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Review

Innovative Pharmaceutical Applications of Liposomes Nanocarriers and Lipid Nanoparticles in Modern Medicine

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Abstract

Lipid-based drug delivery systems have emerged as a cornerstone in modern pharmaceutical research, offering innovative solutions to overcome limitations associated with conventional drug therapies. The article provides comprehensive information about liposomes and lipid nanoparticles by showing their structural foundations and various ways to categorize them and their different formulation techniques which follow Quality by Design principles. The development of advanced nanocarriers which include tocosomes and nanoliposomes and programmable lipid nanoparticles has transformed drug delivery systems from their original liposome design through enhancements in product stability and product targeting capabilities and product delivery control mechanisms. The study compares liposomal systems with surfactant-based systems to show that carrier selection needs to match both therapeutic needs and formulation capabilities of the drug. The article describes how lipid nanoparticles function in targeted cancer therapies and neurological disease treatments and systemic disease management while demonstrating their capacity to enhance drug absorption and decrease toxic effects throughout the body. Emerging delivery platforms such as oral, dermal, and rapidly dissolving systems highlight advancements in patient-centric drug administration. The combination of smart programmable nanocarriers and artificial intelligence technology has enabled accurate drug delivery control which supports the creation of customized medical treatments. The existing progress needs to address three major challenges which include problems with producing products at an industrial scale and obtaining regulatory authorization and maintaining long-term safety. Future perspectives focus on developing multifunctional nanocarriers which respond to stimuli and provide solutions for diverse medical treatment requirements. The current medical field has achieved a revolutionary change through lipid-based drug delivery systems which connect traditional drug delivery methods with cutting-edge medical treatment methods.

Keywords: lipid nanoparticles; liposomes; targeted drug delivery; nanocarriers; controlled drug release

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1. Introduction to Liposomes and Lipid Nanoparticles in Modern Medicine

Lipid-based drug delivery systems have emerged as a transformative approach in modern medicine because they provide better therapeutic results while decreasing harmful effects and they deliver medications more accurately to their intended targets. The initial research demonstrated that liposomal formulations extended the duration of drug presence in the bloodstream while their passive targeting systems enhanced drug distribution to tumor tissues through the enhanced permeability and retention effect [1]. The research results created a basis which researchers used to develop lipid vesicles as delivery systems for anticancer and other medical treatments.

Liposomes function as drug delivery systems because their membrane structure enables them to store water-soluble and fat-soluble medications. The materials exhibit biocompatibility and biodegradability while they also protect drugs from degradation which makes them suitable for controlled delivery and targeted delivery. Researchers can achieve specific site delivery and track intracellular movement because advances in liposomal design enable them to use ligands which improve the accuracy of medical treatment [2].

The development of stealth liposomes further enhanced the clinical applicability of lipid-based systems by decreasing their recognition and elimination through mononuclear phagocyte system processes. Surface modification with polyethylene glycol successfully extended circulation duration while enhancing drug distribution and decreasing immune reaction, which resulted in better treatment results for cancer and other medical conditions [3].

The field of lipid nanoparticles has evolved since its beginning as a liposome-based technology which now incorporates both cutting-edge formulation methods and surface modification technologies. The systems have created a pathway for delivering complex biomolecular substances which include nucleic acids and proteins, leading to the development of therapeutics that use nanotechnology as their foundation. The movement of lipid-based carriers from research models to their current use as approved medical products demonstrates their vital function in developing contemporary drug delivery systems and personalized medicine approaches [4].

2. Structural Fundamentals and Classification of Liposomal Systems

Liposomal systems use multiple phospholipid bilayers to create an aqueous core which enables them to absorb both water-soluble and fat-soluble medications through their central core and their outer membrane structure. The physicochemical properties of liposomes which include their membrane fluidity and permeability and stability depend on three factors which are their lipid composition and cholesterol content and environmental factors of pH and temperature [5]. Pharmaceutical applications depend on liposomes because their structural flexibility enables multiple uses.

The classification of liposomes is typically conducted through two criteria which determine their size and lamellarity because these factors influence their ability to load drugs and their drug release patterns. Multilamellar vesicles (MLVs) consist of multiple lipid bilayers and are typically used for sustained release, whereas small unilamellar vesicles (SUVs) and large unilamellar vesicles (LUVs) offer improved bioavailability and are suitable for targeted delivery due to their reduced size and uniform distribution [6].These classifications enable researchers to design liposomal systems which meet specific therapeutic needs.

