Available online on 15.06.2026 at http://ajprd.com

Asian Journal of Pharmaceutical Research and Development

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Review Article

Exosomes: Emerging Therapeutic Nanocarriers in Drug Delivery & Disease Diagnostics

Chirag G. Chavda[1], Bhavin D. Pandya[1], Kautuk P. Shah[1], Ajay K. Saluja[1], Shreyash A. Diwakar[2]

[1]Krishna School of Pharmacy & Research, A Constituent School of Drs. Kiran & Pallavi Patel Global University (KPGU), Krishna Edu Campus, Varnama, Vadodara, Gujarat, India.

[2]Genezen Institute of Pharmacy, Delol, Godhra, Gujarat–389310, India

A B S T R A C T

Exosomes are naturally occurring extracellular vesicles with diameters ranging from approximately 30 to 150 nm, secreted by a wide variety of cell types. They serve as important mediators of intercellular communication by transporting bioactive molecules such as proteins, lipids, DNA, RNA, and other nucleic acids between cells. Owing to their inherent biocompatibility, structural stability, low immunogenicity, and ability to traverse biological barriers, including the blood–brain barrier, exosomes have emerged as highly promising nanocarriers for therapeutic and diagnostic applications. Unlike many synthetic delivery systems, such as liposomes and polymeric nanoparticles, exosomes exhibit enhanced resistance to metabolic degradation and possess natural targeting capabilities. Generated during various physiological and pathological processes, these vesicles have gained considerable interest in the field of precision medicine for their potential to address disease mechanisms at the molecular level. This review outlines the fundamental biology of exosomes, including their origin, classification, physicochemical characteristics, and cargo composition relevant to drug delivery. It further explores their therapeutic potential in areas such as cancer treatment, neurological diseases, and tissue regeneration. In addition, the application of exosome-based systems for the delivery of small-molecule drugs, proteins, and nucleic acids is discussed, along with an overview of leading organizations and research groups actively involved in the development and clinical evaluation of exosome-derived therapeutic platforms.

Keywords: Exosomes, Extracellular vesicles (EVs), Nano Targeted drug delivery Therapeutic nanocarriers, Disease diagnostics, Theranostics.

A R T I C L E I N F O: Received 15 Jan. 2026; Review Complete 26 April, 2026; Accepted 19 May. 2026; Available online 15 June. 2026

Cite this article as:

Chavda CG, Pandya BD, Shah KP, Saluja AK, Diwakar SA, Exosomes: Emerging Therapeutic Nanocarriers In Drug Delivery & Disease Diagnostics, Asian Journal of Pharmaceutical Research and Development. 2026; 14(3):-471-480.

DOI: **http://dx.doi.org/10.22270/ajprd.v14i3.1773**

*Address for Correspondence:

Chirag G. Chavda, Krishna School of Pharmacy & Research, A Constituent School of Drs. Kiran & Pallavi Patel Global University (KPGU), Krishna Edu Campus, Varnama, Vadodara, Gujarat–391243, India.

INTRODUCTION

Efficient drug distribution plays a vital role in ensuring the therapeutic effectiveness and safety of pharmaceutical agents. Over the years, various nanocarrier-based drug delivery systems, including liposomes, micelles, dendrimers, polymeric nanoparticles, and inorganic nanoparticles, have been developed to enhance modern drug administration. These delivery platforms are designed to optimize the pharmacokinetic and pharmacodynamic (PK–PD) profiles of drugs, thereby improving therapeutic outcomes while minimizing off-target effects, reducing drug-associated toxicity, and increasing the overall therapeutic index.[1]

Despite their advantages, these delivery systems encounter several limitations, such as restricted organ-specific targeting, toxicity arising from their physicochemical properties, and the potential to trigger undesirable immune responses.[1]To address these limitations, researchers have increasingly focused on developing innovative drug delivery strategies. Among the emerging technologies in nanomedicine, exosomes have attracted considerable interest

as a promising and versatile delivery platform. Exosomes are nanoscale extracellular vesicles, typically ranging from 30 to 100 nm in diameter, that are actively released by various cell types. They are naturally present in several biological fluids, including blood, cerebrospinal fluid, urine, and saliva, and serve as important mediators of intercellular communication through the transfer of bioactive molecules.[2]

These nanoscale vesicles exhibit unique characteristics that make them highly attractive candidates for drug delivery systems. They consist of a phospholipid bilayer membrane that encloses a wide range of bioactive molecules, including proteins, nucleic acids, and lipids, enabling efficient transport and communication between cells.[2]

Exosomes facilitate communication between cells through the transfer of bioactive molecules, including proteins, messenger RNAs (mRNAs), and microRNAs (miRNAs), to recipient cells, thereby modulating cellular activities and regulating various signalling pathways. Additionally, their ability to cross the blood–brain barrier (BBB) makes them particularly valuable for neurological applications, as they can improve nervous system function and motor performance. This unique capability also allows for the repeated intravenous administration of drug-loaded exosomes with minimal adverse effects, highlighting their potential as safe and effective therapeutic delivery vehicles.[1, 3]

The growing interest in exosomes as a drug delivery platform is largely attributed to their ability to overcome many of the limitations associated with conventional delivery systems. Exosomes possess excellent biocompatibility, high stability, and low immunogenicity, making them highly suitable for the targeted transport of therapeutic agents. Moreover, their natural ability to cross biological barriers and preferentially accumulate in specific cells or tissues improves delivery efficiency while minimizing unintended effects on non-target sites. In addition, the lipid bilayer structure of exosomes provides a protective microenvironment for encapsulated therapeutic cargo, shielding it from enzymatic degradation and thereby enhancing its stability and bioavailability.[4, 5]

Exosomes can be loaded with a wide range of biologically active molecules as well as compounds that are prone to degradation, making them effective and versatile carriers for the delivery and transport of such therapeutic agents.[6,7]

In recent years, substantial research efforts have been directed toward utilizing exosomes as advanced drug delivery vehicles. These natural nanocarriers demonstrate significant potential for transporting pharmaceuticals, genetic materials, and other therapeutic agents, which can be encapsulated within their lumen or attached to their surface through various engineering and modification strategies to enhance their functional properties. Therapeutic payloads may be incorporated into exosomes using multiple loading methods, including passive incubation and active techniques such as electroporation or sonication. Furthermore, exosomes can be surface-engineered to display specific ligands, peptides, or antibodies, facilitating targeted delivery to particular cells or tissues. In addition to drug delivery, exosomes have been extensively investigated for diverse biomedical applications, including vaccine development, photodynamic and immunotherapeutic interventions, gene editing and gene therapy, protein delivery, regenerative medicine, and numerous other therapeutic and diagnostic purposes.[1, 8, 9]

The aim of this review is to provide a thorough overview of the latest advances and research progress in the application of exosomes as therapeutic delivery vehicles. It offers a concise discussion of exosome classification, biological characteristics, and molecular composition. Furthermore, the review examines various strategies employed to engineer exosomes for targeted drug delivery and explores their applications in specific therapeutic areas, including oncology, neurological diseases, and regenerative medicine. It also highlights the use of exosomes for the delivery of a broad spectrum of therapeutic agents, such as small-molecule drugs, nucleic acids, and proteins, while emphasizing their emerging role in vaccine development.

