**RESEARCH PAPER**

# Modern Drug Delivery Strategies for Traditional Ayurvedic Medicines: A Review

Dr. Meenu Srivastava Khare[1], Dr. Akanksha Chandel[2], Dr. Ranjeet Sawant[3], Dr. Reena S Yadav[4] and Dr. Amit Nampalliwar[5]

*[1]Professor & HOD, Department of Rachana Sharir (Anatomy), Sri NPA Government Ayurveda college Raipur-492010 Chhattisgarh, India, Pt. Deendayal Upadhyay Memorial Health Science and Ayush University of Chhattisgarh, Raipur, Chhattisgarh, India.*

*[2]Reader, Department of Prasuti Tantra and Streeroga (Gynaecology & Obstetrics) Government Ayurved College & Hospital, Bilaspur-495001 Chhattisgarh, Pt. Deendayal Upadhyay Memorial Health Science and Ayush University of Chhattisgarh, Raipur, Chhattisgarh, India.*

*[3]Associate Professor and HOD, Department of Rasashastra and Bhaishajya Kalpana (Pharmaceutics and Clinical Pharmacy), K. G. Mittal Ayurved College, Mumbai-400002, India, Maharashtra University of Health Sciences, Nashik*

*[4]Associate Professor, Department of Rasashastra and Bhaishajya Kalpana (Pharmaceutics and Clinical Pharmacy), Shree Saptashrungi Ayurved College, Nashik-422003, India, Maharashtra University of Health Sciences, Nashik*

*[5]Associate Professor & HOD, Department of Roga Nidan & Vikriti Vigyana (Pathology), Government Ayurved College & Hospital, Bilaspur-495001(C.G.), India, Pt. Deendayal Upadhyay Memorial Health Science and Ayush University of Chhattisgarh, Raipur, Chhattisgarh, India*

*[1]Orchid id: 0009-0002-2857-3946, [2]Orcid Id: 0000-0001-7838-2924, [3]Orcid Id: 0000-0003-4249-1488, [4]Orcid Id: 0009-0003-5997-2170 and [5]Orcid Id: 0000-0002-6587-5735*

*Corresponding Author: Ranjeet Sawant, drranjeet.sawant@gmail.com*

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## 1. ABSTRACT

Ayurvedic formulations have been widely utilized for their therapeutic potential; however, their clinical effectiveness is often limited by poor solubility, instability, low bioavailability, and lack of controlled drug delivery. Modern drug delivery systems (MDDS) offer advanced formulation strategies to overcome these limitations and enhance the pharmaceutical performance of herbal medicines. This review focuses on the design, development, and evaluation of novel delivery systems, including polymeric nanoparticles, solid lipid nanoparticles, liposomes, phytosomes, and controlled release carriers for Ayurvedic formulations. Particular emphasis is placed on formulation techniques, physicochemical characterization, encapsulation efficiency, and drug release kinetics. In addition, green synthesis approaches for developing biocompatible and eco-friendly nanocarriers are discussed. These advanced systems significantly improve stability, absorption, and targeted delivery of phytoconstituents, thereby enhancing their pharmacokinetic profile. Despite these advancements, challenges such as large-scale manufacturing, reproducibility, and regulatory compliance remain critical. Overall, this review provides a formulation-oriented perspective on the application of modern drug delivery technologies for improving the efficiency and global acceptability of Ayurvedic therapeutics.

**Keywords**: *Ayurvedic formulations; Novel drug delivery systems; Nanotechnology; Polymeric nanoparticles; Solid lipid nanoparticles; Liposomes; Phytosomes; Controlled drug release; Bioavailability enhancement; Herbal nanocarriers*

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## 2. INTRODUCTION

The advancement of pharmaceutical sciences has highlighted the critical role of efficient drug delivery systems in enhancing the therapeutic performance of medicinal agents. Drug delivery not only influences the bioavailability of active compounds but also determines their stability, release behavior, and overall clinical effectiveness. Traditional Ayurvedic formulations, despite their long history of use and therapeutic benefits, often face several pharmaceutical challenges. These include poor aqueous solubility, instability of active phytoconstituents, variability in drug release, and lack of site-specific delivery. Such limitations significantly reduce the bioavailability and therapeutic efficiency of herbal drugs, thereby restricting their broader application in modern healthcare systems. Ayurvedic medicines are primarily composed of complex mixtures of bioactive compounds derived from plant, mineral, and natural sources. While these compounds exhibit significant pharmacological potential, their effectiveness is often compromised due to poor absorption, rapid metabolism, and degradation under physiological conditions. In

