RESEARCH PAPER

Ayurvedic Medicinal Plants As Novel Drug Delivery Agents: Bridging Traditional Knowledge And Modern Pharmacology

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Abstract

The advancement of drug delivery systems has become a critical focus in pharmaceutical research due to the persistent limitations of conventional dosage forms, including poor bioavailability, low solubility, rapid metabolism, and lack of site-specific targeting. In this context, natural materials derived from medicinal plants have gained significant attention as promising alternatives to synthetic excipients. Ayurvedic medicinal plants, with their rich history of therapeutic use, offer a diverse range of bioactive compounds and functional biomaterials that can be effectively utilized in modern drug delivery systems. This review explores the potential of Ayurvedic medicinal plants as novel drug delivery agents, emphasizing their dual role as both therapeutic entities and formulation excipients. Key categories such as plant-derived polymers, bioenhancers, and lipid-based materials are discussed in relation to their functional applications in enhancing drug solubility, stability, permeability, and controlled release. Traditional Ayurvedic concepts, including *Anupana*, *Yogavahi*, and *Samskara*, are critically analyzed and correlated with modern pharmacokinetic and formulation principles. Furthermore, the review highlights the mechanisms by which plant-based systems improve drug delivery, including bioavailability enhancement, mucoadhesion, permeation modulation, and targeted delivery. The integration of these materials into advanced platforms such as nanoparticle-based and transdermal systems is also examined. Despite challenges related to standardization, variability, and regulatory acceptance, Ayurvedic medicinal plants present a sustainable, biocompatible, and multifunctional approach to drug delivery. Overall, this review underscores the potential of bridging traditional Ayurvedic knowledge with contemporary pharmaceutical technologies to develop innovative and efficient drug delivery systems.

Keywords: Ayurveda; Drug Delivery Systems; Bioenhancers; Phytopolymers; Nanocarriers

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1. Introduction

Development of effective drug delivery systems is among the primary objectives in the field of pharmaceutical science since the efficacy of drugs strongly relies upon pharmacodynamics and pharmacokinetics. The ability of drugs to reach their intended targets within the body, maintain their concentrations at therapeutic levels for a specified time, and remain active is essential in ensuring optimal clinical outcomes. Nevertheless, despite their extensive use, conventional drug delivery systems are typically associated with several constraints, including poor aqueous solubility, inadequate bioavailability, metabolic degradation, lack of targeting capabilities, and undesirable systemic effects. Such constraints not only limit the efficiency of these drugs but also increase the possibility of adverse effects. This has led to an increased demand on the creation of novel drug delivery systems capable of overcoming these obstacles by enhancing drug stability, absorption, and controlled as well as targeted release [1]. The exploration of natural materials as an alternative to synthetic excipients in drug delivery systems has received much focus in the past few years. Of these, medicinal plants have become a very promising resource because of their abundant source of bioactive compounds and functional biomaterials. The Ayurvedic medicinal plants, especially, are very important due to their long history of therapeutic use and well-documented pharmacological properties. One of the oldest traditional systems of medicine, Ayurveda offers a holistic approach to health and disease management, not just in terms of drug formulation, but also includes the notion of drug synergy, bioavailability improvement,

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and individual therapy. The Ayurvedic principles that govern Ayurvedic formulations can be successfully applied to modern drug delivery in the form of innovative solutions to modern-day pharmaceutical problems [2,3].

The combination of modern pharmacology and traditional knowledge has become a trend that can be used as a promising solution to the shortcomings of the traditional methods of drug delivery. Ethnopharmacology provides a key interface in this integration, providing the scientific justification of traditional medicinal use and the discovery of plant-based materials with convenient physicochemical and biological characteristics. The materials are not only able to be used as a therapeutic agent, but also as a carrier, stabilizer, permeation modulator, and bioavailability modulator in a pharmaceutical formulation. This twofold capability contributes greatly to their usefulness in the drug delivery studies and helps with the implementation of a sophisticated therapeutic system design [4].

Traditionally, medicinal plants were mainly studied in terms of their pharmacological properties, but due to the recent developments that occurred in the pharmaceutical sciences, attention has switched towards their applications as functional excipients. Plant-derived resources, which consist of gums, mucilage, resins, lipids, among others, have many varied beneficial characteristics, which include being biocompatible, biodegradable, nontoxic, and capable of controlling the release and permeability of the drug. All these properties render them very appropriate in the creation of new drug delivery systems like controlled-release formulations, mucoadhesive systems, and lipid-based carriers. Moreover, they may be used to enhance the physicochemical stability of drugs, as well as to increase their therapeutic efficacy, which is why these materials can help to overcome multiple limitations related to synthetic excipients [7, 9].

