

# Exosome-Mediated Drug Delivery: A Novel Approach for Precision Therapeutics

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## ABSTRACT

The development of efficient and targeted drug delivery systems remains a significant challenge in modern therapeutics, particularly in the treatment of complex and chronic diseases. Conventional delivery approaches are often associated with limitations such as poor bioavailability, lack of specificity, and systemic side effects, necessitating the exploration of advanced delivery platforms. In this context, exosomes have emerged as promising natural nanocarriers due to their unique biological properties and ability to facilitate intercellular communication.

Exosomes are nanosized extracellular vesicles that carry a diverse range of biomolecules, including proteins, lipids, and nucleic acids, enabling them to modulate various physiological and pathological processes. Their inherent biocompatibility, low immunogenicity, and capability to cross biological barriers, such as the blood-brain barrier, make them highly suitable for targeted drug delivery applications. Furthermore, advancements in engineering strategies have enhanced their cargo loading efficiency and targeting specificity, thereby improving their therapeutic potential.

This review provides a comprehensive overview of the biology and physicochemical characteristics of exosomes, along with the underlying mechanisms involved in exosome-mediated drug delivery. It further discusses their therapeutic applications across multiple disease conditions, including cancer, neurological disorders, cardiovascular diseases, and metabolic disorders. Additionally, the advantages, limitations, and recent advancements in exosome-based delivery systems are critically evaluated, with particular emphasis on their translational potential.

In conclusion, exosomes represent a promising and innovative platform for targeted drug delivery, bridging the gap between biological systems and nanotechnology. Continued research and technological advancements are essential to overcome existing challenges and facilitate their successful integration into clinical practice.

**Keywords:** Exosomes; Drug delivery; Extracellular vesicles; Targeted therapy; Nanocarriers; Therapeutics; Biomedical applications

## I. INTRODUCTION

The development of effective drug delivery systems remains a critical challenge in modern therapeutics, particularly in the treatment of complex and chronic diseases. Conventional drug delivery approaches often suffer from limitations such as poor bioavailability, lack of target specificity, rapid systemic clearance, and undesirable side effects (Allen et al., 2013). These limitations significantly reduce therapeutic efficacy and highlight the need for advanced delivery strategies.

In recent years, nanotechnology-based drug delivery systems have gained considerable attention due to their ability to enhance drug stability and targeting efficiency. However, synthetic nanocarriers often exhibit issues related to toxicity, immunogenicity, and limited biocompatibility, which restrict their clinical application (Blanco et al., 2015). As a result, biologically derived nanocarriers have emerged as promising alternatives.

Exosomes, a subtype of extracellular vesicles ranging from 30 to 150 nm in diameter, are naturally secreted by various cell types and play a crucial role in intercellular communication (Kalluri et al., 2020). These vesicles carry a diverse range of biomolecules, including proteins, lipids, and nucleic acids, enabling them to modulate physiological and pathological processes.

Their inherent stability, low immunogenicity, and ability to cross biological barriers make exosomes highly attractive candidates for targeted drug delivery (Yáñez-Mó et al., 2015). Furthermore, recent advancements in bioengineering have enabled the modification of exosomes to enhance their therapeutic efficiency and targeting specificity (Luan et al., 2017).

This review aims to provide a comprehensive overview of exosome-based drug delivery systems, focusing on their biological characteristics, mechanisms of action, therapeutic applications, and recent advancements, along with the challenges associated with their clinical translation.

## II. BIOLOGY AND PHYSICOCHEMICAL CHARACTERISTICS OF EXOSOMES

Exosomes are nanosized extracellular vesicles that play a critical role in intercellular communication by transporting bioactive molecules between cells. Typically ranging from 30 to 150 nm in diameter, exosomes are enclosed by a lipid bilayer membrane that originates from the endosomal compartment of the parent cell. Their physicochemical properties, including size, surface charge, membrane composition, and stability, significantly influence their biological functions and therapeutic potential. These vesicles are widely distributed in biological fluids such as blood, urine, saliva, and cerebrospinal fluid, highlighting their systemic relevance and accessibility for diagnostic and therapeutic applications (Raposo et al., 2013).