In addition, the review addresses large-scale exosome production and industrial manufacturing approaches, with a focus on commercial organizations that have developed exosome-based platforms for medical applications. Future prospects, challenges, and opportunities associated with the development and optimization of exosome-mediated drug delivery systems are also discussed. By consolidating current knowledge and recent technological advancements, this review seeks to underscore the vast potential of exosomes as next-generation drug delivery carriers. A deeper understanding of these innovations can assist researchers and healthcare professionals in refining exosome-based therapeutic strategies and enhancing their clinical benefits. Ultimately, the utilization of exosomes as drug delivery vehicles holds significant promise for transforming the field of drug delivery, enabling more precise, effective, and targeted therapeutic interventions.

Types of Exosomes:

Exosomes are a specialized class of extracellular vesicles (EVs) that were initially identified as cellular structures involved in the removal of unwanted or waste materials. However, subsequent research has revealed their crucial role in intercellular communication, as they transport functional proteins, nucleic acids, metabolites, and other signalling molecules to recipient cells. These nanosized vesicles originate from endosomal compartments within cells and are released into the extracellular environment through a regulated biogenesis process. Exosomes contain a diverse range of bioactive constituents, including lipids, proteins, growth factors, nucleic acids, and various metabolites, which collectively contribute to their biological functions and therapeutic potential.[10, 11]

Exosome biogenesis occurs through a series of three key steps. First, the plasma membrane undergoes endocytosis, resulting in the formation of early endosomes, which subsequently mature into late endosomes. Second, the membrane of the late endosome invaginates inward, generating intraluminal vesicles (ILVs) within specialized structures known as multivesicular bodies (MVBs). Finally, these MVBs fuse with the plasma membrane of the parent cell, releasing the enclosed intraluminal vesicles into the extracellular environment. Once secreted, these vesicles are known as exosomes. [12]

Exosomes are nanosized, spherical vesicles enclosed by a lipid bilayer membrane and are secreted by virtually all cell types in the human body. Once released, they are distributed throughout the body via systemic circulation, facilitating communication between distant cells and tissues. Based on their origin and method of production, exosomes can generally be categorized into three groups: natural exosomes, engineered or modified exosomes, and artificial exosomes.Natural exosomes can be further classified into animal-derived and plant-derived exosomes. Animal-derived exosomes are commonly divided into those originating from normal cells and those derived from tumor cells. A wide variety of cell types, including epithelial cells, endothelial cells, mesenchymal stem cells (MSCs), macrophages, dendritic cells, and other immune cells, naturally secrete exosomes. The biological functions and therapeutic potential of exosomes largely depend on their cellular source. For example, MSC-derived exosomes have attracted considerable attention as promising therapeutic agents and drug delivery vehicles due to their regenerative and immunomodulatory properties. In contrast, macrophage-derived exosomes can influence the tumor microenvironment and have demonstrated notable antitumor effects. Variations in origin contribute to differences in exosomal composition, biological activity, drug-loading capacity, and therapeutic outcomes. The pronounced anticancer potential observed in macrophage-derived exosomes underscores the importance of source-specific characteristics in determining their biomedical applications.[3, 6]

Exosomes can be isolated from a variety of biological fluids, including blood, serum, urine, saliva, and milk. Their presence in these biofluids has attracted significant interest due to their potential applications in both diagnostics and therapeutics. For example, milk-derived exosomes have been successfully investigated as carriers for the delivery of therapeutic agents such as paclitaxel. Furthermore, exosomal microRNAs (miRNAs) present in serum have demonstrated value as diagnostic and prognostic biomarkers in conditions such as spinal cord injuries, while specific miRNA expression patterns in exosomes have shown promise for the early detection and monitoring of endometrial cancer.To enhance their therapeutic performance, naturally derived exosomes can be engineered or modified to improve drug loading efficiency, targeting capability, biodistribution, and overall therapeutic efficacy. Such modifications can be achieved through two principal approaches: alteration of the exosomal cargo within the vesicle or modification of the exosomal surface to enhance targeting and functionality.In addition to natural and engineered exosomes, artificial or synthetic exosomes have been developed to replicate the structural and functional characteristics of their natural counterparts. These biomimetic vesicles are typically produced using two major strategies: cell-based approaches, which utilize cellular components to generate exosome-like vesicles, and lipid membrane engineering techniques, which construct vesicles from synthetic or biologically derived lipid membranes. These methods enable the creation of exosome-inspired delivery systems with customizable properties for therapeutic applications.[3, 6, 13]

Tumor-derived exosomes possess unique surface antigens that mirror the characteristics of their parent cancer cells, making them highly significant in oncology research. These vesicles play important roles in tumor progression by regulating cancer cell proliferation, metastasis, immune modulation, and intercellular communication within the tumor microenvironment. In addition, they have emerged as valuable biomarkers for cancer diagnosis, prognosis, and disease monitoring. For instance, a study by Wu and colleagues demonstrated that suppressing exosome secretion in colorectal cancer may help reduce metastatic spread, highlighting the therapeutic potential of targeting exosome-mediated pathways.Plant-derived exosome-like nanoparticles (ELNs), obtained from edible sources such as ginger, grapes, carrots, and grapefruit, share several structural and functional similarities with mammalian exosomes. These naturally occurring nanovesicles have attracted growing attention due to their biocompatibility and therapeutic potential. Research suggests that plant-derived ELNs may contribute to the prevention and management of liver disorders and support intestinal health by exerting anti-inflammatory and protective effects, making them promising candidates for future drug delivery and nutraceutical applications.[6, 14, 15]

Characteristics, Composition and Isolation of Exosomes:

Exosomes are nanosized, membrane-enclosed vesicles characterized by their distinctive size, lipid composition, and protein content. Typically ranging from 30 to 100 nm in diameter, these spherical structures are surrounded by a phospholipid bilayer membrane. Their small size and streamlined architecture enable them to efficiently circulate within biological systems and cross physiological barriers such as the blood–brain barrier (BBB), making them attractive candidates for drug delivery applications. Exosomes originate from the endosomal compartment of parent cells and are released into the extracellular environment through a regulated secretion process.The molecular composition of exosomes is highly complex and includes a diverse array of proteins, lipids, and nucleic acids. Commonly identified proteins include heat shock proteins (HSP70 and HSP90), membrane transport and fusion proteins, GTPases, annexins, flotillin, and members of the tetraspanins family such as CD9, CD63, CD81, and CD82. Among these, integrins and tetraspanins are particularly abundant and play important roles in exosome function. Integrins facilitate cell adhesion and contribute to the interaction of exosomes with target cells, while proteins such as thrombospondin, CD55, CD59, lactadherin, ALIX, and TSG101 are frequently used as exosomal markers. Exosomes are also enriched with proteins from the Rab family, which are involved in vesicle trafficking and secretion.In addition to proteins, exosomes contain a variety of lipids, including sphingomyelin, phosphatidylcholine, phosphatidylethanolamine, phosphatidylserine, phosphatidylinositol, and gangliosides such as GM3. These lipids contribute to membrane stability, structural integrity, and interactions with extracellular proteins. Furthermore, exosomes carry genetic material in the form of messenger RNA (mRNA) and various non-coding RNAs, enabling them to regulate gene expression and cellular functions in recipient cells.Despite their considerable therapeutic and diagnostic potential, exosome research continues to face several technical challenges. These include the need for more efficient isolation and purification techniques, improved

methods for distinguishing exosomes from other extracellular vesicles, enhanced analytical and characterization tools, and strategies to increase production yield. Overcoming these limitations is essential for the successful clinical translation of exosome-based therapies and requires the development of rapid, reliable, and scalable isolation and characterization technologies.[16–20]

Exosome isolation is a fundamental step in biological and biomedical research, and significant progress has been made in developing more efficient and reliable separation techniques. Traditional methods such as differential centrifugation and ultracentrifugation continue to be widely employed due to their robustness, reproducibility, and established reliability. However, newer approaches have been introduced to overcome the limitations associated with conventional techniques. Ultrafiltration offers an effective means of concentrating exosomes, whereas size-exclusion chromatography enhances sample purity and recovery efficiency. Precipitation-based methods, including commercially available isolation kits, provide simple, rapid, and user-friendly alternatives for exosome extraction. Immunoaffinity capture techniques utilize exosome-specific surface markers and antibodies to achieve highly selective isolation of targeted exosome populations. Additionally, microfluidic technologies have emerged as promising platforms for rapid, sensitive, and precise exosome isolation, particularly in point-of-care and clinical diagnostic applications.Collectively, these advancements have enabled more efficient, selective, and application-specific exosome isolation strategies, thereby accelerating progress in diagnostics, therapeutic development, and the study of intercellular communication.[20–23]

Application of Exosomes as Therapeutic agents:

Exosomes have gained global recognition as versatile biomaterials with broad applications in modern biomedicine and are increasingly being utilized to develop more effective therapeutic strategies for a wide range of diseases. Initially regarded as cellular waste products, exosomes have, over the past two decades, been recognized as important mediators of intercellular communication with significant diagnostic and therapeutic value. Their natural targeting ability, excellent stability, and biological compatibility make them attractive candidates for clinical applications.Due to their nanoscale size, biocompatibility, low immunogenicity, biodegradability, stability, and minimal toxicity, exosomes serve as highly effective drug delivery vehicles capable of transporting therapeutic agents to specific target sites. They have been explored for numerous biomedical applications, including immunotherapy, gene delivery, vaccine development, tissue engineering and regeneration, as well as biomarker-based diagnosis and treatment of diseases such as cancer, cardiovascular disorders, diabetes, and neurological conditions. Furthermore, surface modification techniques can enhance exosomal targeting efficiency, biodistribution, and therapeutic performance. Once they reach their target cells, exosomes can release their cargo through membrane fusion or cellular uptake mechanisms such as endocytosis and phagocytosis, enabling efficient delivery of therapeutic payloads.[3, 16]

Exosomes as drug delivery system for therapeutic molecules and biomolecules:

Exosomes are extracellular membrane-bound vesicles secreted by a wide variety of cells and play a fundamental role in intercellular communication and the regulation of physiological processes. In addition to their biological functions, they have emerged as highly effective carriers for the delivery of therapeutic agents across cellular membranes. Owing to their unique characteristics—including excellent biocompatibility, low toxicity, prolonged circulation, and target specificity; exosomes and exosome-mimetic vesicles are considered superior drug delivery platforms.Compared with conventional delivery systems such as liposomes, polymeric nanoparticles, and metallic nanomaterials, exosomes offer enhanced delivery efficiency and greater targeting precision. Exosomes derived from immune cells, tumor cells, and mesenchymal stem cells (MSCs) have shown considerable promise as nanoscale carriers for drugs, biomolecules, and other therapeutic agents. For example, studies have demonstrated that exosome-encapsulated curcumin exhibits improved solubility, stability, and bioavailability compared with free curcumin. In animal models of Alzheimer's disease, this formulation enhanced cognitive performance and produced significant neuroprotective and anti-Alzheimer effects, highlighting the therapeutic potential of exosome-based drug delivery systems.[3, 40, 41]

Both in-vitro and in-vivo studies have demonstrated that antibiotic-loaded exosomes can provide superior therapeutic outcomes compared with the administration of free antibiotics alone. For example, research has shown that exosomes derived from mouse RAW264.7 macrophages and loaded with linezolid, an antibiotic effective against methicillin-resistant *Staphylococcus aureus* (MRSA), achieved greater infection control than free linezolid while exhibiting no significant cytotoxic effects on macrophages. This finding highlights the potential of exosome-based systems to enhance antimicrobial efficacy and targeted drug delivery.Beyond antibiotics, exosomes are capable of transporting a wide range of bioactive molecules, including proteins, nucleic acids, growth factors, and lipids, to specific target cells. Through the delivery of these molecular cargos, exosomes can influence gene expression and modulate both physiological and pathological processes. Their ability to efficiently transport therapeutic agents to desired sites has generated considerable interest in applications such as gene therapy, RNA interference, and other advanced treatment strategies aimed at regulating cellular and genetic functions.[17, 42]