The other significant feature of Ayurvedic herbal plants is that the medicinal plants can improve the efficacy of drugs through synergies. The use of polyherbal preparations, a distinctive feature of Ayurvedic medicine, can show how the interaction of several components of plants can work in a complementary way to enhance therapeutic effects. Such interactions can be pharmacokinetic, increasing the absorption of drugs, stabilizing active constituents, or simultaneously multi-targeting of biological pathways. This is very similar to the current combination therapy and multifunctional drug delivery, in which several drugs are combined into a single preparation with a view to better efficacy and less toxicity [10, 11].

The fast developments in the field of nanotechnology and pharmaceutical sciences have also broadened the range of plant-based materials in drug delivery. The development of plant-mediated nanoparticles and nanoformulations has presented the opportunities to enhance the solubility of the drug, its stability, and targeting efficiency. Some of the advantages of such nano-scale systems include: high drug loading capacity, controlled release profiles and high cellular uptake. Moreover, green synthesis of nanoparticles using plant extracts aids the elimination of toxic chemical reagents, hence making the delivery of drugs through environmentally friendly and biocompatible means. Such developments have assisted in transforming the traditional herbal medicines into scientifically proven therapeutic systems that can be clinically utilized [12, 13].

In spite of all these positive indications, there are several problems that hinder the application of such plant-based drug delivery systems. Among the most serious is the problem with the variability of the plants' structures caused by their geographical origin, cultivation conditions, and processing methods. Additionally, they do not meet some criteria such as standardization, have limited validation and regulation, and therefore, cannot be considered an acceptable solution for mainstream pharmaceutical practice. To overcome these obstacles, there should be created a multilayered approach that can combine the accumulated experience and knowledge together with modern techniques of analysis, formulation, and regulation and help obtain effective solutions with high quality [14, 15].

With regard to that, this review will be a detailed exploration of the utilization of Ayurvedic medicinal plants as new drug delivery systems. This review covers such aspects as the classification of these agents, their mechanisms of actions and applications, thus creating a scientifically grounded model of connection between the traditional philosophy of Ayurveda and modern drug delivery technology.

2. Ayurvedic Concepts that apply to drug delivery.

Ayurveda is a holistic and carefully developed medical system, which focuses not only on the therapeutic effectiveness of medicinal substances but also on how they should be administered, processed, and react in the body. The Ayurvedic pharmacological principles are entrenched in maximizing the effectiveness of drugs by using suitable formulation and delivery techniques. Even though these ideas were developed in a classical setting, they lead to dramatic parallels with the contemporary drug delivery science, especially in the field of bioavailability promotion, formulation development, and synergies. Consequently, the Ayurvedic principles can serve as a useful conceptual model to comprehend and create plant-based drug delivery systems that will conform to modern pharmaceutical methods.

2.1 Anupana (Vehicle Concept)

The term Anupana is used in reference to the simultaneous administration of a drug using a certain vehicle or medium to improve and maximize its therapeutic effect and delivery in the body. The most common substances in Ayurvedic use are Anupana,

which can be milk, honey, ghee, and herbal decoctions, each of which is chosen according to the physicochemical properties of the medication, and the intended effect on the body. Such types of vehicles play a critical role in assessing solubility, absorption, and distribution of drugs, even targeting certain organs. The concept of the use of excipient and carrier in pharmaceutical science in drug delivery system is directly linked to the use of Anupana. For example, lipid vehicles such as ghee can help in solubilization and absorption of drugs through formation of micelle and increase permeability of the intestines. Likewise, aqueous media help in the dissolution and dispersion of hydrophilic compounds. This principle emphasizes the significance of the delivery vehicle in defining drug performance, an essential idea in modern formulation science, especially in lipid-based drug delivery systems and methods of enhancing solubility [16, 17].

2.2 Yogavahi (Bioenhancers)

Yogavahi substances are those that increase the therapeutic effect of the drugs co-administered, but which do not play a significant role in pharmacological effect in their own right. This principle is very similar to the contemporary idea of bioenhancers that are applied to enhance the bioavailability of drugs by affecting physiological and biochemical events that affect drug absorption and metabolism. The action of plant-derived bioenhancers occurs by various mechanisms, such as inhibition of drug-metabolizing enzymes, such as cytochrome P450, regulation of efflux transporters, such as P-glycoprotein, and an increase in membrane permeability. All of these measures decrease drug degradation, enhance systemic availability and enhance the therapeutic effect. Bioenhancers can also modify the membrane fluidity and allow transport of drugs across the cell membranes, which can enhance absorption. Yogavahi is especially relevant in the context of oral drug delivery whereby the efficacy of drugs is often limited by the first-pass metabolism and low permeability. With the incorporation of bioenhancers into formulations, the goal can be met of attaining better pharmacokinetic profiles and lower dosage requirement, which are major targets in drug delivery design today [18, 19].