The biological behavior of exosomes is closely associated with their cellular origin and the physiological or pathological state of the parent cell. They possess the ability to protect their molecular cargo from enzymatic degradation and facilitate efficient delivery to recipient cells. Their inherent stability in circulation and low immunogenicity distinguish them from synthetic nanocarriers, making them highly suitable for drug delivery applications (Yáñez-Mó et al., 2015). A detailed understanding of their biogenesis, molecular composition, and isolation techniques is essential for optimizing their use in therapeutic systems.

### 2.1 Biogenesis and Secretion Pathways

The formation of exosomes is a highly regulated intracellular process that occurs through the endosomal pathway. It begins with the inward budding of the plasma membrane, leading to the formation of early endosomes. These early endosomes subsequently mature into late endosomes, within which intraluminal vesicles (ILVs) are generated through the inward budding of the endosomal membrane. The accumulation of ILVs results in the formation of multivesicular bodies (MVBs), which serve as precursors to exosomes (Colombo et al., 2014).

The sorting of cargo into ILVs is mediated by both endosomal sorting complex required for transport (ESCRT)-dependent and ESCRT-independent mechanisms. The ESCRT machinery facilitates the selective incorporation of proteins and nucleic acids into developing vesicles, while alternative pathways involving lipids such as ceramide also contribute to vesicle formation (Hessvik et al., 2018).

Following their formation, MVBs can undergo two distinct fates: they may fuse with lysosomes for degradation or merge with the plasma membrane to release ILVs into the extracellular environment as exosomes. The secretion of exosomes is influenced by various cellular factors, including calcium levels, cellular stress, and signaling pathways, which regulate vesicle trafficking and release (Théry et al., 2002).

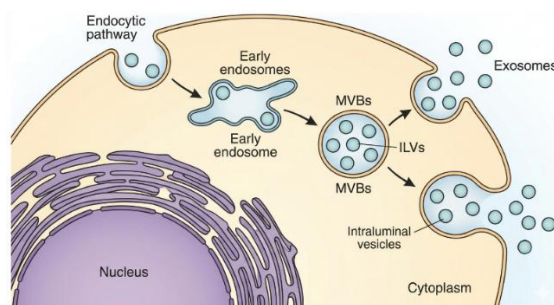


Fig 1 Biogenesis Pathway

### 2.2 Molecular Composition of Exosomes

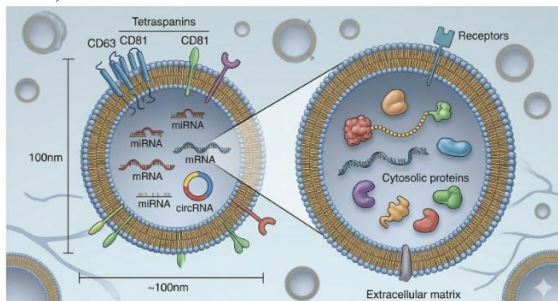
Exosomes possess a highly complex and dynamic molecular composition that reflects the characteristics of their parent cells. They are enriched with a wide range of biomolecules, including proteins, lipids, and nucleic acids, which collectively determine their functional properties and biological activity.

Exosomal proteins include membrane-associated proteins such as tetraspanins (CD9, CD63, CD81), which are commonly used as exosomal markers. Other proteins include heat shock proteins, cytoskeletal proteins, and enzymes involved in metabolic processes. Additionally, proteins associated with vesicle formation and trafficking, such as Alix and TSG101, play crucial roles in maintaining exosome structure and function (Simons et al., 2009).

The lipid composition of exosomes is characterized by high levels of cholesterol, sphingomyelin, and phospholipids, which contribute to membrane rigidity and stability. This unique lipid profile enhances the resistance of exosomes to enzymatic degradation and supports their prolonged circulation in biological fluids.

Exosomes also carry various nucleic acids, including messenger RNA (mRNA), microRNA (miRNA), and other non-coding RNAs. These genetic materials can be transferred to recipient cells, where they modulate gene expression and influence cellular processes such as proliferation,

differentiation, and immune responses (Valadi et al., 2007).