Exosomes for delivery of Proteins:

Exosomes are naturally occurring nanovesicles that possess an intrinsic ability to transport protein cargo to recipient cells, making them promising vehicles for the targeted treatment of various diseases. Since exosomes secreted by most cell types naturally carry endogenous proteins, they serve as efficient biological carriers for the delivery of therapeutic proteins and peptides. This inherent protein-transport capability highlights the suitability of exosome-based systems as effective platforms for protein and peptide delivery in advanced therapeutic applications.[43]

Exosomes are naturally occurring membrane-bound vesicles that can carry a variety of protein ligands and bioactive molecules. During their formation, these molecules become organized within specialized microdomains inside the exosomal membrane, providing a protective and biologically relevant environment for biomacromolecules. This natural membrane architecture helps preserve the structural integrity and biological activity of membrane-associated proteins, thereby enhancing the effectiveness of protein-based therapies.For example, researchers have developed GALA-modified exosomes by engineering dendritic cell-derived exosomes with pH-responsive GALA peptides. These engineered vesicles were designed to contain streptavidin (SAV), a protein with strong affinity for biotin, along with lactadherin (LA), an exosome-targeting protein. Such modified exosomes have demonstrated potential for improving antigen delivery and facilitating intercellular communication within tumor environments. Similarly, exosomes loaded with immunomodulatory molecules such as ovalbumin or α-galactosyl ceramide have shown the ability to stimulate adaptive immune responses while minimizing the induction of invariant natural killer T-cell anergy, highlighting their promise as advanced platforms for immunotherapy and vaccine development.[44, 45, 57, 58]

Researchers have developed exosome-based delivery platforms to transport therapeutic proteins across the blood–brain barrier, thereby enhancing treatment strategies for neurological disorders. For instance, exosome-mediated delivery of the antioxidant enzyme catalase has been shown to reduce neuroinflammation and holds promise for the management of neurodegenerative diseases. Similarly, exosomes loaded with PH20 hyaluronidase have been engineered to improve tumor penetration by degrading hyaluronan within the tumor extracellular matrix, facilitating more effective therapeutic delivery.In another study, exosome-mediated delivery of signal-regulatory protein-α (SIRPα) demonstrated greater antitumor efficacy compared with conventional delivery using ferritin-based nanocages, resulting in enhanced inhibition of tumor growth. Although protein nanocages remain a widely used platform for protein therapeutics, exosome-based systems are increasingly being explored as superior alternatives due to their natural targeting ability, biocompatibility, and improved delivery efficiency.[1, 8, 44]

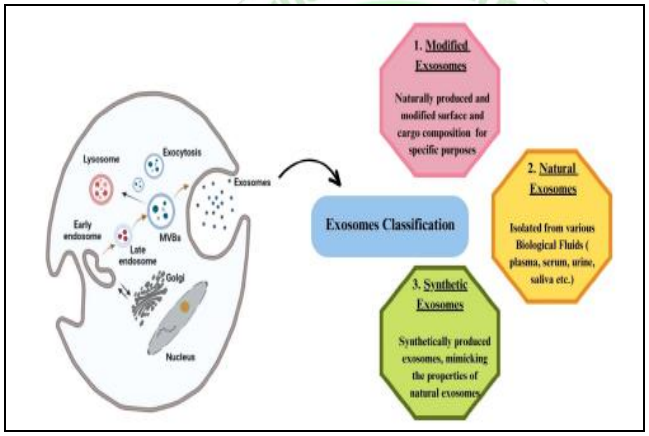

Figure 1: Biogenesis of exosome and its classification in accordance with origin.

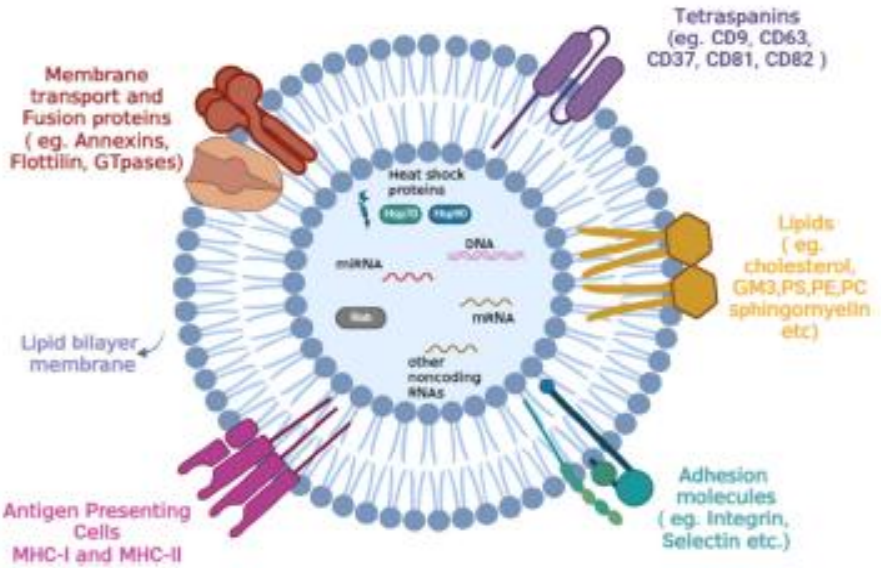

Figure 2: Composition of Exosome.

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Exosomes in delivery of genetic substances and gene therapy:

Exosomes have emerged as highly effective gene delivery vehicles due to their natural ability to protect nucleic acids from degradation and facilitate targeted intracellular transport. They are particularly valuable for delivering RNA-based therapeutics, such as small interfering RNAs (siRNAs) and microRNAs (miRNAs), which regulate gene expression and are often preferred over DNA-based therapies because of their lower risk of genetic mutation. Since these RNA molecules are highly susceptible to enzymatic degradation and cellular entrapment, exosomes provide a protective and biocompatible delivery platform that enhances their stability, circulation time, and therapeutic efficacy.Stem cell-derived exosomes have shown considerable promise in gene therapy, especially for cardiovascular diseases, by efficiently transporting nucleic acid cargo to target cells. In cancer therapy, miRNA-loaded exosomes have demonstrated the ability to suppress tumor growth and invasion in both laboratory and animal studies. Furthermore, exosomes are being explored as carriers for advanced gene-editing technologies such as CRISPR/Cas9. Engineered exosomes loaded with CRISPR/Cas9 components have successfully achieved targeted gene delivery, highlighting their potential in precision medicine. Additionally, exosome-associated mRNA delivery has shown promise in treating conditions such as familial hypercholesterolemia by reducing liver lipid accumulation and lowering circulating LDL cholesterol levels. Overall, exosomes represent a safe, efficient, and targeted platform for next-generation gene therapy applications.[16, 60]

