International Journal of Pharmacognosy and Herbal Drug Technology (IJPHDT)
ISSN: 3049-1630, Vol. 02, Issue No.02, 2025 (pp. 01-16)
AKT PUBLICATION
REVIEW ARTICLE
https://www.aktpublication.com/index.php/ijphdt

An Overview of Drug Delivery Methods Based on Nanotechnology and Herbal Remedies

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ABSTRACT

The integration of nanotechnology with herbal medicine has revolutionized drug delivery by addressing major problems with traditional herbal preparations' irregular therapeutic effectiveness, rapid metabolism, and poor bioavailability. Bioactive herbal compounds have been enhanced in solubility, stability, and controlled release due to nanocarriers like liposomes, polymeric nanoparticles, solid lipid nanoparticles (SLNs), dendrimers, and nanoemulsions. This provides targeted delivery with reduced systemic toxicity. With these advances, the therapeutic value of herbal-based medicines for chronic diseases such as cancer, cardiovascular disease, neurological disorders, and microbial infections has significantly enhanced. Besides enhancing herbal medicine absorption and efficacy, nanotechnology-based drug delivery systems also meet the increasing demand for natural and biocompatible treatments globally. They are not generally employed in the clinic, however, due to hindrances such as high production costs, scalability issues, complex regulatory environment, and potential long-term toxicity. Creation of biodegradable nanocarriers, extensive in vivo and clinical studies, and artificial intelligence application for optimizing drug formulation and delivery systems must be the primary focus of future work. Development of drug delivery systems that integrate the advantages of nanotechnology and herbal medicine could make the way to more individualized and targeted therapeutics. In order for nano-herbal drug delivery systems to enter into clinical trials and become successful, interdisciplinary collaboration and technological advances will be necessary in order to address existing challenges. This will enhance healthcare outcomes globally and revolutionize modern pharmacotherapy.

Key Words:

Nanotechnology, Herbal Medicine, Drug Delivery, Poor Bioavailability, Rapid Metabolism, Nanocarriers, Liposomes, Polymeric Nanoparticles, Solid Lipid Nanoparticles (SLNs)

Article History:

Received Jan 25,2025

Accepted Feb 15,2025

Published Feb 28,2025

1. INTRODUCTION

The synergy of herbal medicine and nanotechnology has brought drug delivery to a remarkable advancement through innovative means of therapeutic efficacy, bioavailability, and targeted delivery. For the improvement of drug stability, regulation of the release rate, and mitigation of systemic toxicity, drug delivery strategies based on nanotechnology employ nanoparticles, liposomes, dendrimers, and nanoemulsions. These nanoscale drug vehicles allow for targeted delivery of medication, reducing side effects and enhancing treatment effectiveness for most diseases, including infectious diseases, cancer, and cardiovascular disease. Devices based on nanotechnology are transforming pharmacotherapy by drug delivery to the cellular level and breaching biological barriers. Widespread use is yet to be bogged down by issues like elevated production costs, possible toxicity, and intricate schemes of regulation. In spite of such constraints, nanomedicine developments are opening doors to increasingly complex drug formulation, which will guarantee better patient outcomes [1].

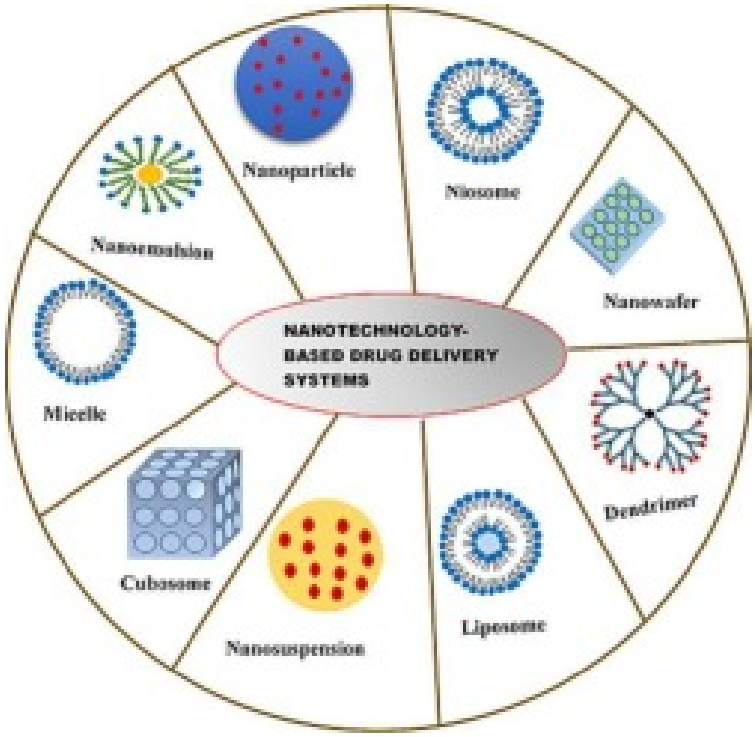

Figure 1: Drug delivery techniques based on nanotechnology [2]