**Fig 2 Molecular Composition Of Exosomes**

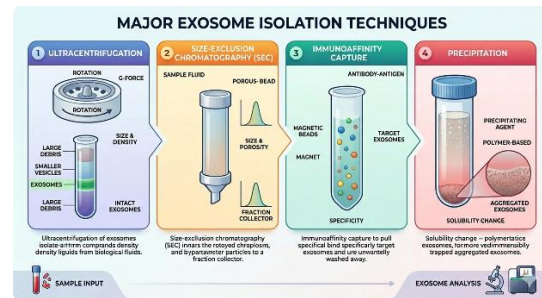
### 2.3 Isolation and Characterization Techniques

The isolation and characterization of exosomes are essential steps for their application in both research and clinical settings. Various techniques have been developed to isolate exosomes based on their size, density, and surface properties.

Differential ultracentrifugation is the most widely used method for exosome isolation, involving sequential centrifugation steps to remove cells, debris, and larger vesicles. Density gradient centrifugation further enhances purity by separating vesicles based on their buoyant density (Li et al., 2017). Alternative approaches such as size-exclusion chromatography and ultrafiltration offer improved efficiency and reduced processing time.

In addition to isolation, accurate characterization of exosomes is crucial to confirm their identity and functional properties. Techniques such as nanoparticle tracking analysis (NTA) are used to determine particle size distribution and concentration, while transmission electron microscopy (TEM) provides detailed visualization of exosome morphology. Molecular characterization methods, including Western blotting and flow cytometry, are employed to detect specific exosomal markers such as CD63, CD81, and CD9 (Dragovic et al., 2011).

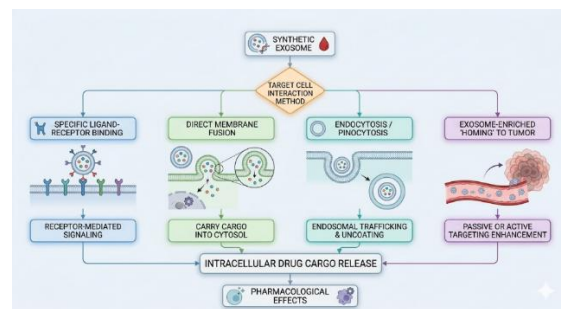
Despite significant progress, challenges such as low yield, contamination, and lack of standardized protocols continue to limit the reproducibility and scalability of exosome isolation methods. Addressing these issues is essential for advancing exosome-based applications in drug delivery and clinical therapeutics.



**Fig 3 Major Exosome Isolation Techniques**

### III. MECHANISMS OF EXOSOME-MEDIATED DRUG DELIVERY

Exosomes function as highly efficient biological nanocarriers that facilitate the delivery of therapeutic cargo through naturally evolved intercellular communication pathways. Their ability to transport a wide range of biomolecules, including proteins, lipids, and nucleic acids, is governed by complex mechanisms involving cellular uptake, targeting specificity, and intracellular release. Unlike conventional drug delivery systems, exosomes exploit endogenous cellular processes, which enhances their delivery efficiency while minimizing immune recognition and degradation. Understanding these mechanisms is essential for optimizing exosome-based therapeutics and improving their clinical applicability.



**Fig 4 Exosome Mediated Drug Delivery**

#### 3.1 Cellular Uptake Mechanisms

The internalization of exosomes by recipient cells is a critical step in drug delivery and occurs through multiple pathways depending on the cell type and physiological conditions. One of the primary mechanisms is endocytosis, which includes clathrin-mediated, caveolin-mediated, and lipid raft-mediated pathways. In these processes, exosomes bind to specific receptors on the cell surface and are subsequently internalized into endosomal compartments (Mulcahy et al., 2014).

In addition to endocytosis, phagocytosis and macropinocytosis contribute to exosome uptake,

particularly in immune cells such as macrophages and dendritic cells. These pathways involve the engulfment of extracellular particles and allow efficient internalization of larger vesicles (Feng et al., 2010).

Another important mechanism is direct membrane fusion, where the exosomal membrane fuses with the plasma membrane of the recipient cell, leading to the direct release of cargo into the cytoplasm. This pathway is considered highly efficient, as it bypasses endosomal degradation and enhances the bioavailability of therapeutic molecules (Parolini et al., 2009).

The choice of uptake mechanism is influenced by factors such as exosome surface composition, size, and the physiological state of the recipient cell, highlighting the complexity of exosome-mediated delivery.

### 3.2 Targeting and Biodistribution

Exosomes possess inherent targeting capabilities due to the presence of specific surface molecules, including proteins, lipids, and glycoproteins, which facilitate selective interaction with recipient cells. These molecules enable ligand-receptor binding, allowing exosomes to preferentially target specific tissues or cell types (Hoshino et al., 2015).