**Author for Correspondence: drranjeet.sawant@gmail.com*

addition, conventional dosage forms such as churna, kwatha, and ghrita lack controlled drug release mechanisms, leading to inconsistent therapeutic outcomes. These challenges necessitate the development of advanced drug delivery approaches that can enhance the performance of Ayurvedic formulations. Modern drug delivery systems (MDDS) have emerged as promising solutions to overcome these limitations by improving solubility, stability, and targeted delivery of therapeutic agents. Recent advancements in nanotechnology and carrier-based systems have enabled the incorporation of herbal drugs into novel delivery platforms such as polymeric nanoparticles, solid lipid nanoparticles, liposomes, and phytosomes. These systems enhance drug dissolution, protect bioactive compounds from degradation, and enable controlled and sustained release. Furthermore, advanced delivery systems improve pharmacokinetic properties, including absorption, distribution, and retention of herbal compounds, thereby increasing their therapeutic efficacy. The integration of modern formulation strategies with traditional Ayurvedic medicines represents a significant step toward bridging the gap between conventional herbal practices and contemporary pharmaceutical science. This approach not only enhances drug delivery efficiency but also contributes to the development of more standardized, reliable, and globally acceptable Ayurvedic therapeutics.

## 3. LITERATURE REVIEW

Recent advancements in pharmaceutical research have increasingly emphasized formulation-driven strategies for optimizing herbal drug delivery systems. Traditional Ayurvedic formulations, although therapeutically effective, often exhibit limitations such as poor solubility, instability, and inadequate bioavailability. To address these challenges, researchers have explored various novel drug delivery systems (NDDS) aimed at improving the physicochemical and pharmacokinetic properties of phytoconstituents (Devi et al., 2010; Bonifácio et al., 2014). Nanotechnology-based delivery systems have gained significant attention due to their ability to enhance drug solubility, stability, and controlled release. Polymeric nanoparticles, solid lipid nanoparticles, and nanoemulsions have been extensively investigated for encapsulating herbal compounds, thereby protecting them from degradation and improving their bioavailability (Bonifácio et al., 2014). These nanoscale systems also facilitate improved cellular uptake and targeted delivery, making them highly suitable for poorly absorbed phytoconstituents. Furthermore, the physicochemical properties of nanoparticles, including particle size and surface charge, play a crucial role in determining stability and drug release behavior (Honary & Zahir, 2013). Liposomal drug delivery systems represent another important advancement in this field. Liposomes, composed of phospholipid bilayers, are capable of encapsulating both hydrophilic and lipophilic compounds, thereby enhancing drug stability and therapeutic efficiency (Allen & Cullis, 2013; Gregoriadis, 2007). Similarly, phytosome technology has emerged as a promising approach for improving the bioavailability of herbal compounds through phospholipid complexation, which enhances membrane permeability and absorption (Kidd & Head, 2005; Barani et al., 2021). Several studies have also focused on specific phytoconstituents such as curcumin, which is known for its wide range of pharmacological activities but suffers from poor bioavailability. Advanced nanoformulations of curcumin have demonstrated improved stability, enhanced absorption, and controlled release, thereby significantly improving its therapeutic potential (Anand et al., 2007; Yallapu et al., 2012; Gupta et al., 2013). Similarly, herbal compounds such as ashwagandha have been investigated for their enhanced delivery using nanocarriers (Singh et al., 2011). In addition to synthetic approaches, green synthesis of nanoparticles using plant extracts has emerged as an eco-friendly and sustainable alternative. These methods utilize natural reducing agents and offer advantages such as reduced toxicity and improved biocompatibility (Ahmed et al., 2016). Emerging technologies, including artificial intelligence, are also being explored to optimize drug delivery system design and formulation parameters (Mak & Pichika, 2019). Overall, existing literature highlights that formulation-oriented approaches, focusing on encapsulation efficiency, particle stability, and controlled release mechanisms, play a critical role in enhancing the performance of Ayurvedic drug delivery systems.