Herbal medicine has long been known to have therapeutic potential, just like nanotechnology. Conventional herbal drug delivery is not without shortcomings, however, such as low bioavailability, quick metabolism, and poor solubility. One of the solutions to these problems is the introduction of nanotechnology into herbal formulations, improving the stability and bioavailability of bioactive compounds like terpenoids, alkaloids, and flavonoids. To improve the therapeutic effectiveness of herbal drugs without sacrificing their inherent benefits, methods such as herbal nanoparticles, herbosomes, and nanoemulsions are being investigated. While

safer and more biocompatible, herbal drug delivery systems tend to have irregular efficacy due to differences in the levels of bioactive molecules. The strengths and limitations of herbal and nanotechnology-based approaches to medicine delivery are compared, highlighting the imperative for conducting more research to create ideal hybrid models of delivery. Increased strength, stability, and customization of drug compositions can be created through the merging of both approaches' strengths, which would further drive the development of personalized medicine [3].

a. Background and Context

Pharmaceutical development of drug delivery systems is aimed at maximizing therapeutic effects with reduced side effects. Nanotechnology-based approaches like nanoparticles, liposomes, dendrimers, and nanoemulsions enable precision targeting, controlled release, and improved bioavailability. Drug delivery systems are full of promise for the treatment of many diseases but have the drawback of high costs, complicated regulations, and the possibility of toxicity.

Although herbal medicine is known to possess natural medicinal properties, it is usually restricted by its restricted solubility and inconsistent absorption. Stability and absorption are improved with the addition of nanotechnology to herbal drug delivery through herbal nanoparticles, herbosomes, and nanoemulsions. Although herbal preparations are less toxic, these need to be optimized further by research. Individualized, targeted, and more efficient drug therapies may be the result of a hybrid system that combines the two systems [4].

b. Objectives of the Review

This review aims to:

- To investigate how modern drug delivery uses nanotechnology.
- To assess the difficulties and effectiveness of medicine administration using herbs.
- To evaluate and contrast the advantages and drawbacks of the two strategies [5].
- To determine the best course for enhancing these delivery methods in the future.

c. Importance of the Topic

Pharmacological drug delivery advances are the key to boosting treatment efficacy, reducing side effects, and maximizing patient compliance. Conventional methods of drug delivery are frequently limited in their potential to address multicauses disorders like cancer and neurologic illnesses because they pose low bioavailability, systemic toxicity, and untargeted bioactivity. Targeted nanomedicine drug delivery has changed pharmacotherapy with high targetability, drug-controlled delivery, and superior drug stability of therapeutic molecules. In spite of these, disadvantages of extensive clinical usage are high costs of production, complicated regulations, and toxicity. Similarly, low solubility, fast metabolism, and uneven absorption are typically the downfall of herbal medicine, even though it is naturally medicinal [6]. A safer and more efficient replacement for man-made drugs, nanotechnology combined with herbal drug delivery improves the stability, solubility, and absorbability of bioactive substances. Herbal drug delivery methods and nanotechnology might be combined together in a hybrid system where they can take advantages of both sides while avoiding both their disadvantages and produce more effective, customized, and site-selective

therapies. In order to improve future pharmaceutical interventions and promote improvement in global healthcare, such a cross-road needs to be investigated urgently.

2. ADVANCEMENTS IN DRUG DELIVERY: INTEGRATING NANOTECHNOLOGY AND HERBAL THERAPIES

One of the major breakthroughs in drug delivery is the combination of herbal medicine and nanotechnology. Traditional medical practices like Ayurveda, Traditional Chinese Medicine (TCM), and Unani have used herbal drugs for centuries. However, their rapid metabolism, low bioavailability, and poor solubility tend to restrict their therapeutic scope. By facilitating the targeted delivery, controlled release, and improved stability of herbal bioactive compounds, nanotechnology offers a novel solution to such problems [7]. As a result of this synergy, nano-herbal drug delivery systems have been developed and are being researched for the treatment of many diseases, including as microbial infections, cancer, cardiovascular disease, and neurological disorders.