The biodistribution of exosomes within the body is influenced by several factors, including their cellular origin, route of administration, and physicochemical properties. For example, exosomes derived from tumor cells often exhibit homing tendencies toward the tumor microenvironment, while those derived from immune cells may preferentially accumulate in lymphoid tissues (Wiklander et al., 2015).

Surface engineering strategies have been employed to enhance targeting specificity. Modifications such as the incorporation of targeting ligands, peptides, or antibodies onto the exosome membrane enable precise delivery to diseased tissues, thereby improving therapeutic outcomes and reducing off-target effects (Kamerkar et al., 2017). Despite these advancements, challenges related to non-specific distribution and accumulation in organs such as the liver and spleen remain significant barriers to achieving optimal targeting efficiency.

### 3.3 Drug Loading Strategies

Efficient loading of therapeutic agents into exosomes is essential for their application as drug delivery vehicles. Drug loading strategies are

broadly classified into passive and active methods, each offering distinct advantages and limitations.

Passive loading involves the incubation of exosomes with therapeutic molecules, allowing diffusion-driven incorporation based on concentration gradients. This method is relatively simple and preserves the structural integrity of exosomes; however, it often results in lower loading efficiency (Haney et al., 2015).

Active loading techniques are employed to enhance drug encapsulation efficiency. Methods such as electroporation temporarily disrupt the exosomal membrane, enabling the entry of nucleic acids and small molecules. Similarly, sonication and extrusion increase membrane permeability, facilitating higher drug loading (Lamichhane et al., 2015).

Another advanced approach is pre-loading of donor cells, where cells are engineered or treated with therapeutic agents, leading to the natural incorporation of these molecules into exosomes during their formation. This strategy ensures efficient encapsulation and maintains the biological functionality of the cargo (Kalluri et al., 2020).

The selection of an appropriate loading method depends on factors such as the type of therapeutic agent, required loading efficiency, and intended clinical application. Optimizing these strategies is crucial for maximizing the therapeutic potential of exosome-based drug delivery systems.

## IV. THERAPEUTIC APPLICATIONS OF EXOSOME-BASED DRUG DELIVERY

Exosome-based drug delivery systems have demonstrated remarkable potential across a wide range of therapeutic areas due to their intrinsic ability to transport bioactive molecules and modulate cellular functions. Their natural origin, stability in circulation, and capacity for targeted delivery make them highly suitable for treating complex diseases where conventional therapies often fail. Exosomes can encapsulate diverse therapeutic agents, including small molecules, proteins, and nucleic acids, enabling their use in multiple disease contexts. Recent studies have highlighted their effectiveness in oncology, neurology, cardiovascular disorders, and metabolic diseases, emphasizing their versatility as next-generation delivery vehicles.

### 4.1 Cancer Therapy

Cancer therapy represents one of the most extensively studied applications of exosome-based drug delivery. Exosomes have the ability to selectively target tumor cells and penetrate the

tumor microenvironment, which is often resistant to conventional treatments. This property enables the efficient delivery of chemotherapeutic agents, small interfering RNA (siRNA), and microRNA (miRNA), thereby enhancing therapeutic efficacy while minimizing systemic toxicity (Tian et al., 2014).

Exosomes also play a dual role in cancer progression and therapy. While tumor-derived exosomes can promote metastasis and immune evasion, engineered exosomes can be designed to deliver tumor-suppressive molecules and inhibit oncogenic pathways. For example, exosomes loaded with siRNA targeting specific oncogenes have demonstrated significant tumor growth inhibition in preclinical models (Kamerkar et al., 2017).

Furthermore, exosomes have been explored as carriers for immunotherapeutic agents. They can modulate immune responses by delivering antigens or immune-regulatory molecules, thereby enhancing anti-tumor immunity. Their ability to evade immune detection also improves the stability and delivery efficiency of anticancer drugs (Kalluri et al., 2020).

#### 4.2 Neurological Disorders

The treatment of neurological disorders remains a major challenge due to the restrictive nature of the blood-brain barrier (BBB), which limits the entry of most therapeutic agents into the central nervous system. Exosomes have emerged as promising carriers capable of crossing the BBB, thereby facilitating targeted delivery of therapeutics to brain tissues (Alvarez-Erviti et al., 2011).