## 4. FORMULATION & DELIVERY MECHANISMS

Modern drug delivery systems (MDDS) applied to Ayurvedic formulations are primarily designed to enhance the physicochemical stability, solubility, and pharmacokinetic behavior of herbal compounds. Conventional herbal formulations often suffer from poor absorption and rapid degradation, which can be effectively addressed through advanced carrier-based systems (Devi et al., 2010). Among these, nanoparticle-based delivery systems have gained considerable attention due to their ability to reduce particle size to the nanoscale, thereby increasing surface area and improving dissolution rate. Polymeric nanoparticles, commonly prepared using biodegradable polymers such as PLGA and chitosan, enable controlled drug release through diffusion and matrix degradation mechanisms (Bonifácio et al., 2014). Similarly, solid lipid nanoparticles (SLNs) offer enhanced stability and biocompatibility, particularly for lipophilic phytoconstituents. Liposomal drug delivery systems represent another significant advancement in herbal drug formulation. Liposomes are phospholipid-based vesicles capable of encapsulating both hydrophilic and lipophilic compounds, thereby improving drug stability and reducing toxicity (Allen & Cullis, 2013; Gregoriadis, 2007). In addition, phytosome technology has been developed to enhance the bioavailability of herbal compounds through the formation of phospholipid complexes, which improve membrane permeability and absorption of phytoconstituents (Kidd & Head, 2005; Barani et al., 2021). Various formulation techniques play a crucial role in the development of these delivery systems. Methods such as solvent evaporation, nanoprecipitation, and high-

pressure homogenization are widely employed to produce nanoparticles with desired characteristics. These techniques influence critical formulation parameters, including particle size, surface charge, and drug encapsulation efficiency. Particle size and zeta potential are particularly important as they determine stability, cellular uptake, and release behavior of the formulation (Honary & Zahir, 2013). Furthermore, drug loading capacity and encapsulation efficiency are key indicators of formulation performance, as they directly impact therapeutic effectiveness and dosing requirements. The optimization of these parameters ensures improved stability, controlled release, and enhanced bioavailability of herbal drugs. Overall, formulation and delivery mechanisms play a central role in transforming traditional Ayurvedic medicines into more efficient and scientifically validated therapeutic systems.

**Comparison of Modern Drug Delivery Systems Used in Ayurvedic Formulations**

| Delivery System | Key Features | Advantages | Limitations | Examples |
|---|---|---|---|---|
| Nanoparticles | Nano size carriers | Improved bioavailability | Stability issues | Curcumin |
| Liposomes | Phospholipid vesicles | Biocompatible | Expensive | Herbal extracts |
| Phytosomes | Phospholipid complex | Better absorption | Limited stability | Flavonoids |
| SLNs | Lipid-based carriers | Controlled release | Low drug loading | Lipophilic drugs |
| Dendrimers | Branched polymers | Targeted delivery | Toxicity concern | Herbal actives |

## 5. NEED FOR MODERNIZATION IN AYURVEDIC DRUG DELIVERY

The increasing global demand for Ayurvedic medicine has emphasized the necessity to modernize its drug delivery systems in order to meet contemporary pharmaceutical, regulatory, and therapeutic standards. Although traditional formulations have demonstrated long-standing clinical benefits, their integration into modern healthcare systems requires scientific validation, formulation standardization, and technological advancement. The incorporation of modern drug delivery approaches offers significant potential to overcome inherent physicochemical limitations and improve the overall performance of herbal therapeutics (Devi et al., 2010; Bonifácio et al., 2014).

### 5.1 Scientific Validation Requirements

One of the primary challenges in Ayurvedic medicine is the lack of robust scientific validation in terms of safety, efficacy, and mechanism of action. Traditional formulations are largely based on empirical knowledge and historical usage rather than evidence derived from controlled experimental studies. Modern pharmaceutical research requires systematic validation through in vitro, in vivo, and clinical studies, along with pharmacokinetic and pharmacodynamic profiling. The absence of such data limits the acceptance of Ayurvedic medicines in evidence-based practice. For example, widely used phytoconstituents such as curcumin have demonstrated significant pharmacological potential but require advanced delivery systems and clinical validation to improve their bioavailability and therapeutic consistency (Anand et al., 2007; Gupta et al., 2013).