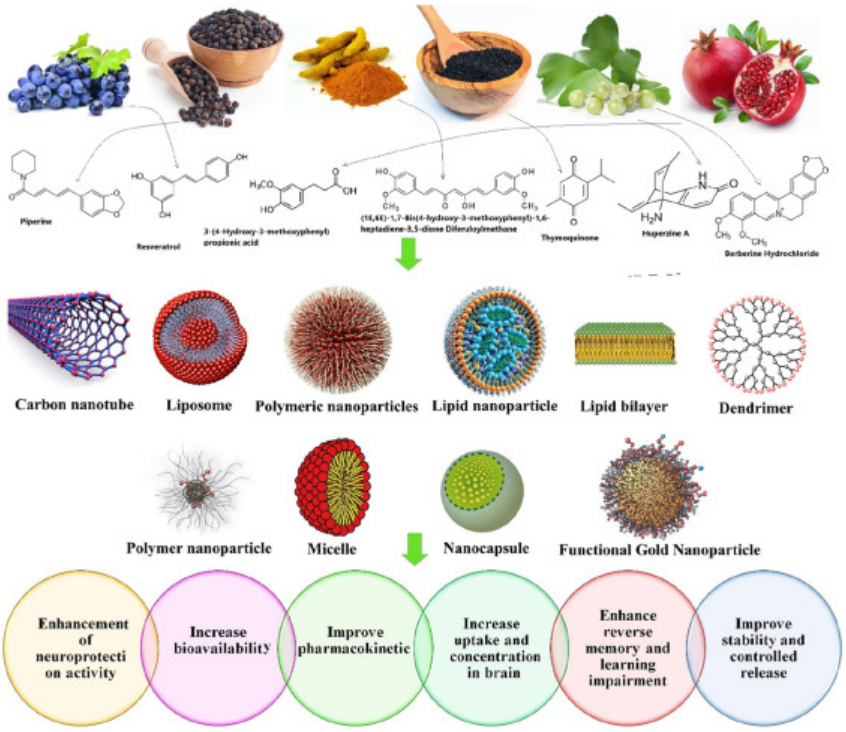

Figure 2: Using Nanotechnology in Herbal Medicine [8]

a. Nanotechnology in Drug Delivery

Through the modification of materials on the nanoscale (1–100 nm), nanotechnology can augment therapeutic action and modify the properties of drugs. medication delivery has been transformed through the emergence of nanocarriers, which enhance solubilization, prevent bioactive molecules from degradation, and enable site-specific medication targeting.

- **Types of Nanocarriers Used in Herbal Drug Delivery**

A number of nanocarriers have been synthesized to improve the stability, bioavailability, and targeted delivery of

herbal drugs, thereby making them more effective. Liposomes made of biocompatible bilayers of phospholipid can successfully encapsulate hydrophobic herbal drugs, as in the case of curcumin-loaded liposomes used to treat cancer. Biodegradable materials such as chitosan, polylactic acid (PLA), and poly (lactic-co-glycolic acid) (PLGA) are used to make polymeric nanoparticles, which offer enhanced cellular absorption and prolonged release [9]. One example of this is quercetin-loaded PLGA nanoparticles for neuroprotection. Poorly soluble herbal medications, such resveratrol-loaded SLNs for cardiovascular benefits, can have their release controlled and their bioavailability increased using solid lipid nanoparticles (SLNs), which are made of solid lipids. As evidenced by ginger extract nanoemulsions' anti-inflammatory properties, oil-in-water or water-in-oil nanoemulsions improve the gastrointestinal absorption of herbal medications. Because of their highly branched architectures, dendrimers provide significant loading capacities for herbal chemicals, including formulations of berberine based on dendrimers for antibacterial purposes. Silver and gold nanoparticles, which are recognized for their antibacterial and anticancer qualities, have also been used in formulations such as neem extract based on gold nanoparticles for antibacterial activity. The therapeutic potential of herbal medicine is greatly increased by these nanocarriers, which guarantee site-specific drug delivery, lessen adverse effects, and increase overall treatment efficacy.

b. Herbal Medicine and Its Challenges in Drug Delivery

Although they have strong therapeutic benefits, herbal medications have drawbacks such as low absorption, volatility, and quick disintegration. By increasing their solubility, stability, and targeted delivery, nanotechnology improves therapeutic results and efficacy.