Exosome-based delivery systems have been investigated in neurodegenerative diseases such as Alzheimer's disease, Parkinson's disease, and Huntington's disease. They can transport neuroprotective agents, anti-inflammatory molecules, and genetic material that regulate neuronal survival and function. For instance, exosomes loaded with siRNA have been shown to reduce the expression of disease-related proteins in the brain, highlighting their therapeutic potential (Cooper et al., 2014).

Additionally, exosomes exhibit low neurotoxicity and high biocompatibility, making them suitable for long-term therapeutic applications. Their ability to mediate intercellular communication further supports their role in modulating disease progression and promoting neural repair.

#### 4.3 Cardiovascular Diseases

Exosomes have gained significant attention in the treatment of cardiovascular diseases due to their role in tissue repair and regeneration. They are involved

in processes such as angiogenesis, cell survival, and inflammation modulation, which are critical for maintaining cardiovascular health (Lai et al., 2010).

In conditions such as myocardial infarction, exosomes derived from stem cells have demonstrated the ability to promote cardiac repair by enhancing endothelial cell function and reducing apoptosis in damaged tissues. These exosomes carry growth factors, cytokines, and regulatory RNAs that contribute to tissue regeneration and functional recovery (Sahoo et al., 2011).

Exosome-mediated delivery of therapeutic molecules has also shown potential in reducing atherosclerosis and cardiac fibrosis. By modulating inflammatory pathways and promoting vascular repair, exosomes offer a novel approach for managing cardiovascular disorders.

#### 4.4 Metabolic Disorders

Exosome-based drug delivery systems have emerged as promising tools in the management of metabolic disorders such as diabetes, obesity, and insulin resistance. These conditions are often associated with complex metabolic dysregulation and chronic inflammation, which can be effectively targeted using exosome-mediated therapies.

In diabetes, exosomes have been shown to protect pancreatic  $\beta$ -cells from oxidative stress and apoptosis, thereby preserving insulin secretion and improving glycemic control (Sun et al., 2018). They can also deliver therapeutic RNAs that regulate genes involved in glucose metabolism and insulin signaling pathways.

Exosomes derived from stem cells and other sources have demonstrated the ability to improve insulin sensitivity and reduce systemic inflammation, which are key factors in the progression of metabolic diseases. Additionally, their role in intercellular communication allows them to modulate metabolic pathways at multiple levels, enhancing their therapeutic effectiveness.

### V. ADVANTAGES AND LIMITATIONS OF EXOSOME-BASED DELIVERY SYSTEMS

Exosome-based drug delivery systems have gained considerable attention due to their unique biological origin and functional versatility. Unlike synthetic nanocarriers, exosomes are naturally derived vesicles that participate in intercellular communication, enabling efficient transport of bioactive molecules. Their inherent properties, such as biocompatibility and targeting ability, make them promising candidates for therapeutic applications.

However, despite these advantages, several technical and translational challenges limit their widespread clinical use. A comprehensive understanding of both their benefits and limitations is essential for evaluating their potential as next-generation drug delivery platforms.

### 5.1 Advantages

One of the most significant advantages of exosomes is their high biocompatibility, as they are derived from endogenous cellular processes. This natural origin allows them to interact seamlessly with biological systems, reducing the risk of toxicity and adverse reactions commonly associated with synthetic carriers (EL Andaloussi et al., 2013). Their compatibility with physiological environments enhances their potential for safe therapeutic applications.

Exosomes also exhibit low immunogenicity, enabling them to evade detection and clearance by the immune system. This property extends their circulation time in the bloodstream, allowing for improved delivery efficiency to target tissues (Yáñez-Mó et al., 2015). In contrast to synthetic nanoparticles, which may trigger immune responses, exosomes are generally well tolerated.

Another key advantage is their intrinsic targeting capability. The presence of specific surface proteins, lipids, and glycoproteins facilitates selective interaction with recipient cells through ligand–receptor binding mechanisms. This targeting ability enables precise delivery of therapeutic cargo, thereby reducing off-target effects and enhancing treatment outcomes (Hoshino et al., 2015).

Exosomes are also capable of crossing biological barriers, including the blood–brain barrier (BBB), which is a major limitation in the treatment of neurological disorders. This unique property expands their applicability in delivering therapeutics to otherwise inaccessible tissues (Alvarez-Erviti et al., 2011).