2.3 Samskara (Processing and Transformation)

Samsakara is the diverse procedures that are used to process medicinal substances to maximize their therapeutic properties and to optimize their delivery properties. These involve grinding, heating, fermentation, purification and amalgamation with other substances all of which may have a considerable effect on the physicochemical properties of the drug. In the modern pharmaceutical analogy, Samskara may be likened to micro-processing and nanoprocessing methods like micronization, nanonization, encapsulation and chemical modification. The reduction of the size of the particle by grinding, as an example, results in a higher surface area of the drug and thus better dissolution and absorption. On the same note, bioactive metabolites that have improved pharmacokinetic properties could be produced through fermentation processes. The Samskara principle highlights that the therapeutic value of a drug does not entirely depend on the properties of the drug but also the manner in which it is processed and formulated. This can be applied considerably in the modern drug delivery systems where the formulation strategies are developed to optimise the drug stability, bioavailability and release profiles [20].

2.4 Synergism of Polyherbal Formulations.

The application of polyherbal preparations is one of the unique characteristics of Ayurvedic medicine as this method presupposes the use of several plant parts in order to attain a great effect. This method is founded on the concept of synergism, whereby the interaction of various constituents produces a net effect that is more than the aggregate of the actions of the constituents. Polyherbal formulations can exhibit synergistic interactions at several levels, which include: pharmacokinetic, pharmacodynamic and physicochemical interactions. Such interactions can increase the absorption of drugs, can increase stability of active compounds, decrease toxicity and allow the ability to target multiple biological pathways simultaneously. This multi-targeted action is especially useful in treating multifactorial and complex diseases, for which mono-drug therapies might not be effective. The latter notion is quite similar to the current combination drug delivery models, in which a number of different agents are included in a single formulation to provide better treatment effects. The applicability of Ayurvedic knowledge in creating efficient and advanced pharmaceutical systems has been emphasized by the incorporation of synergistic principles in designing drug delivery systems [21,22].

A combination of the above Ayurvedic principles, such as Ayurvedic concept of Anupana, Yogavahi, Samskara, and polyherbal synergism, all emphasize the significance of designing formulations, increasing bioavailability, and multi-component interaction as an effort towards maximizing therapeutic effect. When applied using the current principles of pharmaceutical science, these principles offer a solid conceptual foundation to the application of the plant-based materials as functional delivery systems in drug delivery systems. It is on this basis that the categorization of Ayurvedic medicinal plants in a systematic manner on the basis of their roles and functional characteristics when it comes to application as drugs is necessary.

