoformulation

S. No.	Preparation Method	Advantages	Disadvantages	References
1.	High-pressure homogenization	Enhanced bioavailability	Complex manufacturing processes	[35]
2.	Wet milling	Improved drug solubility	Potential stability issues	[36]
3.	Co-precipitation method	Targeted drug delivery	Regulatory challenges	[37]
4.	Solvent evaporation technique	Reduced systemic toxicity	Batch-to-batch variability	[38]
5.	Emulsion-based methods	Prolonged drug release	High production costs	[39]
6.	Plant-mediated synthesis	Enhanced therapeutic efficacy	Limited scalability	[40]
7.	Phytofabrication	Reduced frequency of dosing	Limited shelf-life	[41]
8.	Nanoprecipitation Technique	Minimized side effects	Potential cytotoxicity	[42]
9.	Spray Drying	Improved patient compliance	Need for specialized equipment	[43]
10.	Electrospinning	Protection of labile drugs	Possibility of drug leakage	[26]
11.	Layer-by-Layer Assembly	Integration of combination therapies	Risk of immune reactions	[44]
12.	Ultrasonication	Potential for personalized medicine	Environmental concerns	[45]

DRUG DELIVERY AND MECHANISM OF ACTION OF NANOFORMULATIONS

Effective delivery of herbal components can be achieved through various advantages offered by nanoparticle drug encapsulation. Key factors such as particle size, shape, and charge, as well as the target cell, play crucial roles in this delivery process. Particle size significantly impacts distribution, efficiency, and cellular uptake of nanoparticles. It also influences the degradation and elimination of nanocarriers [46,47]. Moreover, the charge of nanoparticles is critical for both their efficiency and the mechanism of drug passage through cell membranes. Surface charges directly affect the stability of drug-particle complexes; higher charges result in faster repulsion, preventing nanoparticle aggregation. Additionally, the charge of particles affects absorption, with positive charges enhancing adhesion and retention within the mucus layer. Particle shape is also an essential factor influencing biological properties. Research indicates that the shape of nanocomplexes can significantly impact their behavior. Polymer micelles have been shown to enhance blood circulation following intravenous injection. Studies have demonstrated a correlation between cellular adhesion and nanoparticle length, suggesting a reverse reaction in certain cases [48]. The mechanism of drug action often involves interactions between cellular receptors and their ligands. Nanodrugs, complex molecules designed for targeting specific receptors, utilize dendrimers and polymer-based nanoparticles for polyanionic receptor-mediated targeting. Overall, understanding and manipulating the size, shape, and charge of nanoparticles are crucial for optimizing drug delivery, particularly in the realm of herbal components [48].

TOXICITY ISSUES ASSOCIATED WITH NANO-HERBAL MEDICINES

Concerns regarding the toxicity of nano-herbal medicines have emerged as an important topic in both scientific research and public discourse [49]. Here's a nuanced exploration of these issues:

Potential Toxicity of Nanoparticles: The primary concern with nano-herbal medicines lies in the inherent toxicity of nanoparticles themselves. Nanoparticles, due to their small size and increased surface area, may exhibit different biological behaviors compared to their bulk counterparts. This altered behavior can lead to unintended toxicological effects, including oxidative stress, inflammation, and cellular damage [20].

Herbal Ingredients: While herbal medicines are often perceived as natural and safe, it's crucial to recognize that not all herbal compounds are benign. Some herbs contain phytochemicals with intrinsic toxicity, especially when taken in high concentrations or in novel formulations such as nanoparticles. Additionally, the variability in composition and potency among herbal products can further complicate safety assessments [50].

Synergistic Effects: Nano-herbal formulations may introduce complex interactions between the nanoparticles and herbal constituents, leading to synergistic or antagonistic effects on toxicity. Understanding these interactions is essential for accurately assessing the safety profile of nano-herbal medicines [51].

Biodistribution and Accumulation: Nanoparticles can exhibit unique biodistribution patterns within the body, potentially accumulating in specific organs or tissues. This accumulation may exacerbate toxicity over time, especially if the nanoparticles persist in the body or undergo biotransformation into more toxic forms [52].