Exosome based drug delivery vehicles for Cancer treatment:

Effective cancer treatment requires precise delivery of therapeutic agents to tumor cells while minimizing damage to healthy tissues. Exosome-based nanocarriers have emerged as promising platforms in oncotherapy due to their natural targeting ability, biocompatibility, low immunogenicity, and enhanced stability compared with conventional delivery systems such as liposomes, micelles, synthetic polymers, and viral vectors. Their ability to protect therapeutic cargo and selectively transport itto tumor sites makes them attractive candidates for targeted cancer therapy.Unlike viral vectors, exosomes present a lower risk of toxicity and insertional mutagenesis. Moreover, their surfaces can be engineered with specific ligands or peptides to improve cell-specific targeting and therapeutic efficacy. Exosomes are also being explored for the delivery of small RNAs, including siRNAs and miRNAs, to regulate disease-related gene expression.Several studies have demonstrated the effectiveness of engineered exosomes in cancer treatment. For example, dendritic cell-derived exosomes modified with the tumor-penetrating peptide iRGD and loaded with doxorubicin exhibited significantly enhanced tumor targeting and antitumor activity. In animal models of breast cancer, these engineered exosomes inhibited tumor growth far more effectively than free doxorubicin or unmodified

exosomes.Exosomes have also shown promise in the treatment of triple-negative breast cancer (TNBC). Exosome-coated siRNA nanoparticles targeting the metastasis-associated gene S100A4 successfully protected siRNA from degradation, improved drug delivery, and significantly suppressed tumor progression and postoperative metastasis in preclinical studies.In addition, exosome-mediated miRNA replacement therapy has demonstrated encouraging results. Exosomes engineered with the EGFR-targeting peptide GE11 were used to deliver the tumor-suppressive let-7a miRNA to breast cancer cells, resulting in efficient cellular uptake and significant inhibition of tumor growth in animal models.Beyond oncology, surface-modified exosomes have also been investigated for other diseases. For instance, exosomes functionalized with the c(RGDyK) peptide and loaded with curcumin successfully targeted ischemic brain lesions and reduced inflammation in experimental models of cerebral ischemia.Overall, engineered exosomes offer a highly promising, targeted, and minimally immunogenic platform for cancer therapy and other precision medicine applications.[61–64]

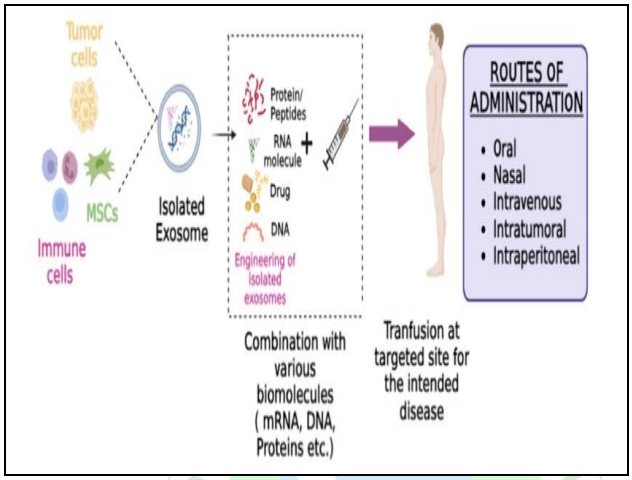

Figure 3: An overview of drug delivery using exosomes.

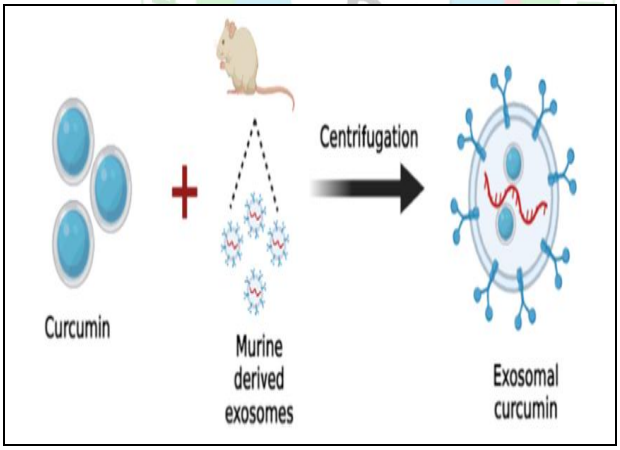

Figure 4: Exosomal curcumin formation by incorporation into murine tumor cell derived exosomes**.**

Exosome based drug delivery vehicles for Parkinson's disease:

Parkinson's disease (PD) is a common age-related neurodegenerative disorder, and effective treatment is often limited by the inability of therapeutic agents to cross the blood–brain barrier (BBB). Due to their nanoscale size and natural BBB-penetrating capability, exosomes have emerged as promising delivery vehicles for neurological therapies. Studies have shown that dopamine-loaded exosomes can efficiently transport dopamine to the brain, producing better therapeutic outcomes than free dopamine in PD models. Additionally, mesenchymal stem cell-derived exosomes promote neurogenesis, restore dopaminergic neurons, and reduce neuroinflammation. Exosome-mediated delivery of α-synuclein antisense oligonucleotides has also demonstrated reduced protein accumulation and improved motor function in experimental Parkinson's disease models. [46, 59, 65–67]

Development and Commercial Therapeutic Materials:

Among the many therapeutic applications of exosomes, one of the most rapidly advancing areas in biomedical engineering is their use as vaccine delivery vehicles. Owing to their excellent biocompatibility, low toxicity, and minimal immunogenicity, exosomes have attracted significant interest as platforms for the development of cell-free vaccines. Researchers are actively exploring

exosome-based vaccines for the prevention and treatment of cancer as well as a wide range of viral and non-viral infectious diseases, recognizing their potential to provide safe and effective immune stimulation.[3, 68]

Exosomes possess the ability to efficiently transport antigens to target cells, making them attractive candidates for the development of virus-free vaccine platforms. Their natural delivery capabilities have been increasingly explored for vaccine applications, including those targeting SARS-CoV-2. In particular, mesenchymal stem cell (MSC)-derived exosomes, known for their pro-angiogenic, anti-inflammatory, and immunomodulatory properties, have been investigated as potential components of next-generation vaccine systems. Exosome-based antigen delivery offers a versatile approach for the rapid development of multivalent protein vaccines capable of addressing emerging viral variants and reducing disease transmission. Notably, clinical evaluation of the STX vaccine has demonstrated encouraging results, highlighting the effectiveness of exosome-mediated protein delivery for SARS-CoV-2 immunization. [69]