### 5.2 Standardization and Quality Control Issues

Standardization remains a critical concern due to the complexity of polyherbal formulations and variability in raw materials. Factors such as geographical origin, cultivation conditions, harvesting time, and processing methods significantly influence the quality and consistency of herbal products. The lack of uniform quality control parameters leads to batch-to-batch variation, affecting safety and efficacy. Modern analytical techniques such as high-performance liquid chromatography (HPLC), spectroscopy, and chromatographic fingerprinting are increasingly employed to ensure quality, purity, and reproducibility of formulations (Bonifácio et al., 2014). Establishing standardized protocols is essential for maintaining consistency and regulatory compliance.

### 5.3 Enhancing Formulation Performance

Traditional Ayurvedic dosage forms often exhibit limitations such as poor solubility, instability, and lack of controlled drug release. These issues can be effectively addressed using modern drug delivery systems, including nanoparticles, liposomes, and phytosomes, which enhance solubility, protect bioactive compounds, and enable controlled release (Allen & Cullis, 2013; Barani et al., 2021). Nanotechnology-based systems improve drug dissolution, permeability, and retention of phytoconstituents, thereby enhancing pharmacokinetic behavior (Bonifácio et al., 2014). Additionally, advanced nanocarriers such as dendrimers offer high drug-loading capacity and precise targeting capabilities, further improving formulation efficiency (Chauhan, 2018).

### 5.4 Regulatory and Commercialization Challenges

Despite increasing global interest, Ayurvedic medicines face several regulatory and commercialization barriers. Variability in international regulatory frameworks for herbal products creates challenges in approval and market access. The lack of standardized guidelines for safety, efficacy, and quality further complicates regulatory processes. In addition, inadequate clinical data, poor documentation, and limited intellectual property protection hinder commercialization efforts. The development of eco-friendly and standardized production techniques, such as green synthesis of nanoparticles, may support regulatory acceptance and sustainability (Ahmed et al., 2016). Aligning Ayurvedic drug development with international regulatory standards is essential for global acceptance and commercialization.

## 6. MODERN DRUG DELIVERY SYSTEMS APPLIED TO AYURVEDA

Modern drug delivery systems (MDDS) have emerged as effective strategies for improving the performance of Ayurvedic formulations by enhancing solubility, stability, and controlled drug release. Traditional herbal drugs often exhibit poor bioavailability due to limited aqueous solubility and rapid degradation under physiological conditions. The application of advanced carrier-based systems enables efficient encapsulation of phytoconstituents, thereby protecting them from degradation and improving their pharmacokinetic behavior (Devi et al., 2010; Bonifácio et al., 2014). Nanoparticle-based delivery systems play a central role in modern herbal drug formulation. By reducing particle size to the nanoscale, these systems significantly increase surface area, leading to enhanced dissolution rate and improved absorption. Polymeric nanoparticles, typically prepared using biodegradable polymers, facilitate controlled and sustained drug release through diffusion and matrix degradation mechanisms. Similarly, solid lipid nanoparticles (SLNs) provide enhanced stability and are particularly effective for delivering lipophilic phytoconstituents (Bonifácio et al., 2014). Liposomal drug delivery systems represent another important advancement in this field. Liposomes are phospholipid-based vesicular carriers capable of encapsulating both hydrophilic and lipophilic compounds, thereby improving drug stability, reducing toxicity, and enhancing therapeutic efficiency (Allen & Cullis, 2013; Gregoriadis, 2007). In addition, phytosome technology involves the complexation of phytoconstituents with phospholipids, which significantly enhances membrane permeability and bioavailability of herbal compounds (Kidd & Head, 2005; Barani et al., 2021). Recent studies have also explored advanced nanocarriers such as dendrimers, which offer high drug-loading capacity and precise targeting capabilities due to their highly branched structure (Chauhan, 2018). Furthermore, nanoformulations of bioactive compounds such as curcumin have demonstrated improved stability, enhanced absorption, and better therapeutic performance compared to conventional formulations (Anand et al., 2007; Yallapu et al., 2012).

Overall, modern drug delivery systems provide a robust platform for optimizing the delivery of Ayurvedic medicines by improving formulation stability, enhancing drug release control, and increasing bioavailability, thereby facilitating their integration into modern pharmaceutical applications.