Liposomes undergo classification based on their size and their material makeup and their functional alterations. The three types of liposomes: conventional liposomes and cationic liposomes and PEGylated liposomes exhibit different surface charge properties which affect their interaction with living organisms. The functional liposomes immunoliposomes and ligand-targeted vesicles function as therapeutic tools which help doctors treat specific diseases while minimizing undesired effects on other body areas [7]. Research classification now includes two additional factors which determine how well materials mix and how long they last under different conditions. Liposomes acquire different structural characteristics through three specific methods: thin-film hydration and ethanol injection and reverse-phase evaporation. Researchers must understand all classifications and preparation methods because this knowledge enables them to develop efficient systems which deliver drugs through liposomal carriers [8].

3. Formulation Strategies and Quality by Design in Lipid Nanocarriers

Formulation strategies for lipid nanocarrier development progress to achieve three goals which include improved permeability and enhanced stability and precise delivery through biological barriers. Ultraflexible liposomes, which include transfersomes and ethosomes, achieve their functional design through the application of edge activators as surfactants which enable membrane deformation and transdermal skin penetration. These systems deliver better drug results at specific

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locations through their ability to control release rates throughout the entire treatment period according to [9]. Advanced liposomal carriers which function as nanovesicular systems require vesicle size and surface charge and encapsulation efficiency optimization to achieve better therapeutic results. The formulation methods enhance drug stability by preventing active molecules from breaking down while they provide controlled drug release and sustainable medication delivery. The use of such nanocarriers enables scientists to deliver biomolecules which require protection while simultaneously enhancing drug delivery into cells according to [10].

The Quality by Design (QbD) framework establishes essential quality attributes and operational procedures which guide the structured progression of lipid-based nanocarrier development. QbD implements risk assessment together with design space optimization to maintain product quality while ensuring consistent production methods and meeting regulatory standards. The desired therapeutic outcomes are achieved by controlling parameters which include lipid composition and preparation method and particle size and zeta potential [11].

The latest developments in liposomal nanotechnology have created new pathways for clinical research by combining cutting-edge formulation methods with production techniques that can be easily expanded to larger volumes. The implementation of advanced design methods which involve surface functionalization and targeted ligand attachment has resulted in better therapeutic efficiency and specific drug effects. The development of lipid nanocarriers has progressed from laboratory testing to established drug delivery systems which medical professionals now use for patient treatment [12].

4. Advanced Lipid Nanocarriers and Functional Nanovesicular Systems

Tocosomes and nanoliposomes and hybrid vesicular systems serve as advanced lipid nanocarriers which enable traditional liposomes to perform additional functions. Tocosomes which researchers created from tocopherol phosphates demonstrate increased antioxidant capabilities and better membrane resilience and enhanced biocompatibility which enables their use in both nutraceutical and therapeutic fields. Scientists use nanoliposomes to deliver drugs more effectively because their small size and large surface area enable better drug absorption into cells [13].

Researchers create modern liposomal formulations to improve treatment results while decreasing harmful effects on the body. Researchers employ optimization methods which involve adjusting lipid makeup and adding stabilizing compounds and altering surface properties to boost drug absorption and body distribution. The functional enhancements enable medical professionals to administer drugs precisely while they manage drug release and minimize negative reactions to treatment especially for patients with cancer and chronic illnesses [14].

Lipid nanoparticles have revolutionized biological drug delivery because they enable the transportation of complicated biomolecules which include proteins and peptides and nucleic acids. The system gained importance in gene therapy and vaccine development because it protects delicate drugs from being destroyed while it enables drug delivery into cells. The systems show excellent biocompatibility and they can be scaled up to various therapeutic uses according to [15]. The internal structure of lipid nanoparticles gets revealed through structural characterization techniques which use small-angle X-ray scattering (SAXS) as a measurement method. The methods investigate bilayer structure and particle shape and encapsulation process which play a crucial role in determining the stability and performance of the formulation. The analytical progress supports the design process which produces effective nanocarrier systems that maintain their performance across multiple tests according to [16].

5. Lipid Nanoparticles in Drug Delivery and Biological Applications

The development of structurally reinforced lipid nanocarriers has introduced improved stability and functionality in drug delivery systems. The sequential assembly method which applies polyelectrolytes to charged liposomes creates durable capsules that possess both improved

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mechanical strength and regulated drug release capabilities. The systems provide effective protection for unstable medications while delivering them through an extended period of time [17].

Lipid nanoparticles have evolved into multifunctional platforms that extend beyond conventional drug delivery roles. The system has the ability to control immune responses while it delivers specific treatments and moves genetic materials which include mRNA and siRNA. The system has achieved extensive use in vaccines, oncology treatment and personalized medicine applications because of its flexibility to adapt to various needs [18].

The development of programmable lipid nanoparticles marks the creation of an advanced delivery system which provides precise control over therapeutic administration. The carriers combine several functional components which enable them to deliver drugs to specific locations while reacting to environmental changes and releasing medication in a controlled manner. The system designed for customizable architecture enables its use in gene editing, personalized medicine, and advanced biomedical therapies [19].