Furthermore, exosomes provide protection to encapsulated therapeutic agents such as proteins, RNA, and small molecules. Their lipid bilayer membrane shields the cargo from enzymatic degradation, ensuring stability and preservation of biological activity during circulation (Valadi et al., 2007). This enhances the effectiveness of delivered therapeutics.

In addition, exosomes demonstrate versatility in cargo loading, as they can carry a wide range of biomolecules, including nucleic acids, proteins, and drugs. This flexibility supports their

use in diverse therapeutic strategies, including gene therapy and immunotherapy (Kalluri et al., 2020).

### 5.2 Limitations

Despite their promising advantages, exosome-based delivery systems face several limitations that hinder their clinical translation. One of the primary challenges is the difficulty in large-scale production. Current isolation techniques, such as ultracentrifugation, are labor-intensive, time-consuming, and yield relatively low quantities of exosomes, making them unsuitable for industrial-scale applications (Lener et al., 2015).

Another major limitation is the lack of standardized isolation and purification protocols. Variability in methods leads to inconsistencies in exosome composition, purity, and functionality, which can affect therapeutic outcomes and reproducibility across studies (Li et al., 2017). This lack of standardization poses significant challenges for regulatory approval.

Exosomes also present stability and storage issues, as their structural integrity and biological activity can be compromised under certain conditions, such as temperature fluctuations and prolonged storage. Maintaining stability without altering their functional properties remains a critical concern (Armstrong et al., 2017).

Additionally, there is limited understanding of their *in vivo* biodistribution and clearance mechanisms. Exosomes may accumulate in non-target organs such as the liver and spleen, potentially reducing delivery efficiency and raising concerns about unintended biological effects (Hoshino et al., 2015).

Another important concern is the risk of carrying unwanted or harmful biomolecules, particularly when derived from diseased or tumor cells. These exosomes may inadvertently promote pathological processes, necessitating careful selection and modification of donor cells (Kalluri et al., 2020).

Finally, regulatory and safety challenges remain significant barriers to clinical application. The complex nature of exosomes makes it difficult to classify them within existing regulatory frameworks, delaying their approval for therapeutic use (EL Andaloussi et al., 2013).

## VI. RECENT ADVANCES AND TRANSLATIONAL PERSPECTIVES

Rapid progress in exosome research over the past decade has significantly advanced their application as drug delivery systems. Between 2019

and 2026, numerous innovations have focused on improving targeting efficiency, cargo loading capacity, scalability, and clinical applicability. These developments have positioned exosomes as a promising platform in next-generation therapeutics, particularly within the framework of precision and personalized medicine. Despite these advancements, challenges related to manufacturing, regulatory approval, and standardization continue to influence their translational potential.

### 6.1 Engineered Exosomes

One of the most significant advancements in recent years is the development of engineered exosomes with enhanced functional properties. Native exosomes possess inherent targeting abilities; however, engineering strategies have been employed to further improve their specificity and therapeutic efficiency. Surface modification is a widely used approach, where targeting ligands such as peptides, antibodies, or aptamers are conjugated onto the exosomal membrane to facilitate selective binding to target cells (Kamerkar et al., 2017; Kalluri et al., 2020).

Genetic engineering of donor cells has also emerged as a powerful strategy to produce exosomes with desired characteristics. By transfecting cells with specific genes, exosomes can be enriched with therapeutic proteins, RNAs, or targeting molecules. For instance, exosomes engineered to express targeting peptides have demonstrated enhanced delivery of small interfering RNA (siRNA) to tumor cells, resulting in improved gene silencing and therapeutic outcomes (Alvarez-Erviti et al., 2011).

Another notable advancement is the use of exosome surface display technologies, which allow for the presentation of functional molecules on the exosome membrane. These modifications enhance cellular uptake and improve biodistribution profiles. Additionally, hybrid engineering approaches combining biological and chemical modifications have further expanded the versatility of exosome-based systems (Mentkowski et al., 2019).

### 6.2 Hybrid and Modified Nanocarriers

To overcome the limitations of natural exosomes, researchers have developed hybrid nanocarrier systems that integrate exosomes with synthetic nanoparticles. These hybrid systems aim to combine the advantages of both platforms, such as the biocompatibility of exosomes and the structural stability of synthetic carriers (Sato et al., 2016).