Regulatory Challenges: Regulatory frameworks for assessing the safety of nano-herbal medicines are still evolving and often face challenges in adequately addressing the complexities of these formulations. Establishing standardized testing protocols and risk assessment strategies tailored to nano-herbal products is essential for ensuring consumer safety [20].

Mitigation Strategies: To address toxicity concerns associated with nano-herbal medicines, rigorous preclinical evaluations are necessary, including comprehensive toxicity profiling, pharmacokinetic studies, and mechanistic investigations into potential adverse effects. Additionally, the development of safe-by-design approaches that integrate principles of nanotoxicology and herbal medicine may help mitigate risks associated with these complex formulations [53].

1. Silver nanoparticles (AgNPs) and toxic effects

Silver nanoparticles (AgNPs) have garnered significant attention for their antimicrobial properties, making them promising candidates for various applications, including medicine, textiles, and consumer products. However, concerns have been raised regarding their potential toxic effects on human health and the environment [54]. AgNPs can induce cytotoxicity through several mechanisms, including the generation of reactive oxygen species (ROS), disruption of cellular membrane integrity, and interference with cellular signaling pathways. Furthermore, their small size allows them to penetrate biological barriers and accumulate in organs and tissues, leading to potential systemic toxicity. Studies have shown that AgNPs can induce adverse effects such as DNA damage, inflammatory responses, and organ toxicity, highlighting the importance of thorough risk assessment and proper regulation in the use of AgNPs to mitigate potential health and environmental risks [55].

2. Polymeric Nanoparticles and toxicity

Polymeric nanoparticles hold significant promise for drug delivery due to their tunable properties and biocompatibility. However, concerns regarding their potential toxicity warrant careful consideration. While many polymers used in nanoparticle formulations are generally regarded as safe, factors such as polymer composition, size, surface charge, and degradation kinetics can influence their toxicity profiles. For instance, certain polymers may exhibit cytotoxicity or immunogenicity upon degradation, leading to adverse effects. Moreover, the accumulation of nanoparticles in vital organs or tissues over prolonged exposure periods raises concerns about long-term systemic toxicity. Therefore, thorough evaluation of the physicochemical properties and biological interactions of polymeric nanoparticles is essential to ensure their safety and efficacy in clinical applications. Additionally, strategies such as surface modification and biodegradable formulations can mitigate potential toxicity risks, enhancing the translational potential of polymeric nanoparticles for targeted drug delivery [56].

ADVANTAGES OF HERBAL NANO-FORMULATIONS

Nano-herbal formulations offer a promising avenue in the field of drug delivery, combining the therapeutic benefits of herbal medicine with the advantages of nanotechnology. One significant advantage lies in their enhanced bioavailability and efficacy, attributed to their smaller particle size and increased surface area, allowing for better absorption and targeted delivery to specific tissues or cells. Moreover, nano-herbal formulations often exhibit improved stability and prolonged release profiles, leading to reduced dosing frequency and enhanced patient compliance [57,58]. Additionally, nanotechnology enables the encapsulation of fragile herbal compounds, protecting them from degradation and improving their shelf life. Furthermore, nano-herbal formulations can be tailored to modulate drug release kinetics and optimize therapeutic outcomes, paving the way for personalized medicine approaches. Overall, the integration of nanotechnology with herbal medicine holds great promise for the development of innovative, efficient, and safer drug delivery systems with potentially broader therapeutic applications [59].