Lipid nanoparticles demonstrate their capacity to deliver therapeutic agents to neuronal tissues through their ability to traverse the blood–brain barrier in Alzheimer's disease research. The system shows two advantages through improved targeting and drug stability which result in sustained drug release making it an effective treatment option for central nervous system disorders [20].

Table. Lipid Nanoparticles in Drug Delivery and Biological Applications.

Aspect	Description	Functional Significance / Applications	References
Structurally Reinforced Lipid Nanocarriers	Sequential polyelectrolyte assembly on charged liposomes forms durable capsules with enhanced mechanical strength and controlled release properties.	Improved stability; protection of unstable drugs; prolonged drug release.	[17]
Multifunctional Lipid Nanoparticles (LNPs)	LNPs function beyond drug delivery, enabling immune modulation and transport of genetic materials such as mRNA and siRNA.	Applications in vaccines, oncology, and personalized medicine; high adaptability.	[18]
Programmable Lipid Nanoparticles	Advanced carriers designed with multiple functional domains for targeting, sensing, and controlled release in response to environmental triggers.	Precision drug delivery; applications in gene editing, personalized therapy, and advanced biomedical treatments.	[19]
Blood–Brain Barrier Penetration	LNPs can traverse the blood–brain barrier, enabling delivery of therapeutics to neuronal tissues.	Effective in CNS disorders such as Alzheimer's disease; improved targeting and sustained drug release.	[20]
Overall Therapeutic Impact	Lipid nanoparticles integrate targeting, protection, and controlled release into a single platform.	Enhanced drug stability, bioavailability, and long-term therapeutic efficacy across multiple disease areas.	[17–20]

6. Comparative Evaluation of Liposomal and Surfactant-Based Systems

Liposomal and surfactant-based drug delivery systems show major differences in their structural design and their capacity to maintain stability and their mechanisms of releasing medication. The phospholipid bilayer structure of liposomes enables them to deliver better biocompatibility and lower toxicity while they can encapsulate drugs that require both hydrophilic and lipophilic properties. The design of niosomes and other surfactant-based systems enables them to deliver better chemical stability and lower costs and simpler formulation procedures, which makes them suitable for specific pharmaceutical uses [21]. The selection of a particular system should be based on the therapeutic requirements since liposomes enable precise drug delivery but surfactant systems deliver better storage stability and production capacity.

7. Application in Targeted Cancer Therapy and Systemic Diseases

Nanoparticle-based drug delivery systems have shown substantial effectiveness for targeted cancer treatment because these systems enhance drug delivery to tumors while reducing harmful effects on the entire body. Colorectal cancer treatment uses lipid-based nanoparticles to deliver chemotherapy drugs and genetic materials, which results in better treatment outcomes through

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enhanced cellular absorption and controlled drug delivery systems [22]. The different ways that lipid nanoparticles deliver medicines throughout the body serve as a mechanism to control systemic diseases through their combination of passive delivery methods and active delivery methods, which include ligand-based targeting and the enhanced permeability and retention effect. The system enables complex drug delivery and biological activity modification, which doctors use to treat various diseases that include cancer and long-term health conditions [18].

8. Oral, Dermal, and Rapidly Dissolving Drug Delivery Applications

Researchers have directed their efforts toward developing new drug delivery methods which enable patients to follow treatment plans better while achieving more effective medical outcomes. Scientists have created new delivery systems which use lipid-based carriers to deliver drugs through oral and skin applications while achieving better drug solubility and stability and controlled drug release. The systems provide higher bioavailability which enables drugs with low absorption rates to maintain their therapeutic effects throughout longer periods of time [23].

The use of mouth-dissolving films and chewable tablets as rapidly dissolving dosage forms enables fast medication effects which doctors find easy to give to their patients who need treatment in both pediatric and geriatric age groups. The formulations enable patients to bypass their swallowing difficulties while they maintain effective drug delivery through buccal and oral mucosal absorption pathways which lead to better patient adherence [24].

9. Programmable Lipid Nanoparticles and Intelligent Drug Delivery

The development of programmable lipid-based nanocarriers enables researchers to create systems which deliver drugs at specific times and locations through their ability to control multiple formulation parameters which include the selection of lipid compounds and the determination of vesicle dimensions and the assessment of particle surface properties. The systems provide continuous targeted treatment which results in better patient outcomes because they need less medication and cause fewer adverse effects throughout the body. Through the use of liposomal nanocarriers researchers can achieve controlled drug delivery which enables better control over drug distribution in the body and results in higher drug absorption rates [25].

The ultraflexible liposomal systems enable smart drug delivery because they change their structural design based on the biological conditions which exist in their surroundings. The system's improved ability to change shape enables it to move through biological barriers with greater speed especially in transdermal use cases because it allows drugs to reach more profound areas which leads to better treatment results. The development of adaptive systems marks a major step forward in creating nanocarrier systems that can respond to changing conditions while delivering efficient results [9].