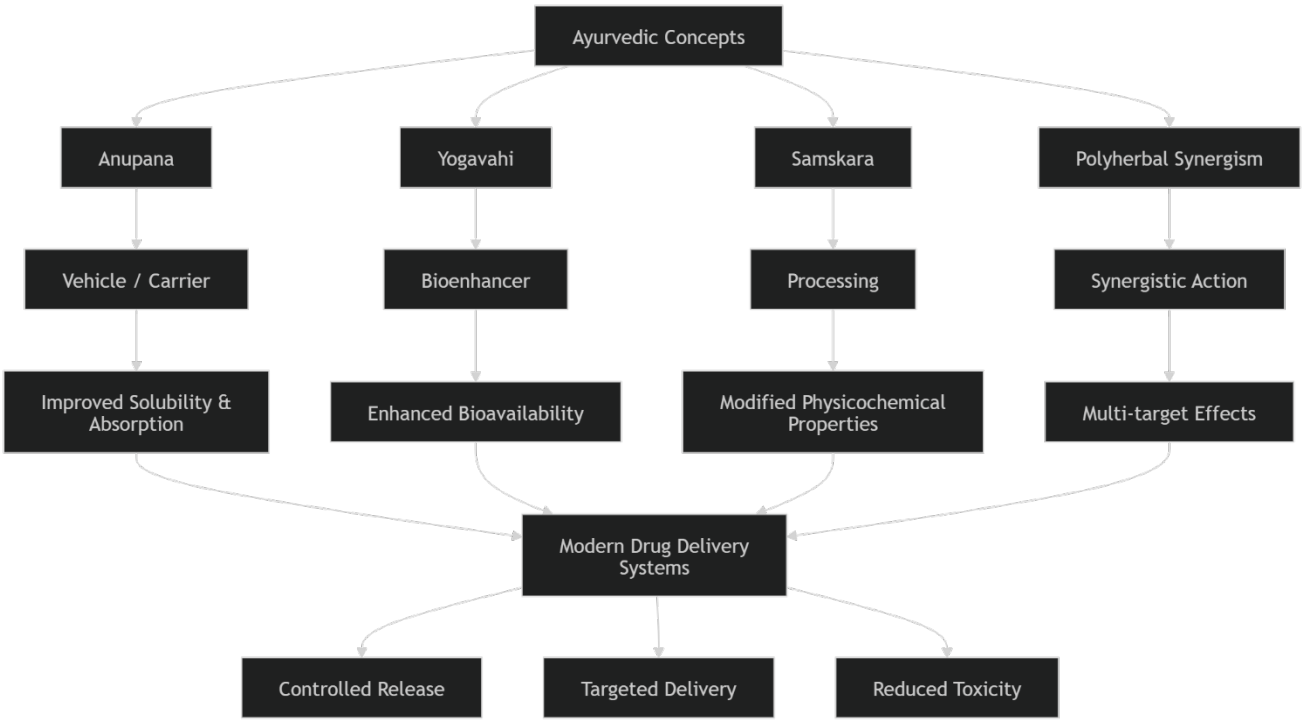

Figure 1. Correlation between Ayurvedic concepts and modern drug delivery principles

3. Classification of Ayurvedic Medicinal Plants in Drug Delivery

Ayurvedic medicinal plants have a great variety of physicochemical and biological characteristics that precondition their high applicability to the modern drug delivery systems. Not only do these plants have potential as bioactive compounds, but they can also be used as functional excipients which can affect the release, stability, and absorption of drugs. Plant-derived polymers and bioenhancers, and lipid-based materials are the two types of ayurvedic medicinal plants which can be classified according to their functions in pharmaceutical preparations. This classification system gives them a systematic framework on how they function in the process of drug delivery and drug improvement. The biggest category under this type of classification is that of natural plant derived polymers. They are natural substances such as gums, mucilage, resins, and polysaccharides that are widely used as they are biocompatible, biodegradable, and non-toxic. A hydrophilic polysaccharide, mucilage, demonstrates outstanding swellability upon coming into contact with aqueous conditions, which generates gel-like matrices that control the release of drugs. This swelling process enables it to deliver drugs long-term in a controlled manner by controlling diffusion and polymer erosion and maintaining the levels of drugs in the circulatory system [23, 24]. Equally, gums found in plants are emulsifying, suspending and stabilizing agents in pharmaceutical preparations. Increased viscosity and formation of protective matrices add to their capacity to increase the stability of the formulation as well as controlled drug release. These materials are especially applicable in the drug delivery systems that are based on a matrix, where they can control the diffusion of drug by controlling the water diffusion and the swelling of the polymer. The latest trends in pharmaceutical technology have also delved further into trying to alter the natural gum to improve its mechanical properties and drug release properties, thus increasing its uses in sophisticated delivery systems [25, 26]. Plant resins and polysaccharides are also important in drug delivery as they possess structural film-forming and encapsulating abilities. The materials find extensive application in coating technologies to prevent environmental degradation of drugs, such as oxidation and exposure to moisture. Polysaccharides, especially, have been noted to be used as drug delivery systems of nanotechnology as a stabilizing and targeting agent. Their ability to interact with the biological membranes helps it to be absorbed better and targeted thus they are of great importance in contemporary pharmaceutical preparations [27, 28]. Another significant group of plant-derived components that considerably enhance the drug bioavailability is bioenhancers. The action of these compounds is through the alteration of physiological mechanisms of drug absorption and metabolism. Bioenhancers increase drug absorption and extend the systemic circulation by inhibiting metabolic enzymes and efflux transporters. It is especially useful when dealing with drugs that cannot be readily absorbed into the body, and that the property of the drug can be used to achieve better therapeutic effects and lower dosage levels [29, 30]. Plant materials that are lipid-based are a key ingredient in modern drug delivery system particularly to drugs that are not well soluble in water. Fixed oils and fatty acids are plant-derived lipids that increase drug solubility by creating emulsions and

micellar structures which improve its dissolution and absorption in the gastrointestinal tract. These systems are also beneficial to the lymphatic transport and enable drugs to bypass hepatic first-pass metabolism and become more accessible to the systemic circulation. Natural lipids usage goes in line with the increasing interest in sustainable and biocompatible pharmaceutical formulations [31, 32].

Their versatility and flexibility are emphasized by the fact that the plant-derived polymers are combined with the bioenhancers and lipids into the drug delivery system. Through the synthesis of these materials, progressing to higher delivery platforms that can solve multiple pharmacokinetic problems can be achieved. The progress in nanotechnology and phytopharmaceutical engineering has also led to an increased use of such materials, allowing to create innovative formulations, with better stability, targeting efficacy, and therapeutic performance [33, 34].