## 7. HERBAL NANOCARRIERS AND GREEN SYNTHESIS APPROACHES

The integration of nanotechnology with herbal medicine has led to the development of herbal nanocarriers, which significantly improve the stability, solubility, and delivery efficiency of phytoconstituents. These systems enhance the pharmacokinetic behavior of herbal compounds by protecting them from degradation and enabling controlled drug release. In parallel, green synthesis approaches for nanoparticle fabrication have gained considerable attention as sustainable and biocompatible alternatives to conventional chemical and physical methods. These approaches align with the principles of Ayurveda, which emphasize natural, safe, and eco-friendly therapeutic systems (Ahmed et al., 2016; Bonifácio et al., 2014).

### 7.1 Green Synthesis of Nanoparticles Using Plant Extracts

Green synthesis involves the utilization of plant extracts, microorganisms, or natural biomolecules for nanoparticle production, eliminating the need for toxic chemicals and energy-intensive processes. Phytochemicals such as flavonoids, phenolics, alkaloids, and terpenoids act as reducing and stabilizing agents, facilitating nanoparticle formation through redox reactions and surface capping mechanisms (Ahmed et al., 2016). This approach has been widely employed for synthesizing metallic nanoparticles such as silver, gold, and zinc oxide nanoparticles. The resulting nanocarriers exhibit improved stability and functional properties due to the presence of surface-bound bioactive compounds.

### 7.2 Biocompatibility and Eco-Friendly Advantages

Green-synthesized nanoparticles demonstrate superior biocompatibility compared to chemically synthesized counterparts due to the absence of toxic reagents. These nanoparticles are biodegradable, exhibit reduced cytotoxicity, and show enhanced compatibility with biological systems. Their eco-friendly nature supports sustainable pharmaceutical development and minimizes environmental impact. Furthermore, the incorporation of herbal constituents enhances therapeutic compatibility and reduces the risk of adverse immune responses (Bonifácio et al., 2014).

Green nanotechnology offers several advantages, including:

- Reduced production cost
- Energy-efficient synthesis
- Safer and non-toxic processes
- Improved interaction between nanocarriers and phytoconstituents

### 7.3 Applications in Ayurvedic Drug Delivery

Herbal nanocarriers developed through green synthesis approaches have shown significant potential in improving formulation performance of Ayurvedic medicines. These systems enhance solubility, stability, and controlled release of phytoconstituents, thereby overcoming the limitations of conventional formulations. Nanoformulations of bioactive compounds such as curcumin have demonstrated improved stability and release characteristics compared to traditional dosage forms (Anand et al., 2007; Yallapu et al., 2012).

Additionally, these nanocarriers can be incorporated into various delivery systems, including oral, topical, and transdermal formulations, enhancing their versatility and

applicability. The integration of herbal knowledge with nanotechnology provides a robust platform for developing advanced and standardized Ayurvedic formulations. However, challenges such as large-scale production, reproducibility, regulatory approval, and long-term safety evaluation remain critical and require further investigation.

## 8. CASE STUDIES AND RECENT ADVANCES

Recent advancements in modern drug delivery systems have significantly improved the formulation performance of Ayurvedic bioactive compounds. Among these, curcumin has been extensively studied due to its wide range of pharmacological properties, although its clinical utility is limited by poor solubility and low bioavailability. Nanoformulations of curcumin, including polymeric nanoparticles, liposomes, and solid lipid nanoparticles, have demonstrated enhanced encapsulation efficiency, improved stability, and controlled drug release profiles compared to conventional formulations (Anand et al., 2007; Yallapu et al., 2012). The reduction in particle size to the nanoscale increases surface area, thereby enhancing dissolution rate and absorption. Additionally, incorporation into lipid-based carriers improves stability under physiological conditions and protects curcumin from rapid degradation. These formulation strategies significantly improve its pharmacokinetic behavior and overall delivery efficiency (Gupta et al., 2013). Beyond curcumin, other herbal bioactives such as ashwagandha have also been investigated using advanced delivery systems. Nanoencapsulation of ashwagandha extracts has shown improved stability and controlled release characteristics, enhancing formulation consistency and performance (Singh et al., 2011). Furthermore, polyherbal formulations such as Triphala have been successfully incorporated into nanoparticle-based systems, demonstrating improved physicochemical stability and release behavior. Overall, these case studies highlight that modern formulation approaches, particularly nanotechnology-based systems, play a crucial role in enhancing encapsulation efficiency, stability, and controlled release of Ayurvedic compounds. These advancements support the development of more efficient and standardized herbal drug delivery systems suitable for modern pharmaceutical applications.