The successful advancement of several biotechnology and pharmaceutical companies has accelerated the development of exosome-based therapeutic products and drug delivery platforms, many of which are currently undergoing preclinical and clinical evaluation. Extensive research in this field has led to numerous innovations, patents, and intellectual property related to exosome production, isolation, engineering, delivery, and therapeutic applications. Exosomes and microRNA-based technologies have shown considerable potential in promoting tissue repair and regeneration. In particular, surface-engineered exosomes have been designed to enhance targeting efficiency and achieve specific therapeutic outcomes. Furthermore, exosome-derived lipid nanovesicles carrying selected nucleic acids and modified surface proteins have emerged as innovative therapeutic tools for neurological disorders characterized by demyelination, such as multiple sclerosis (MS), by supporting remyelination and neural repair processes.[3, 33]

Future Perspectives:

Exosomes have attracted considerable attention as advanced therapeutic carriers due to their ability to efficiently deliver a wide range of natural and synthetic therapeutic agents. Their inherent biocompatibility, biodegradability, low toxicity, stability, and ability to cross the blood–brain barrier make them highly advantageous for drug delivery applications. Naturally secreted by various cell types, exosomes have shown potential in the diagnosis and treatment of numerous diseases, including neurological, cardiovascular, immunological, and dermatological disorders. They are also being explored for vaccine development, tissue regeneration, and gene therapy. Surface engineering strategies further enhance their targeting ability and therapeutic efficacy, while their unique structure protects nucleic acids from degradation, improving the delivery of biomolecules such as siRNA, DNA, and mRNA. Despite these advantages, challenges related to large-scale production, safety characterization, manufacturing costs, immune responses, and clinical translation remain. Nevertheless, ongoing efforts by pharmaceutical and biotechnology companies have led to the development of several exosome-based therapeutic platforms that are currently advancing through clinical evaluation.

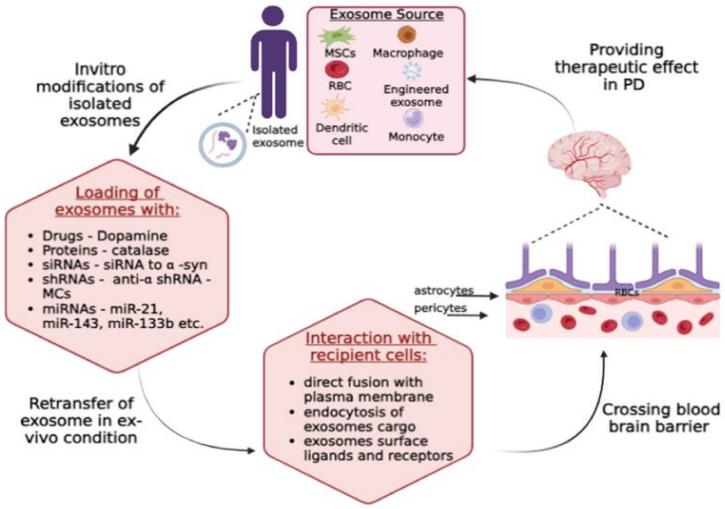

Figure 5: Pharmacodynamic therapy using exosomes as nano-delivery systems.

CONCLUSION:

Exosomes have emerged as highly promising natural nanocarriers with significant applications in drug delivery, disease diagnosis, and precision medicine. Their excellent biocompatibility, low immunogenicity, ability to cross biological barriers, and capacity to transport diverse therapeutic molecules provide distinct advantages over conventional synthetic delivery systems. Advances in understanding exosome biogenesis, cargo loading, and surface engineering have improved their targeting capabilities and therapeutic effectiveness. In parallel, exosomes have gained recognition as valuable diagnostic biomarkers due to their stability in biological fluids and their ability to reflect the molecular characteristics of

their parent cells, making them particularly useful for liquid biopsy applications in cancer, neurological, cardiovascular, and infectious diseases. Despite their immense potential, challenges such as standardized isolation methods, scalable manufacturing, efficient cargo loading, and a better understanding of their in vivo behavior remain. Continued progress in exosome engineering, large-scale production, synthetic biology, and microfluidic technologies is expected to accelerate their clinical translation, positioning exosome-based therapeutics and diagnostics as key components of future personalized healthcare and nanomedicine.

REFERENCES:

1. Sen S, Xavier J, Kumar N, Ahmad M, Ranjan O, "Exosomes as natural nanocarrier-based drug delivery system: recent insights and future perspectives", *Biotech*,**2023**, 13:101.
2. Doyle L, Wang M,"Overview of extracellular vesicles, their origin, composition, purpose, and methods for exosome isolation and analysis", *Cells*,**2019**, 8:727.
3. Kucuk N, Primozic M, Knez Z, Leitgeb M,"Exosomes engineering and their roles as therapy delivery tools, therapeutic targets, and biomarkers",*Int J Mol Sci*. **2021**, 22:43–95.
4. Kim H, Jang H, Cho H, "Recent advances in exosome-based drug delivery for cancer therapy"*Cancers*,**2021**, 13: 35–44.
5. Akuma P, Okagu O, Udenigwe C, "Naturally occurring exosome vesicles as potential delivery vehicle for bioactive compounds"*Front Sustain Food Syst*,**2019**,3: 23.
6. Zhang Y, Bi J, Huang J, Tang Y, Du S, Li P, "Exosome: a review of its classification, isolation techniques, storage, diagnostic and targeted therapy applications"*Int J Nanomed*,**2020**, 15:6917–6934.
7. Daßler-Plenker J, Kuttner V, Egeblad M,"Communication in tiny packages: exosomes as means of tumor-stroma communication"*Biochim Biophys Acta Rev Cancer*,**2020**, 1834–1873.
8. Chen H, Wang L, Zeng X, "Exosomes, a new star for targeted delivery"*Front Cell Dev Biol*.,**2021**, 9:27, 28.
9. Liang Y, Duan L, Lu J, Xia J,"Engineering exosomes for targeted drug delivery. *Theranostics*,**2021**, 11:31–33.
10. Johnstone R, Adam M, Hammond J, Orr L, Turbide C,"Vesicle formation during reticulocyte maturation: Association of plasma membrane activities with released vesicles (exosomes)"*J. Biol. Chem*.,**1987**, 262:9412–9420.
11. Simons M, Raposo G, "Exosomes: vesicular carriers for intercellular communication"*Curr. Opin. Cell Biol*. **2009**, 21:575–581.
12. Qin J, Xu Q, "Functions and application of exosomes" *Acta Pol Pharm*.,**2014**, 71:537–543.
13. Agrawal AK, Aqil F, Jeyabalan J,"Milk-derived exosomes for oral delivery of paclitaxel"*Nanomed Nanotechnol. Biol. Med*., **2017**, 13:1627–1636.
14. Wu B, Sun D, Ma L, et al. Exosomes isolated from CAPS1-overexpressing colorectal cancer cells promote cell migration. *Oncol Rep*.,**2019**, 42:2528–2536.
15. Mu J, Zhuang X, Wang Q,"Interspecies communication between plant and mouse gut host cells through edible plant derived exosome-like nanoparticles" *Mol Nutr Food Res*.,**2014**, 58:1561–1573.
16. Ha D, Yang N, Nadithe V,"Exosomes as therapeutic drug carriers and delivery vehicles across biological membranes: current perspectives and future challenges"*Acta Pharm Sin B*.,**2016**,6:287–296.
17. Vlassov AV, Magdaleno S, Setterquist R, Conrad R, "Exosomes: current knowledge of their composition, biological functions, and diagnostic and therapeutic potentials" *Biochim Biophys Acta Gen Subj*.,**2012**,18 (20):940–948.
18. Kalani A, Tyagi A, Tyagi N,"Exosomes: mediators of neurodegeneration, neuroprotection and therapeutics"*Mol Neurobiol*.,**2014**,49:590–600.
19. Subra C, Laulagnier K, Perret B, Record M, "Exosome lipidomic unravels lipid sorting at the level of multivesicular bodies"*Biochimie*,**2007**, 89:205–212.
20. Liu W-z, Ma Z-j, Kang X-w, "Current status and outlook of advances in exosome isolation"*Anal Bioanal Chem*,**2022**, 414:7123–7141.
21. Yu L-L, Zhu J, Liu J-X, "A comparison of traditional and novel methods for the separation of exosomes from human samples"*BioMed Res Int*.,**2018**, 34–36.
22. Sidhom K, Obi P, Saleem A, "A review of exosomal isolation methods: is size exclusion chromatography the best option"*Int J Mol Sci*.,**2020**, 21:64–66.
23. Martins T, Vaz M, Henriques A,"A review on comparative studies addressing exosome isolation methods from body fluids"*Anal Bioanal Chem*.**2023**, 415: 1239–1263.
24. Shi J, Zhang Y, Yao B, "Role of exosomes in the progression, diagnosis, and treatment of gliomas"*Med Sci Mon Int Med J Exp Clin Res: international medical journal of experimental and clinical research*,**2020**, 26, 924021–924023.
25. Whiteside T,"Exosomes carrying immunoinhibitory proteins and their role in cancer" *Clin Exp Immunol*.,**2017**, 189:259–267.
26. Li S-p, Lin Z-x, Jiang X-y, Yu X-y. Exosomal cargo-loading and synthetic exosome-mimics as potential therapeutic tools. *Acta Pharmacol Sin*.,**2018**, 39:542–551.
27. O'Brien K, Breyne K, Ughetto S, Laurent L, Breakefield X, "RNA delivery by extracellular vesicles in mammalian cells and its applications"*Nat Rev Mol Cell Biol*., **2020**, 21:585–606.
28. Sarko D, McKinney C, "Exosomes: origins and therapeutic potential for neurodegenerative disease" *Front Neurosci*. **2017**, 11:82.
29. Luarte A, B´atiz LF, Wyneken U, Lafourcade C,"Potential therapies by stem cell-derived exosomes in CNS diseases: focusing on the neurogenic niche"*Stem Cell Int*., **2016**, 59, 60.
30. Liu C, Su C, "Design strategies and application progress of therapeutic exosomes"*Theranostics*,**2019**, 9:10–15.
31. Hu Q, Su H, Li J, et al. Clinical applications of exosome membrane proteins. *Precision Clinical Medicine*,**2020**, 3:54–66.
32. Zhu L, Oh JM, Gangadaran P, "Targeting and therapy of glioblastoma in a mouse model using exosomes derived from natural killer cells"*Front Immunol*.,**2018**, 9.
33. Abdelsalam M, Ahmed M, Osaid Z, Hamoudi R, Harati R. Insights into exosome transport through the blood–brain barrier and the potential therapeutical applications in brain diseases. *Pharmaceuticals*.,**2023**, 16:571.
34. Hao S-C, Ma H, Niu Z-F, Sun S-Y, Zou Y-R, Xia H-C,"hUC-MSCs secreted exosomes inhibit the glioma cell progression through PTENP1/miR-10a-5p/PTEN pathway"*Eur Rev Med Pharmacol Sci*.,**2019**, 23:10013–10023.
35. Liu C-G, Song J, Zhang Y-Q, Wang P-C. "MicroRNA-193b is a regulator of amyloid precursor protein in the blood and cerebrospinal fluid derived exosomal microRNA- 193b is a biomarker of Alzheimer's disease"*Mol Med Rep*.,**2014**, 10:2395–2400.
36. Pusic AD, Pusic KM, Kraig RP,"What are exosomes and how can they be used in multiple sclerosis therapy"*Expert Rev Neurother*.,**2014**, 14:353–355.
37. Xin H, Li Y, Buller B, "Exosome-mediated transfer of miR-133b from multipotent mesenchymal stromal cells to neural cells contributes to neurite outgrowth"*Stem Cell*., **2012**, 30:1556–1564.
38. Zhang Z, Chopp M,"Exosomes in stroke pathogenesis and therapy"*J. Clin. Invest*., **2016**, 126:1190–1197.
39. Xiong Y, Mahmood A, Chopp M,"Emerging potential of exosomes for treatment of traumatic brain injury"*Neural Regener Res*.,**2017**, 12–19.
40. Gutierrez-Millan C, Calvo Díaz C, Lanao J, Colino C,"Advances in exosomes-based drug delivery systems"*Macromol Biosci*.,**2021**, 21, 60–69.
41. Wang H, Sui H, Zheng Y, "Curcumin-primed exosomes potently ameliorate cognitive function in AD mice by inhibiting hyperphosphorylation of the Tau protein through the AKT/GSK-3β pathway"*Nanoscale*.,**2019**, 11:7481–7496.
42. Yang X, Shi G, Guo J, Wang C, He Y, "Exosome-encapsulated antibiotic against intracellular infections of methicillin-resistant Staphylococcus aureus"*Int. J. Nanomed*., **2018**, 13:80–95.
43. Graner M, Alzate O, Dechkovskaia A, "Proteomic and immunologic analyses of brain tumor exosomes"*Faseb J*., **2009**, 23:15–41.
44. Cho E, Nam G-H, Hong Y, "Comparison of exosomes and ferritin protein nanocages for the delivery of membrane protein therapeutics"*J. Contr. Release*.,**2018**, 279:326–335.
45. Th´ery C, Zitvogel L, Amigorena S, "Exosomes: composition, biogenesis and function" *Nat Rev Immunol*.,**2002**, 2:569–579.
46. Qu M, Lin Q, Huang L, "Dopamine-loaded blood exosomes targeted to brain for better treatment of Parkinson's disease"*J. Contr. Release*,**2018**, 287:156–166.
47. Sun D, Zhuang X, Xiang X, "A novel nanoparticle drug delivery system: the anti-inflammatory activity of curcumin is enhanced when encapsulated in exosomes"*Mol Ther*. **2010**, 18:1606–1614.
48. Saari H, L´azaro-Ib´a˜nez E, Viitala T, Vuorimaa-Laukkanen E, Siljander P, Yliperttula M, "Microvesicleand exosome-mediated drug