- **Importance of Herbal Medicine**

Bioactive substances include alkaloids, flavonoids, polyphenols, and terpenoids, which have a variety of pharmacological qualities that are advantageous to human health, are abundant in herbal remedies. For instance, boswellic acid of frankincense contains robust anti-inflammatory activities, and the curcumin of turmeric is a great antioxidant. Similarly, Panax species ginseng offers neurological benefits, the resveratrol of grapes contains anticancer activity, and berberine of Berberi's species contains antimicrobial activity [10]. However, despite these healing properties, herbal compounds are often not as strong due to limited stability, aqueous insolubility, and rapid degradation within the body. To enhance their absorption, stability, and site-specific action, advanced drug delivery methods are needed since these problems compromise their bioavailability and therapeutic activity.

- **Challenges in Herbal Drug Delivery**

Most herbal chemicals are poorly soluble in the gut, which translates to poor bioavailability, and this often compromises their medicinal benefits. Their fast metabolism owing to their low half-life also yields low medication concentrations in the systemic circulation and lowers their effectiveness. The bioavailability of herbal bioactives is also curbed by their stability under physiological conditions, since they are prone to enzyme degradation before they reach the target sites. The non-selective distribution of normal herbal extracts to the

body lowers their therapeutic value since they are not target specific. With the enhancement of solubility, stability, and controlled release as well as the targeted delivery of herbal bioactives, nanotechnology offers an excellent method for solving these and enhancing therapeutic outcomes and efficacy as a whole [11].

c. Applications of Nano-Herbal Drug Delivery Systems

By increased solubility, stability, and targeted delivery, nanotechnology increases the therapeutic efficacy of herbal constituents in the management of diabetes, cancer, neurological disorders, cardiovascular disorders, inflammation, and infection. Herbal medicines with nanotechnology provide better disease control, sustained action, and enhanced bioavailability.

a) **Cancer Therapy**

Nanotechnology increases targeted drug delivery and solubility, improving the therapeutic efficacy of herbal compounds against cancer. Nanoparticles conjugated with herbal extracts such as green tea polyphenols increase photothermal therapy against cancer, while curcumin-loaded nanocarriers provide improved penetration into tumors and greater therapeutic efficiency. Resveratrol-filled liposomes also offer sustained release, increasing anticancer efficacy and minimizing systemic toxicity [12].

b) **Neurological Disorders**

Nanotechnology enhances solubility and site-specific drug delivery, enhancing the efficacy of herbal products in cancer treatment. Gold nanoparticles loaded with herbal extracts like green tea polyphenols enhance photothermal cancer therapy, while curcumin-loaded nanoparticles exhibit enhanced tumor penetration and higher therapeutic value. In addition, resveratrol-loaded liposomes facilitate controlled release, enhancing anticancer activity and reducing systemic toxicity.

c) **Cardiovascular Diseases**

Herbal drug delivery via nanotechnology has a profound positive impact on cardiovascular health. Nanoencapsulated flavonoids such as rutin and catechins lowered cholesterol and oxidative stress. Resveratrol-loaded solid lipid nanoparticles (SLNs) protect cardiac tissue from ischemia-reperfusion injury, enhancing heart health, while liposomes of herbal extracts enhance blood flow and help in the treatment of hypertension [13].

d) **Anti-Inflammatory and Pain Management**

The efficacy of anti-inflammatory herbal compounds is enhanced by nanotechnology, which enhances their bioavailability. Although curcumin-loaded SLNs are commonly employed to manage chronic inflammatory diseases such as rheumatoid arthritis and inflammatory bowel conditions, offering sustained and effective relief, nano-encapsulated boswellic acid effectively suppresses inflammation linked with arthritis.

e) **Antimicrobial and Antiviral Therapies**

Significant antibacterial and antiviral effects have been demonstrated by herbal substances that have been nanoformulated. Neem extract and silver nanoparticles work well together to fight infections because of their potent antibacterial properties. Furthermore, against SARS-CoV-2, nano-formulated andrographolide has shown antiviral activity, underscoring the promise of nanotechnology

in creating herbal-based antiviral therapies [14].

f) **Diabetes Management**

Through increased bioavailability of plant-derived chemicals, herbal nanomedicine is critical in the control of diabetes. Glucose metabolism is boosted by bitter melon extract-loaded nanoparticles and helps in blood sugar regulation. Likewise, curcumin nano-formulations are efficient in fighting diabetes-induced oxidative stress, improving glycemic control and mitigating disease-related impacts.