**Recent Advances in Herbal Nanoformulations"**

| Compound | Delivery System | Improvement |
|---|---|---|
| Curcumin | Nanoparticles | ↑ Bioavailability |
| Ashwagandha | Liposomes | ↑ Stability |
| Triphala | Nanoemulsion | ↑ Release control |

## 9. EVALUATION AND CHARACTERIZATION TECHNIQUES

The development of modern drug delivery systems for Ayurvedic formulations requires comprehensive evaluation and characterization to ensure quality, safety, and therapeutic efficacy. Various physicochemical and biological parameters are systematically assessed to understand the performance of herbal nanocarriers and advanced delivery systems. These evaluation techniques provide critical insights into formulation stability, drug release kinetics, and bioavailability, which are essential for optimizing formulation design and ensuring reproducibility (Devi et al., 2010; Bonifácio et al., 2014).

### 9.1 Particle Size and Zeta Potential

Particle size is a crucial parameter influencing drug release, dissolution rate, cellular uptake, and overall bioavailability. Nanoparticles typically range from 1 to 1000 nm, and a reduction in particle size significantly increases surface area, thereby enhancing drug dissolution and absorption. Techniques such as dynamic light scattering (DLS), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) are widely employed to determine particle size distribution and morphology. Zeta potential measures the surface charge of nanoparticles and serves as an important indicator of colloidal stability. A higher absolute zeta potential value (positive or negative) indicates stronger electrostatic repulsion between particles, preventing aggregation and improving stability. Formulations with zeta potential values greater than ±30 mV are generally considered stable (Honary & Zahir, 2013).

### 9.2 Drug Loading and Encapsulation Efficiency

Drug loading refers to the amount of drug incorporated within the carrier relative to the total weight of the formulation, whereas encapsulation efficiency represents the percentage of drug successfully entrapped within the delivery system. These parameters are critical for evaluating formulation efficiency and therapeutic potential. Analytical techniques such as UV-visible spectroscopy, high-performance liquid chromatography (HPLC), and centrifugation methods are commonly used for their determination. High drug loading and encapsulation efficiency contribute to improved therapeutic performance and reduced dosing frequency (Allen & Cullis, 2013).

### 9.3 In Vitro and In Vivo Studies

In vitro studies are conducted to evaluate drug release kinetics, permeability, and cytotoxicity under controlled laboratory conditions using dissolution testing, diffusion models, and cell culture assays. In vivo studies, performed in animal models or clinical settings, assess pharmacokinetic and pharmacodynamic parameters, including absorption, distribution, metabolism, and excretion (ADME). The correlation between in vitro and in vivo findings is essential for predicting real-time biological performance and optimizing drug delivery systems.

### 9.4 Stability Studies

Stability studies are essential to determine the shelf life and storage conditions of drug delivery systems. These studies evaluate the physical, chemical, and microbiological stability of formulations under varying environmental conditions such as temperature, humidity, and light exposure. Parameters including particle size, drug content, pH, and physical appearance are monitored over time. Stability testing is generally conducted according to International Council for Harmonisation

(ICH) guidelines to ensure standardization and regulatory compliance. Stable formulations maintain their integrity, efficacy, and safety throughout their intended shelf life (ICH, 2003).

## 10. CHALLENGES AND LIMITATIONS

The development of advanced drug delivery systems for Ayurvedic formulations presents several technical and practical challenges that limit their large-scale application. One of the primary issues is achieving uniform particle size distribution, which is critical for ensuring consistent drug release, stability, and bioavailability. Variations in particle size can lead to unpredictable pharmacokinetic behavior and reduced formulation efficiency (Honary & Zahir, 2013). Maintaining the physicochemical stability of nanoformulations is another significant challenge. Factors such as aggregation, phase separation, and chemical degradation of phytoconstituents can adversely affect formulation performance during storage and administration. In addition, achieving high encapsulation efficiency while minimizing drug leakage remains a critical concern in carrier-based systems, as these parameters directly influence therapeutic effectiveness (Bonifácio et al., 2014). Scale-up and reproducibility also pose major limitations in the development of herbal drug delivery systems. Formulation techniques that are effective at the laboratory scale often face difficulties during industrial-scale production due to process variability and lack of standardized manufacturing protocols. This issue is further complicated by the inherent variability of herbal raw materials, which can lead to batch-to-batch inconsistencies in formulation quality (Devi et al., 2010).