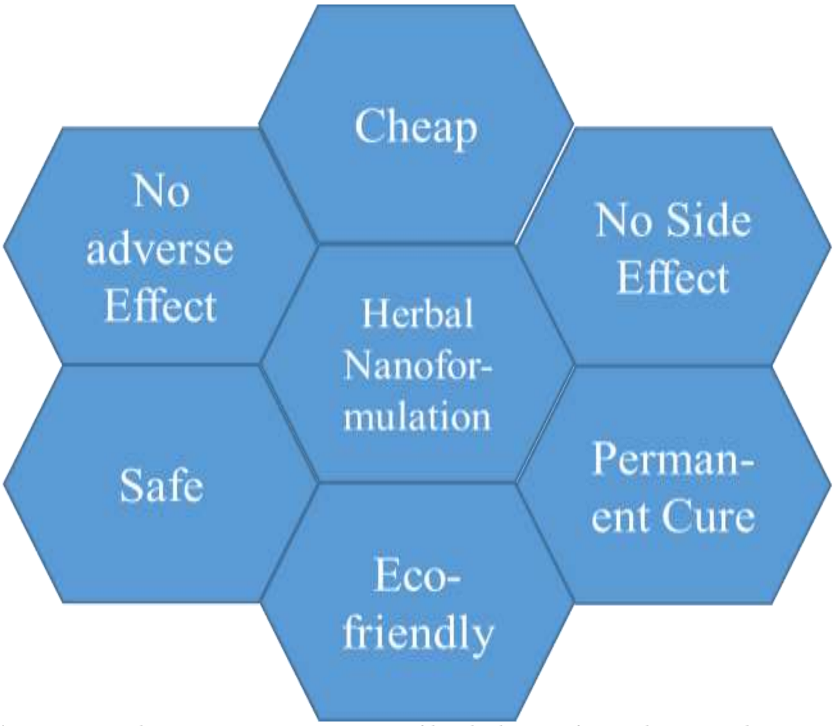

Figure 2: Schematic reorientation of herbal nanoformulation Advantages

FUTURE PROSPECTS OR DEVELOPMENTS OF NANOFORMULATION

The future of nanoformulations holds immense promise for revolutionizing drug delivery and therapeutics across various fields. With ongoing advancements in nanotechnology, including nanomaterial synthesis, characterization techniques, and targeted delivery strategies, nanoformulations are poised to address current challenges in drug efficacy, safety, and patient compliance [60]. Emerging trends suggest a shift towards multifunctional nanosystems capable of simultaneous imaging, diagnosis, and therapy, thus enabling personalized medicine approaches. Moreover, the integration of smart materials and stimuli-responsive nanoparticles holds potential for controlled drug release, triggered by physiological cues or external stimuli. The development of biocompatible and biodegradable nanocarriers further enhances their translational potential, minimizing toxicity and improving drug bioavailability [61]. Additionally, the application of nanotechnology in vaccine delivery, gene therapy, and regenerative medicine offers novel avenues for combating infectious diseases, genetic disorders, and tissue regeneration. Collaborative efforts between interdisciplinary research fields, regulatory agencies, and industry stakeholders are vital for advancing nanoformulations from bench to bedside, ensuring their safe and effective translation into clinical practice. As nanoformulations continue to evolve, they are poised to play a pivotal role in shaping the future of healthcare, ushering in an era of targeted, personalized, and precision medicine [62].

CONCLUSION

In conclusion, the systematic review highlights significant advancements and promising prospects in the field of herbal-nano formulations. Through a comprehensive analysis of current literature, it is evident that nanoformulations offer novel solutions for enhancing the therapeutic efficacy, bioavailability, and targeted delivery of herbal compounds. The integration of nanotechnology with traditional herbal medicine holds immense potential for addressing various healthcare challenges, including chronic diseases, infectious ailments, and cancer treatment. Moreover, the development of biocompatible nanocarriers and innovative delivery systems enables precise control over drug release kinetics, minimizing adverse effects and maximizing therapeutic outcomes. However, despite the substantial progress, several challenges such as scalability, regulatory approval, and long-term safety assessments need to be addressed for successful clinical translation. Future research endeavors should focus on elucidating the underlying mechanisms, optimizing formulation parameters, and conducting rigorous clinical trials to validate the efficacy and safety of herbal-nano formulations. Overall, the convergence of herbal medicine and nanotechnology represents a promising frontier in healthcare, offering transformative opportunities for improving patient outcomes and advancing personalized medicine approaches.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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