Table 1. Ayurvedic medicinal plants and their functional roles in drug delivery

Plant / Plant-derived material	Major functional component	Drug delivery role	Pharmaceutical significance	References
Piper nigrum	Piperine	Bioenhancer	Enhances drug absorption and reduces metabolism	[3,10,18]
Zingiber officinale	Gingerols, shogaols	Permeation enhancer	Improves gastrointestinal absorption	[18,23]
Curcuma longa	Curcumin	Carrier-compatible phytoconstituent	Useful in nanoformulations	[29,33]
Aloe vera	Mucilage, polysaccharides	Polymer / gel-forming agent	Sustained release and mucoadhesion	[24,41]
Plant gums and mucilage	Polysaccharides	Matrix former / stabilizer	Controlled drug release systems	[23,30]
Plant-derived oils	Fatty acids	Lipid vehicle	Improves solubility of hydrophobic drugs	[33,47]
Polyherbal formulations	Multiple phytoconstituents	Synergistic system	Enhances bioavailability and multi-target action	[18,41,47]

4. Mechanisms of Action in Drug Delivery

Ayurvedic medicinal plants have been found to have a significant role in the drug delivery system through the ability to regulate the important pharmacokinetic processes such as drug absorption, distribution, metabolism and elimination. These delivery systems act on molecular and cellular levels, which allows better therapeutic results due to increased bioavailability, controlled release, and specific delivery.

Among the key mechanisms, there is an increase in the bioavailability of the drugs. Bioenhancers made of plants may suppress drug-metabolizing enzymes, e.g., cytochrome P450 isoforms, and, therefore, reduce first-pass metabolism and elevate systemic drug concentration. Also, these substances regulate efflux transporters like P-glycoproteins that are involved in restricting drug uptake by actively conveying drugs out of the intestinal cells. Plant-based systems promote increased intracellular accumulation of drugs and enhance absorption by inhibition of these transporters [35, 36].

The other mechanism is also the enhancement of drug solubility and dissolution. Lots of lipids and surfactant-like compounds of vegetable origin improve the dispersion of the drug, creating micellar structures, thereby increasing the availability of surfaces to be absorbed. It is especially helpful in the case of hydrophobic drugs, where dissolution may be the rate-limiting step of absorption. Enhanced solubility helps in improved pharmacokinetics and therapeutic effects.

The other important mechanism that is promoted by plant-derived polymers is controlled and sustained drug release. These materials create hydrophilic matrices that swell when in contact with biological fluids to create a gel barrier to control diffusion of drugs. Diffusion, swelling and erosion processes control the release of drugs through such systems and make sure that the drugs act long and reduce the frequency of dosing. This controlled release property decreases fluctuation of plasma drug concentration and enhances adherence by the patients [37, 38].

Mucoadhesion and enhancement of permeation are also important properties in drug delivery enhancement. Plant-based polymers are highly mucoadhesive and so the formulations of drugs will stick to the mucosal surfaces and increase the residence time at the absorption site. This augmented contact improves drug uptake owing to the fact that the concentration gradient is maintained. Moreover, such materials have the potential to modify the epithelial barrier activity, promoting drug delivery across biological barriers.

Another mechanism of importance that can be facilitated by plant-based systems is targeted drug delivery. Passive targeting mechanisms like the enhanced permeability and retention effect, can be used to accumulate nanoparticles made out of plant materials in diseased tissues. Moreover, carriers that are based on plants can be functionalized to attain active targeting, thus enhancing the specificity of the drug and decreasing off-target effects. This method is specifically

useful in the treatment of some diseases like cancer, where specific delivery is crucial in maximizing the therapeutic effect whilst reducing the toxicity [39, 40].

Green nanotechnology has also been integrated with Ayurvedic medicinal plants, which has increased the field of drug delivery mechanism. Plant-mediated nanoparticles synthesis involves the use of phytoconstituents as reducing and stabilising agents, which leads to the production of environmentally friendly and biocompatible nanocarriers. Such nanoparticles are more stable, have a higher drug loading capability and targeted efficacy which makes them very useful in advanced pharmaceutical applications [41, 42].

Polypherbal formulations have synergistic mechanisms that also play an important role in drug delivery. Some of the components of plants can be combined with one another to facilitate drug uptake, stabilize active components and enhance pharmacokinetic properties. The multi-component therapy allows simultaneous control of a variety of pathways, and this approach results in an improved response to therapy. These synergies are similar to current-day strategies of combination drug delivery, in which several agents are employed to gain increased efficacy [43, 44].