Moreover, the complexity of polyherbal formulations presents additional challenges in formulation design, characterization, and evaluation. The presence of multiple bioactive constituents with varying physicochemical properties makes it difficult to achieve uniform encapsulation and predictable release behavior. Interactions between phytoconstituents and carrier materials may also affect stability and therapeutic performance. Regulatory challenges further limit the development and commercialization of these systems. The lack of well-defined guidelines for herbal nanomedicines, along with insufficient clinical validation and safety data, creates barriers to regulatory approval and global acceptance. Addressing these challenges requires the development of standardized protocols, advanced characterization techniques, and robust quality control systems to ensure the safety, efficacy, and reproducibility of Ayurvedic drug delivery systems.

## 11. FUTURE PERSPECTIVES AND DIRECTIONS

Future research in Ayurvedic drug delivery systems should focus on the optimization of formulation parameters, development of scalable manufacturing techniques, and the design of advanced carrier systems with improved stability and reproducibility. The translation of laboratory-scale formulations into commercially viable products requires robust process optimization, standardization, and quality control to ensure consistency and regulatory compliance (Devi et al., 2010). Emerging advancements in nanotechnology are expected to play a crucial role in the development of next-generation herbal drug delivery systems. The design of multifunctional nanocarriers with enhanced drug-loading capacity, controlled release behavior, and targeted delivery capabilities can significantly improve the performance of phytoconstituents (Bonifácio et al., 2014). In addition, novel carrier systems such as dendrimers and lipid-based nanostructures offer promising opportunities for improving formulation efficiency and delivery precision (Chauhan, 2018). The integration of green synthesis approaches into nanocarrier development is another important future direction. Eco-friendly synthesis methods utilizing plant-based materials can enhance biocompatibility, reduce toxicity, and support sustainable pharmaceutical development (Ahmed et al., 2016). Furthermore, advancements in analytical and characterization techniques will enable better understanding and control of formulation properties, thereby improving reproducibility and stability. Artificial intelligence (AI) and computational modeling are also expected to transform the field of drug delivery by enabling predictive formulation design, optimization of process parameters, and identification of suitable carrier systems (Mak & Pichika, 2019). These technologies can significantly reduce development time and improve formulation efficiency. Overall, future progress in Ayurvedic drug delivery will depend on a multidisciplinary approach integrating nanotechnology, pharmaceutical engineering, and data-driven methodologies. Such advancements will facilitate the development of standardized, efficient, and globally acceptable herbal drug delivery systems.

## 12. CONCLUSION

Modern drug delivery systems have emerged as powerful tools for enhancing the formulation and delivery efficiency of Ayurvedic medicines. By addressing critical challenges such as poor solubility, instability, low bioavailability, and lack of controlled release, these advanced technologies significantly improve the physicochemical and pharmacokinetic performance of herbal formulations. Carrier-based systems, including nanoparticles, liposomes, and phytosomes, provide improved stability, enhanced drug loading, and controlled release behavior, thereby increasing overall formulation efficiency. Furthermore, the integration of nanotechnology and green synthesis approaches offers promising opportunities for developing biocompatible, sustainable, and effective herbal drug delivery systems. Despite these advancements, challenges related to standardization, scalability, reproducibility, and regulatory approval remain significant barriers to commercialization. Future progress in this field will depend on the optimization of formulation techniques, adoption of advanced characterization methods, and the development of robust manufacturing processes. A multidisciplinary approach combining pharmaceutical sciences, nanotechnology, and modern analytical tools is essential for translating these innovations into clinically

relevant and globally accepted therapeutic systems. Overall, modern drug delivery strategies hold immense potential to transform traditional Ayurvedic formulations into scientifically validated, efficient, and commercially viable pharmaceutical products.

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