3. NANOTECHNOLOGY-BASED DRUG DELIVERY SYSTEMS: ADVANCES AND APPLICATIONS

Nanotechnology has transformed the delivery of drugs, providing targeted, accurate, and efficient therapies. Such drugs improve patient compliance, reduce side effects, and improve drug absorption [15]. The development and uses of drug delivery systems through nanotechnology are addressed in this article.

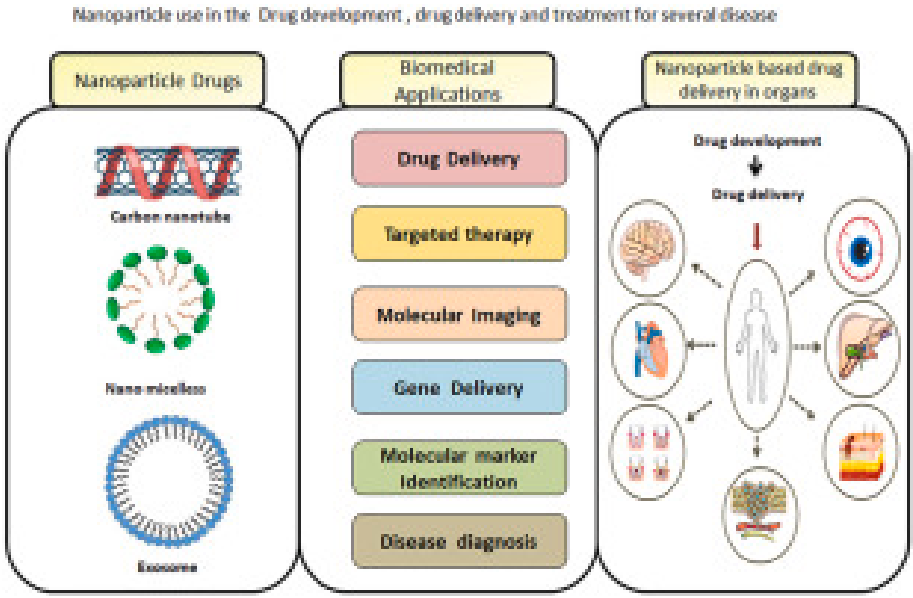

Figure 3: Nanoparticle Applications in Drug Delivery and Development [16]

a. Introduction to Nanotechnology in Drug Delivery

Through the modification of materials at the nanoscale (1–100 nm), new drug delivery modes that enhance therapeutic effects are created using nanotechnology. Nanoscale carriers overcome physiological barriers such as enzymatic hydrolysis and rapid body elimination by enhancing medication solubility, stability, and bioavailability. Nanocarriers provide targeted and sustained medication release, reducing systemic toxicity and optimizing therapeutic efficacy. The capacity of nanotechnology to deliver drugs to specific areas has transformed medicine and improved the management of infections, neurological diseases, and chronic conditions [17].

b. Types of Nanotechnology-Based Drug Delivery Systems

Drug delivery systems based on nanotechnology can be divided into various types according to its makeup and mode of action.

a. Lipid-Based Nanocarriers

The biocompatibility and capability to encapsulate hydrophobic and hydrophilic drugs confer lipid-based nanocarriers broad acceptance. Liposomes consist of vesicular, spherical vesicles made up of lipid bilayers that strengthen drug stability, allow targeted delivery of the drug, and suppress side effects. Solid lipid nanoparticles (SLNs) are a perfect choice for long-term drug activity as they stabilize the medicine and ensure sustained release of the drug [18]. Increased drug entrapment and bioavailability are made possible by the increased drug-loading capacity and enhanced stability of nanostructured lipid carriers (NLCs) compared to SLNs.

b. Polymeric Nanoparticles

Biodegradable polymers PLGA (poly (lactic-co-glycolic acid)), chitosan, and PEG (polyethylene glycol) are used to create polymeric nanoparticles, which enhance the solubility of drugs and enable controlled and sustained release of the drug. Owing to their well-defined architecture, dendrimers—branched nanosized polymers—have a high drug-loading capability and enable targeted drug delivery. By enabling extended circulation and drug deposition at the site of disease, these polymeric systems augment the efficacy of treatment.