Table 2. Mechanisms involved in drug-delivery enhancement

Mechanism	How it works	Drug delivery outcome	Ayurvedic relevance	References
Enzyme inhibition	Inhibits CYP450 enzymes	Reduces first-pass metabolism	Yogavahi concept	[16,19]
Efflux transporter modulation	Inhibits P-glycoprotein	Improves absorption	Oral drug delivery	[18,35]
Permeation enhancement	Alters membrane integrity	Enhances drug transport	Transdermal/oral delivery	[25,36]
Mucoadhesion	Adhesion to mucosal surfaces	Increased residence time	GI and buccal delivery	[23,34]
Matrix swelling	Polymer hydration and gel formation	Sustained drug release	Mucilage-based systems	[30,38]
Lipid solubilization	Micelle/emulsion formation	Improved solubility	Lipid-based DDS	[33,37]
Nanocarrier targeting	Plant-mediated nanoparticle synthesis	Targeted delivery	Nanoherbal systems	[34,46]

5. Applications in Drug Delivery Systems

The use of Ayurvedic medicinal plants in drug delivery systems has greatly increased over the past years due to their multifunctional characteristics and integration with the modern pharmaceutical technologies. These biomaterials of plant origin are currently used extensively within different delivery systems, such as oral, transdermal, nanoparticle-based, and targeted drug delivery systems. They are especially useful in overcoming the drawbacks of the traditional formulations by their capacity to improve the solubility of drugs, their stability, and bioavailability.

The most commonly used method of drug delivery is the oral drug delivery systems, as it is the most convenient method of administration and is also patient compliant. Nevertheless, issues with drug solubility and first-pass metabolism frequently limit the efficacy of drugs. Trying to achieve oral polymers that are of plant origin such as mucilage and gums, have been successfully incorporated in oral preparations to achieve controlled and prolonged drug delivery. These substances are hydrophilic matrices which control the dissolution and absorption of drugs and thus enhance therapeutic efficacy. Moreover, bioenhancers based on plants will enhance the absorption rates, and reduce the metabolic breakdown resulting in an elevation of systemic drug concentration.

Utilizing Ayurvedic medicinal plants in transdermal drug delivery system has also been found to be very advantageous. The skin is a formidable obstacle to entry of drugs; in fact phytoconstituents of medicinal plants can be used as natural permeation enhancers. The combination of these compounds with the lipid structure of the stratum corneum is what causes the skin to be more permeable and transfer drugs across the skin. Also, polymers derived out of plants have a good film-forming and adhesive property, which is why they can be used to create transdermal patches and gels [45].

One of the most promising uses of plant-derived materials is the nanoparticle-based drug delivery systems. Green synthesis of nanoparticles using plant extracts has facilitated the creation of biocompatible and eco-friendly nanocarrier. These nanoparticles have a high drug loading capacity, increased stability and better targeting efficiency. They are easier to get into the cell due to their nanoscale size, and drugs can be delivered efficiently to particular tissues. These systems have been especially promising in the delivery of anticancer and antimicrobial agents, where specific and efficient delivery of drugs is essential to enhance therapeutic effects [46, 47].

The targeted drug delivery systems also show the possibility of Ayurvedic medicinal plants in contemporary therapeutics. Plant-based nanocarriers can also take advantage of the physiological features,

including increased permeability and retention of tumor tissues, to passively target them. Moreover, phytoconstituents are applicable to the functionalization of drug carriers to enable active targeting and enhance drug specificity and minimized off-target effects. Plant-based systems have been incorporated into specific delivery systems that have greatly enhanced the treatment of complicated illnesses like cancer and chronic inflammatory conditions [48].

All in all, the use of Ayurvedic medicinal plants in drug delivery systems shows that they are versatile and can be used to improve therapeutic performance. Their incorporation with the latest technologies remains to stimulate the research and development of pharmaceutical products.

Table 3. Applications of Ayurvedic plant-based materials in drug delivery systems

Drug delivery system	Role of plant-based material	Advantage	Application area	References
Oral drug delivery	Polymer matrix, bioenhancer	Improved bioavailability	Chronic therapy	[3,10,18]
Transdermal delivery	Permeation enhancer, film former	Better skin penetration	Long-term therapy	[11,42]
Nanoparticle systems	Stabilizer and reducing agent	Enhanced targeting and stability	Cancer therapy	[33,46]
Lipid-based systems	Oil carrier	Improved solubility	Poorly soluble drugs	[37,39]
Polyherbal systems	Multi-component synergy	Multi-target action	Complex diseases	[2,18]
Targeted delivery	Functionalized carriers	Reduced toxicity	Oncology	[44,45]
Green nanotechnology	Plant-mediated nanoparticle synthesis	Sustainable DDS	Advanced formulations	[46,47]

6. Comparative Advantages Over Synthetic Systems

Ayurvedic medicinal plants in the delivery of drugs have a number of benefits over traditional synthetic compounds and are becoming more popular in new pharmaceutical uses. These natural materials are unique in their physicochemical and biological properties that allow them to be utilized as effective carriers, excipients, and bioavailability enhancers. The fact that they are compatible with biological systems and they have multifunctional properties helps enhance safety and efficiency of drug delivery systems.