Scientists now develop lipid nanoparticles as advanced systems which combine multiple functions to achieve Targeting, sensing abilities and controlled release functions. The carriers serve multiple therapeutic needs because they can be customized to deliver genes and treat immune system disorders, which goes beyond their standard drug delivery functions. The system gains treatment accuracy because it uses physiological signals as input which improves its treatment performance but needs more research [18].

10. Emerging Trends and Future Clinical Applications

The application of artificial intelligence for designing nanocarriers represents a groundbreaking approach which scientists use to study drug delivery systems. The AI-based models enable researchers to optimize formulation parameters while predicting how nanoparticles will behave and they speed up drug delivery system development which results in better system performance and consistent results. The method improves accuracy for creating lipid-based delivery systems which can handle intricate medical treatments [26].

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Stealth liposomes continue to play a significant role in advancing clinical applications by improving circulation time and reducing immune system recognition. Surface modification techniques such as PEGylation enable better targeting outcomes while minimizing toxic effects, which makes them essential for ongoing use in cancer therapy and systemic drug delivery applications [3].

Researchers work on developing better liposomal formulations which can provide more effective treatments because they need to decrease harmful effects. The implementation of surface engineering together with lipid optimization and controlled release mechanisms enables better pharmacokinetic performance which results in improved patient outcomes that help medical professionals adopt lipid-based nanocarriers in their practices. [14]. The capacity of lipid nanoparticles to deliver complex drugs through their flexible and scalable design will make them the primary technology for future drug delivery systems. The treatment of vaccines and gene therapy together with personalized medicine shows how their presence in contemporary medical care systems continues to grow. The ongoing development of nanotechnology and formulation science will enhance their ability to deliver clinical results and achieve success in translational research [18].

Table. Emerging Trends and Future Clinical Applications in Drug Delivery.

Aspect	Description	Clinical / Technological Significance	References
Artificial Intelligence in Nanocarrier Design	AI-based models are used to optimize formulation parameters, predict nanoparticle behavior, and accelerate drug delivery system development.	Enhances precision, reproducibility, and efficiency in designing advanced nanocarriers, especially lipid-based systems.	[26]
Stealth Liposomes and PEGylation	Surface modification techniques such as PEGylation improve circulation time and reduce immune system recognition.	Enables prolonged systemic circulation, improved targeting, and reduced toxicity, particularly in cancer therapy.	[3]
Advanced Liposomal Formulation Strategies	Integration of surface engineering, lipid optimization, and controlled release mechanisms to enhance pharmacokinetics.	Improves therapeutic efficacy, minimizes side effects, and supports wider clinical adoption.	[14]
Lipid Nanoparticles in Modern Therapeutics	LNPs offer flexible, scalable platforms for delivering complex drugs including nucleic acids and biologics.	Expanding role in vaccines, gene therapy, and personalized medicine.	[18]
Future Clinical Translation	Continuous advancements in nanotechnology and formulation science are improving scalability, safety, and clinical performance.	Facilitates successful translation from research to clinical practice; supports precision medicine.	[18,26]

Conclusion

Lipid-based drug delivery systems have significantly transformed pharmaceutical sciences by providing versatile and efficient platforms for therapeutic delivery. The article conducted a comprehensive investigation which traced the development of liposomes and lipid nanoparticles from their basic structural elements to their current state which contains advanced nanocarrier technologies that offer superior operational capabilities. The classification and formulation strategies show how lipid composition and vesicle size and preparation techniques determine drug delivery performance.

The integration of Quality by Design principles has enabled the development of reproducible and optimized formulations which achieve consistent results while meeting regulatory standards. Advanced lipid nanocarriers which include tocosomes and nanoliposomes show enhanced performance through their superior stability and biocompatibility and drug delivery capabilities. Lipid nanoparticles have become essential instruments for transporting complex biomolecules which enable their use in gene therapy and oncology and neurological disorder treatment.

The researchers found that liposomal and surfactant-based systems require specific delivery platforms which should be chosen according to the targeted medical goals and the properties of the drug formulations. The rising significance of alternative delivery methods, which include oral and dermal and rapidly dissolving delivery systems, demonstrates the current trend of developing treatment methods that improve patient adherence and treatment results.

The development of programmable and intelligent lipid nanocarriers, which artificial intelligence enables, represents a major breakthrough for precision medicine. The systems provide controlled drug delivery which targets specific areas while responding to needs thus enhancing treatment results and reducing side effects. The experts expect nanotechnology and formulation science to create new developments because they continue to face challenges with scalability and safety and regulatory approval.

Lipid-based nanocarriers create a dynamic and developing research area which has the potential to transform drug delivery and clinical therapeutics thus creating new opportunities for personalized treatment methods.

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