c. Metallic and Inorganic Nanoparticles

Applications of metallic nanoparticles are numerous and include drug delivery, bioimaging, to targeted therapy. Imaging, photothermal therapy, and targeted drug delivery—especially in cancer therapy—all find extensive use of gold nanoparticles. Through their controlled release systems, silica nanoparticles are potent drug carriers that improve therapeutic specificity and bioavailability. Quantum dots—nanoscale semiconductor particles—facilitate targeted therapy and function as imaging agents in cancer diagnosis by accumulating in tumor tissues.

d. Carbon-Based Nanomaterials

Carbon nanomaterials have attracted attention because of their high drug-loading capacity and biocompatibility. Carbon nanotubes are a good platform for cancer treatment through gene therapy and intracellular drug delivery [19]. Due to their enormous surface area, graphene-based nanocarriers are highly efficient for drug loading and sustained release, enhancing their bioavailability and therapeutic efficacy.

c. Advances in Nanotechnology for Drug Delivery

Drug delivery has advanced significantly as a result of nanotechnology's increased precision, control, and multifunctionality [20].

a. Targeted Drug Delivery

Through the facilitation of site-specific delivery of drugs, functionalized nanoparticles enhance therapeutic efficacy and reduce off-target effects [21]. For example, folic acid or antibody-conjugated cancer-targeting nanoparticles ensure that chemotherapeutic drugs deposit in tumor cells alone, while sparing healthy tissues.

b. Stimuli-Responsive Drug Release

Drugs may be designed to release from nanocarriers upon specific stimuli, including light, pH, temperature, or enzymes [22]. For

instance, pH-sensitive nanoparticles provide targeted drug action and reduce systemic toxicity by releasing their drug cargo in the acidic tumor environment.

c. Controlled and Sustained Release

Extended medication delivery enabled by nanotechnology reduces frequency of dosing and enhances compliance of patients. To achieve steady blood glucose and reduce the necessity of frequent injections in diabetes therapy, polymeric nanoparticles have been engineered for long-term insulin delivery [23].

d. Multifunctional Nanocarriers

Theranostics is the concept that nanocarriers can enable therapy, allow imaging, and administer drugs simultaneously [24]. For instance, gold nanoparticles are employed in photothermal therapy, which uses light absorption and heat generation to kill cancer cells, as well as tumor imaging.

d. Applications of Nanotechnology in Medicine

By increasing medication efficacy and precision in a variety of therapeutic domains, nanotechnology is revolutionizing medicine [25].

a. Cancer Therapy

Targeted chemotherapy and photothermal therapy are made possible by nanoparticles, which lessen adverse effects and enhance treatment results. Doxil® (liposomal doxorubicin) is a well-known example, which promotes drug accumulation in tumors while reducing harm to healthy organs [26].

b. Neurological Disorders

Drug distribution across the blood-brain barrier (BBB) is made easier by nanocarriers, which enhances the management of neurological disorders like Parkinson's and Alzheimer's [27]. Neuroprotective medication-carrying polymeric nanoparticles improve brain-targeted drug delivery, supporting neuronal repair and protection [28].

c. Infectious Disease Treatment

By increasing medication penetration into bacterial biofilms, nanoparticles enhance antibiotic administration and fight antimicrobial resistance. Because of their strong antibacterial properties, silver nanoparticles are useful in the fight against bacterial infections [29].

d. Gene Therapy

In gene therapy applications, nanoparticles are used as non-viral vectors to carry genetic material. CRISPR-loaded nanoparticles, which guarantee accurate gene editing with little immunological reaction, are being investigated for the treatment of genetic illnesses [30].

e. Vaccine Delivery

The delivery of vaccines has been transformed by nanotechnology, which enhances immunological response and antigen stability [31]. The incorporation of lipid nanoparticles in mRNA COVID-19 vaccines was a significant advancement that sped up vaccine development by enabling effective distribution and immune activation.