Among the most remarkable benefits, their natural biocompatibility should be considered, which reduces the likelihood of toxicity and the development of adverse immune responses to the minimum. In contrast to most synthetic polymers, which can cause irritation or immunogenicity, biomass-derived materials are generally harmless and the biological systems are more accustomed to them. This guarantees safer delivery of drugs especially in chronic therapies and delicate patients. The reduced possibility of adverse effects is also beneficial in enhancing patient compliance and in formulating patient friendly formulations.

Another desirable trait of plant-based materials is biodegradability. Naturally, these materials are decomposed in the body into non-toxic products and, therefore, there are minimal chances of their accumulation and the development of chronic toxicity. The property is especially useful in controlled-release and implantable drug delivery systems, whose gradual degradation of the carrier material is vital to a long-term release of the drug, and the safe elimination of the material out of the body. The foreseeable degradation characteristics of these materials also make them even more compatible in high-technology pharmaceutical preparations.

Plant-derived materials are cheap and of high availability in addition to having a good safety profile. Their natural occurrence is sufficient and their extraction and processing is not highly complex thus can be economically viable in bulk quantities. This is handy particularly in developing and resource limited regions where cost effective and resourceful health solutions are of utmost importance. Such materials can greatly decrease the cost of production without compromising the therapeutic activity.

Sustainability of the environment through the use of natural delivery systems is another factor that makes sustainability much more attractive in such cases. The usage of renewable sources and green technologies in this respect is related to the concept of green chemistry, making the impact of the drug production on the environment negligible. The aspect is even more relevant from the perspective of sustainable development and environmentally friendly healthcare activities [49]. Moreover, plant products tend to have more than one purpose in one formula. Therefore, plant materials can act as stabilizers, bioenhancers, carriers and emulsifying agents, eliminating the necessity to use synthetic additives. This aspect is not only more convenient in the sense that fewer components will have to be incorporated, but also more efficient and stable for the formula as a whole.

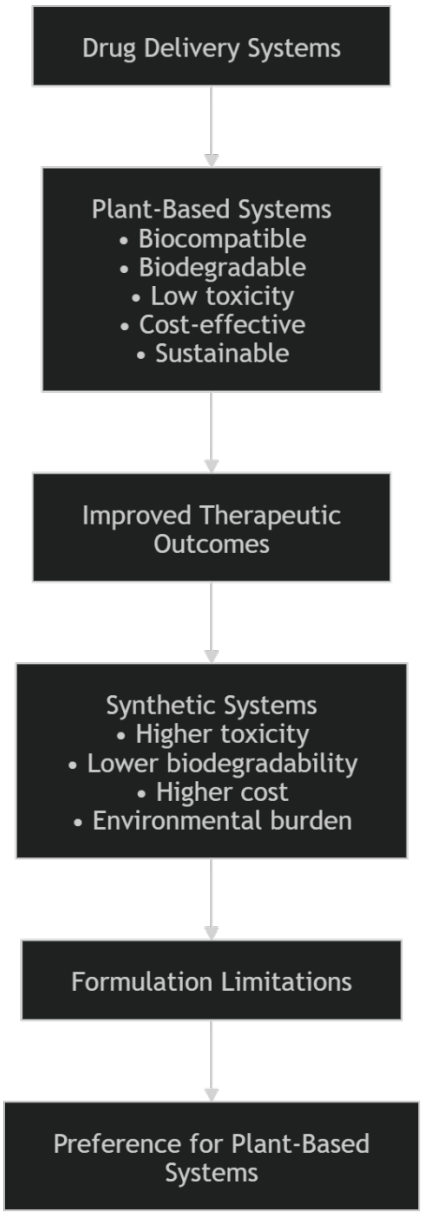

Figure 2. Comparative advantages of plant-based and synthetic drug delivery systems

7. Challenges and Limitations

While medicinal herbs used in Ayurvedic medicine possess a plethora of advantages, there are certain issues that should be overcome in order to facilitate the incorporation of such plants into pharmaceuticals; hence, a thorough investigation of these problems is imperative for the success of transferring the technology to the clinical setting. Although these plant-based systems show a high therapeutic potential, their application in the development of modern medicines is limited by scientific, technological, and regulatory factors.