Exosome-liposome hybrids represent one of the most studied approaches, where exosomal membranes are fused with liposomes to enhance drug loading capacity and stability. These hybrid vesicles demonstrate improved pharmacokinetics and increased circulation time compared to native exosomes (Rayamajhi et al., 2019).

Polymer-based modifications have also been explored to improve exosome functionality. For example, coating exosomes with polyethylene glycol (PEG) can enhance their stability and reduce clearance by the reticuloendothelial system. Similarly, incorporation of magnetic nanoparticles enables controlled targeting through external magnetic fields, offering a novel strategy for site-specific drug delivery (Kim et al., 2018). Furthermore, bioinspired vesicles, such as exosome-mimetic nanovesicles, have been developed to address scalability issues. These vesicles are artificially generated but retain key characteristics of natural exosomes, allowing for large-scale production while maintaining functional efficiency (Jang et al., 2013).

### 6.3 Clinical Translation and Regulatory Challenges

Despite promising preclinical results, the clinical translation of exosome-based drug delivery systems remains in its early stages. Several clinical trials have been initiated to evaluate the safety and efficacy of exosome-based therapies, particularly in cancer and regenerative medicine (Kalluri et al., 2020). Early-phase studies have demonstrated favorable safety profiles, with minimal immunogenicity and toxicity.

However, multiple challenges must be addressed to enable successful clinical application. One of the primary concerns is the lack of standardized protocols for exosome isolation, purification, and characterization. Variability in production methods can lead to inconsistencies in exosome quality, composition, and therapeutic performance (Lener et al., 2015).

Scalability is another critical issue, as large-scale production of exosomes with consistent quality remains difficult. Current methods such as ultracentrifugation are not suitable for industrial-scale manufacturing, necessitating the development of more efficient and reproducible techniques (Armstrong et al., 2017).

Regulatory challenges also pose significant barriers to clinical translation. Exosomes are complex biological products, and their classification—whether as biologics, drug delivery

systems, or combination products—remains unclear. This ambiguity complicates the approval process and requires the establishment of specific regulatory guidelines (EL Andaloussi et al., 2013).

Additionally, safety concerns related to potential off-target effects and the presence of unwanted biomolecules must be carefully evaluated. Ensuring the purity and safety of exosome preparations is essential for minimizing risks associated with therapeutic use.

## VII. Conclusion

Exosomes have emerged as a highly promising platform in the field of targeted drug delivery, owing to their unique biological origin and functional versatility. Their ability to naturally transport a wide range of bioactive molecules, including proteins, lipids, and nucleic acids, enables efficient intercellular communication and therapeutic intervention. Unlike conventional drug delivery systems, exosomes offer distinct advantages such as high biocompatibility, low immunogenicity, and the capacity to cross complex biological barriers, including the blood–brain barrier, thereby expanding their applicability across diverse disease conditions (Yáñez-Mó et al., 2015).

The comprehensive understanding of exosome biology, including their biogenesis, molecular composition, and mechanisms of cellular uptake, has significantly contributed to their development as effective nanocarriers. Advances in drug loading strategies and surface engineering have further enhanced their targeting specificity and therapeutic efficiency. Moreover, their successful application in areas such as cancer therapy, neurological disorders, cardiovascular diseases, and metabolic conditions underscores their potential as versatile delivery systems in modern medicine (Kalluri et al., 2020).

Despite these promising attributes, several challenges continue to limit the clinical translation of exosome-based therapeutics. Issues related to large-scale production, lack of standardized isolation and characterization protocols, and concerns regarding stability and safety remain significant barriers. Additionally, regulatory complexities associated with their classification and approval further complicate their integration into clinical practice (Lener et al., 2015).

Recent advancements, particularly in engineered exosomes and hybrid nanocarrier systems, have addressed some of these limitations and provided new directions for improving their functionality and scalability. Ongoing clinical

studies are expected to provide further insights into their safety, efficacy, and long-term therapeutic potential.

In conclusion, exosomes represent a transformative approach in drug delivery, bridging the gap between biological systems and nanotechnology. Continued interdisciplinary research, coupled with technological innovations and regulatory advancements, is essential to fully harness their potential. With sustained progress, exosome-based drug delivery systems are likely to play a pivotal role in the advancement of precision medicine and the development of next-generation therapeutics.

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