delivery enhances the cytotoxicity of Paclitaxel in autologous prostate cancer cells"*J. Contr. Release*,**2015**, 220:727–737.
49. Tian Y, Li S, Song J,"A doxorubicin delivery platform using engineered natural membrane vesicle exosomes for targeted tumor therapy"*Biomaterials*,**2014**, 35: 2383–2390.
50. Lai R, Tan S, Teh B, "Proteolytic potential of the MSC exosome proteome: implications for an exosome-mediated delivery of therapeutic proteasome"*Int. J. Proteomic*,**2012**, 907–971.
51. Kooijmans S, Aleza C, Roffler S, van-solinge W, Vader P,Schiffelers R,"Display of GPI-anchored anti-EGFR nanobodies on extracellular vesicles promotes tumour cell targeting"*J. Extracell Vesicles*,**2016**, 5: 310–353.
52. Aspe J, Diaz Osterman C, Jutzy J, Deshields S, Whang S, Wall N,"Enhancement of Gemcitabine sensitivity in pancreatic adenocarcinoma by novel exosome-mediated delivery of the Survivin-T34A mutant"*J. Extracell Vesicles*,**2014**, 3: 232–244.
53. Limoni S, Moghadam M, Moazzeni S, Gomari H, Salimi F,"Engineered exosomes for targeted transfer of siRNA to HER2 positive breast cancer cells"*Appl. Biochem. Biotechnol*.,**2019**, 187:352–364.
54. Vinas J, Burger D, Zimpelmann J, "Transfer of microRNA-486-5p from human endothelial colony forming cell–derived exosomes reduce ischemic kidney injury" *Kidney Int*.,**2016**, 90:1238–1250.
55. Skog J, Wurdinger T, Van Rijn S, "Glioblastoma microvesicles transport RNA and proteins that promote tumour growth and provide diagnostic biomarkers"*Nat Cell Biol*., **2008**, 10:1470–1476.
56. Alhasan A, Patel P, Choi C, Mirkin C,"Exosome encased spherical nucleic acid gold nanoparticle conjugates as potent microRNA regulation agents" *Small*,**2014**, 10: 186–192.
57. Peng H, Ji W, Zhao R, "Exosome: a significant nano-scale drug delivery carrier"*J. Mater Chem. B*., **2020**, 8:7591–7608.
58. Gehrmann U, Hiltbrunner S, Georgoudaki A, Karlsson M, N-aslund T, Gabrielsson S, "Synergistic induction of adaptive antitumor immunity by codelivery of antigen with α-galactosyl ceramide on exosomes" *Cancer Res*.,**2013**, 73:3865–3876.
59. Kobayashi M, Sawada K, Miyamoto M, "Exploring the potential of engineered exosomes as delivery systems for tumor-suppressor microRNA replacement therapy in ovarian cancer"*Biochem. Biophys. Res. Commun*.,**2020**, 527:153–161.
60. Ye Y, Zhang X, Xie F, "An engineered exosome for delivering sgRNA: Cas9 ribonucleoprotein complex and genome editing in recipient cells"*Biomater. Sci*. **2020**, 8:2966–2976.
61. Yin H, Yang J, Zhang Q, Wang H, Xu J, Zheng J, "iRGD as a tumor-penetrating peptide for cancer therapy"*Mol Med Rep*.,**2017**, 15:2925–2930.
62. Zhao L, Gu C, Gan Y, Shao L, Chen H, Zhu H,"Exosome-mediated siRNA delivery to suppress postoperative breast cancer metastasis"*J. Contr. Release*,**2020**, 318:1–15.
63. Ohno S, Takanashi M, Sudo K, "Systemically injected exosomes targeted to EGFR deliver antitumor microRNA to breast cancer cells"*Mol. Ther*., **2013**, 21(1): 185–191.
64. Tian T, Zhang HX, He C, "Surface functionalized exosomes as targeted drug delivery vehicles for cerebral ischemia therapy"*Biomaterials*. **2018**, 150: 137–149.
65. Yu H, Sun T, An J,"Potential roles of exosomes in Parkinson's disease: from pathogenesis, diagnosis, and treatment to prognosis."*Front Cell Dev Biol*.,**2020**, 8:86.
66. Vilaca-faria H, Salgado A, Teixeira F, "Mesenchymal stem cells-derived exosomes: a new possible therapeutic strategy for Parkinson's disease"*Cells*,**2019**, 8:118.
67. Yang J, Luo S, Zhang J, "Exosome-mediated delivery of antisense oligonucleotides targeting α-synuclein ameliorates the pathology in a mouse model of Parkinson's disease"*Neurobiol. Dis*.,**2021**, 148, 105–118.
68. Santos P, Almeida F, "Exosome-based vaccines: history, current state, and clinical trials"*Front Immunol*.,**2021**, 12, 511–565.
69. Cacciottolo M, Nice J, Li Y, "Exosome-based multivalent vaccine: achieving potent immunization, broadened reactivity, and strong T-cell responses with nanograms of proteins"*Microbiol. Spectr*.,**2023**, 11, 323–325.