The absence of standardization of plant-derived materials can be considered to be one of the main issues. Compositional variability is inherent in medicinal plants and depends on factors like geographical origin, climatic conditions, soil characteristics, harvesting time, and post-harvest processing methods. This inconsistency results in the variability of the concentration of active constituents, thus influencing the reproducibility, quality, and therapy reliability of drug delivery systems. This is one of the significant drawbacks of obtaining uniformity, which is a paramount condition of pharmaceutical development and a regulatory license.

The variability between batches also makes the formulation development more complicated since variations in extraction mechanisms, processing parameters, and storage can change the physicochemical characteristics of plant-derived ingredients. These differences can affect the kinetics of drug release, stability, and the overall therapeutic performance. In this respect, standard extraction processes, analytical techniques that have already been tried and true, and quality controls must be instituted. Complex analytical techniques like those involving chromatography and spectroscopy are vital for the purposes of ensuring accuracy and consistency.

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The second limitation that comes into account is that there has been no extensive clinical validation. There have been many in vitro and preclinical experiments showing the capability of such drug delivery systems using plants. However, the clinical studies are poorly designed. The reason for this problem is that it provides very limited clinical data and therefore one cannot rely on it in evidence-based medicine. Furthermore, because of the aforementioned factor, it also cannot be used on a mass level. Therefore, there is a need to do systematic clinical studies for closing this gap.

Another major challenge to the introduction of Ayurvedic medicinal plants in the modern pharmaceutical system is regulatory problems. The absence of clearly defined and internationally harmonized regulatory measures to provide herbal drugs gives rise to uncertainties in approvals and delays commercialization. In addition, it is difficult to be accepted in the entire globe due to the discrepancies in the rules and regulations in various regions. Standardized guidelines have to be established on quality, safety and efficacy assessment to facilitate easier approval of the regulations and translating it to industry.

Further, the issue of stability as well as scalability is also a significant concern. Plant materials can also be vulnerable to environmental factors such as temperatures, light, moisture and oxidizing factors that may lead to degradation of the active constituents and loss of stability of the formulations. This can adversely affect shelf life and efficacy of treatment. Moreover, finding a way of translating laboratory into industrial production without losing quality and quantity and simultaneously making it cost-effective is a significant issue in pharmaceutical production.

The solutions for these limitations would require a multi-disciplinary strategy that integrates both the Ayurvedic practice and the contemporary science approaches, including the advanced formulation practices, analytical methods, and regulatory science. It is imperative that all relevant stakeholders, including the industry, research institutions, and regulatory authorities, collaborate in ensuring that standardization and innovation become possible. Future research and technological development would likely contribute substantially to resolving these challenges and even exploiting Ayurvedic medicinal plants as a novel drug delivery system [50].

8. Conclusion

Ayurvedic medicinal plants are a precious and not yet well-explored source of drug delivery systems, which combine the ancient wisdom with the present-day pharmaceutical medicine. Their different physicochemical and biological properties enable them to perform more than the therapeutic role of functional excipients, bioenhancers and carriers that can considerably improve the performance of the drug delivery.

Combining polymers of plant-based sources, bioenhancers, and lipid-based materials into pharmaceutical formulations has shown a significant potential in overcoming significant issues with traditional drug delivery systems, such as low solubility, low bioavailability, and targeted delivery. In addition, the incorporation of these materials in superior delivery systems particularly nanotechnology-based systems has been capable of enhancing drug stability, release and site-specific targeting, which enhanced the overall therapeutic effects. The Ayurvedic medicinal plants are not only multifunctional and synergistic but also have unique combinations of synergies that may be used to design sophisticated yet efficient drug delivery systems. The Ayurvedic drugs and the principles underlying their usage in the context of conventional pharmacological practices provide an excellent starting point and direction for developing a novel and patient-oriented therapy.

Even though there are many advantages associated with Ayurvedic medicines, standardization, reproducibility, clinical validation, and acceptance in the regulatory bodies regarding their widespread utilization remain as major problems. To overcome these drawbacks, a multi-disciplinary strategy involving optimization of analytical methods, formulating techniques, and regulation of standards is required. In summary, the rational utilization of the Ayurvedic medicinal plants as components of the contemporary drug delivery systems holds immense potential in generating safer, effective, and sustainable medicinal products. It is hoped that further research in this field will contribute to the integration of traditional medicine and modern pharmacology, giving rise to the drug delivery system of the future generation.

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