Table 1: Reference Table

Authors	Study	Focus Area	Methodology	Key Findings

Sandhiya and Ubaidulla (2020) [32]	Comprehensive review of herbal drug formulations and pharmaceutical carriers	Herbal drug delivery systems, bioavailability enhancement	Review of various delivery systems (nanoparticles, liposomes, phytosomes), evaluation processes (in vitro and in vivo studies)	Nanotechnology-based carriers improve bioavailability and therapeutic efficacy of herbal drugs by addressing poor solubility and rapid metabolism.
Sarella et al. (2024) [33]	Investigation of aquasomes as a novel drug delivery system	Aquasomes, targeted drug delivery, biocompatibility	Review of aquasome properties, crystalline core structure, drug encapsulation	Aquasomes preserve bioactivity of sensitive biomolecules, offer biocompatibility, controlled release, and higher stability compared to traditional drug carriers, useful in chronic disease treatment.
Sharma et al. (2021) [34]	Applications of nanotechnology in cancer management	Nanotechnology, cancer treatment and diagnostics	Review of nanoparticles, nanocarriers, nanoemulsions, their role in drug targeting and imaging	Nanotechnology improves cancer treatment and diagnostics through precise drug targeting, enhanced imaging, and reduced toxicity, leading to better patient outcomes.
Sim and Wong (2021) [35]	Integration of nanotechnology in imaging and drug delivery	Nanotechnology in imaging, drug delivery	Review of nanoparticles as contrast agents in imaging (MRI, CT scans), drug delivery systems	Nanotechnology improves medical imaging precision and drug formulation efficacy, optimizing treatment outcomes and minimizing side effects.

Sultana et al. (2022) [36]	Review of nano-based drug delivery systems	Nano-based drug delivery, precision medicine	Review of conventional and emerging drug delivery methods, including lipid-based nanocarriers, dendrimers	Nanotechnology enhances drug solubility, stability, and controlled release, with potential to redefine modern pharmacotherapy and improve targeted treatments.

4. INTEGRATION OF HERBAL REMEDIES IN MODERN DRUG DELIVERY APPROACHES

Herbal remedies have been used for millennia to cure a variety of illnesses, but because of developments in pharmaceutical sciences and nanotechnology, their use into contemporary medication delivery methods has drawn a lot of attention. The medicinal value of traditional herbal extracts is usually constrained by their instability, low bioavailability, and variable rates of absorption. To counter these challenges and enhance the efficacy of herbal-based therapies, modern drug delivery methods offer innovative solutions [37].

Polymeric nanoparticles, SLNs, liposomes, and NLCs are some examples of nanotechnology-based delivery systems that are truly milestones in terms of the merger of herbal medicine. The active ingredients in the herbal extracts become more soluble, stable, and targetable thanks to these nanoformulations. For instance, the renowned antioxidant and anti-inflammatory compound curcumin, derived from turmeric, is not absorbed well and is weakly soluble in water. Nevertheless, in several studies, liposomal and polymeric nanoparticle-loaded curcumin revealed enhanced bioavailability and therapeutic effect.

Phytosomes, phospholipid-mediated drug delivery systems with enhanced delivery of poorly water-soluble herbal chemicals, are another technique promising results. The binding between the cell membranes and herbal bioactives is favored by phytosomes, thereby increasing the penetration and efficiency of therapy. It has been largely applied in case of herbal extracts with enhanced pharmacokinetic features when presented in the form of phytosomes, for instance, ginkgo biloba and silymarin from milk thistle.

Microneedle-based transdermal systems and herbal-filled hydrogels are now also gaining recognition as delivery modes, especially in pain management treatments and skin therapy procedures. Both of these diminish the necessity of repeated dosages while enhancing therapeutic benefits of the herbal extracts due to their control and sustained delivery. Herbal-incorporated nanofibers have also been explored for potential use in healing wounds, whereby bioactive plant-derived chemicals promote tissue regeneration with decreased infections [38].

Despite such advances, hurdles such as regulatory clearance, large-scale production, and standardization stand in the way of wide application of herbal-based nanomedicines. Safety issues and potential interactions with synthetic drugs need to be considered, along with ensuring consistency in herbal preparations. But with constant advances in bioengineering and drug delivery technologies, integrating herbal remedies with modern drug delivery methods holds huge promise for developing medicines that are safe, natural, and patient-friendly.

5. DISCUSSION

Improving the bioavailability, stability, and controlled release of herbal chemicals through the combination of nanotechnology with herbal-based drug delivery systems ensures improved therapeutic efficacy and compliance of the patient. Liposomes, nanoparticles, and nanoemulsions are some nano-formulations that significantly improve the pharmacokinetics as well as the solubility of hydrophobic herbal compounds, thereby making them more potent in curing chronic diseases such as diabetes and cancer. The potential of these developments in revolutionizing personalized treatment and conventional medicine is enormous. Scalability, regulatory approval, cost-effectiveness, and safety remain challenges, however [39]. Long-term toxicity, developing sustainable nanocarriers, and AI-driven optimization for ease of clinical translation should be the focus of future studies.

a. Interpret and Analyze the Findings

Among the possible remedies to the issues inherent in traditional herbal formulations is the combination of herbal-based drug delivery systems with nanotechnology. It is indicated from the results that the bioavailability, controlled release, and stability of herbal ingredients are immensely promoted by nano-based carriers such as liposomes, nanoparticles, and nanoemulsions. With the guarantee of more targeted and sustained release of drugs, these nano-formulations ensure better therapeutic efficacy at reduced side effects and increased patient compliance. Furthermore, application of lipid-based and polymeric nanoparticles has proved to ensure enhanced permeability and solubility of hydrophobic herbal components, resulting in improved pharmacokinetic profiles.

b. Discuss Implications and Significance

These results have significant implications for drug research and clinical use. With the delivery of consistent dosage and reproducible pharmacological activity, nanotechnology-formulated herbal remedies with improved stability and bioavailability can potentially transform natural medicine. This innovation is of special significance in the management of chronic conditions like cancer, diabetes, and neurodegenerative disorders, for which herbal remedies have conventionally been utilized but have been hampered by the issue of absorption and metabolism. Additionally, nano-herbal formulation development stems from the call for natural pharmaceuticals, which could be useful in raising the acceptability among patients and diminishing reliance on artificial drugs. Personalized medicine is made possible by the convergence of nanotechnology and herbal medicine, with the latter enabling customized treatment based on individual pharmacokinetics and genetic susceptibility of the patient [40].

c. Highlight Gaps and Suggest Future Research Directions:

Despite such advances, a number of problems are still awaiting resolution. Long-term toxicity and safety of nano-herbal products are among the major areas of research deficiency awaiting extensive in vivo and clinical studies. Scalability and cost-effectiveness of mass production of herbal drugs by nanotechnology are also major hurdles in their widespread adaptation. Standardization of production processes and ensuring regulatory compliance for nano-herbal products need further research. In addition, additional research must be conducted to minimize any immunogenic or cytotoxic effects of nanomaterials' interaction with biological systems. To ensure sustainability, subsequent studies should focus on the development of environmentally friendly and biodegradable nanocarriers. One interesting area of research that simplifies predicting drug behavior and efficacy is the use of artificial intelligence and machine learning in optimizing nano-herbal formulations. For nano-herbal drug delivery systems to move from the research stage to clinical use, all these problems have to be overcome.

6. CONCULSION

The synergism of nanotechnology and herbal medicine in drug delivery is a revolutionary advancement in modern pharmacotherapy, addressing significant concerns such as the irregular therapeutic efficacy of traditional herbal drugs, their huge metabolism, and their poor bioavailability. To enhance solubility, stability, and controlled release of bioactive agents—and consequently their therapeutic efficacy in chronic diseases such as cancer, cardiovascular diseases, neurological disorders, and metabolic disorders—nanocarriers such as liposomes, polymeric nanoparticles, SLNs, dendrimers, and nanoemulsions have played an indispensable role. The nanoformulations enhance the treatment efficacy with minimum systemic toxicity and side effects through targeted delivery of medication at the cellular level. In addition, biocompatibility and sustainability of herbal-based nanoformulations provide a natural and safer alternative to conventional synthetic drugs in favor of increasing the use of plant-based medicine. Yet a series of barriers hinder their full clinical uptake, including prohibitive production costs, scale issues, regulatory challenges, and potential long-term toxicity. The development of cost-effective and biodegradable nanocarriers, rigorous in vivo and clinical trials to ensure safety and efficacy, and AI-based optimization methods for precise medication formulation and delivery should be the primary objectives of future studies in a bid to bridge these limitations. Moreover, exploration of hybrid approaches that leverage the strengths of both nanotechnology-based and herbal systems could revolutionize personalized medicine through the provision of customized treatments according to a patient's individual pharmacokinetics and genetic susceptibility. To develop standardized protocols and facilitate the seamless translation of nano-herbal drug delivery systems from the laboratory to clinical use, interdisciplinary collaborations among pharmacologists, nanotechnologists, and regulatory bodies will be essential as the field evolves. This will ultimately enhance global healthcare outcomes.

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