

Mechanisms of intercellular communication via extracellular vesicles (Exosomes) in physiological systems

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ABSTRACT

Through the active transfer of biomolecules, exosomes, a subtype of nanoscale extracellular vesicles, are essential for intercellular communication. The finding that exosomes play a crucial function in a number of physiological processes has raised interest in them in recent years. This review article aimed to provide a comprehensive understanding of the mechanisms of exosome-mediated intercellular communication in physiological systems. The biogenesis, chemical makeup, and methods of exosome contact with target cells were the main topics of a recent literature search that was carried out using major scientific databases. The endosomal pathway, which includes the creation of multivesicular bodies, produces exosomes, which are then discharged into the extracellular environment by exocytosis. Exosomes can alter signaling cascades and gene regulation in recipient cells thanks to their chemical cargo, which consists of proteins, lipids, and nucleic acids like microRNAs. Exosomes support a number of biological processes in a physiological setting, such as immune response regulation, neural communication, cardiovascular homeostasis, reproductive processes, and metabolic balance. Exosomes are effective and flexible communication mediators because of their capacity to communicate biological information in a targeted and safe way. By coordinating intercellular communication, exosomes are essential for preserving homeostasis. Future exosome applications in the biomedical area are anticipated to be supported by a fuller comprehension of this mechanism.

Introduction

One essential mechanism that underpins the synchronization of biological processes in physiological systems is intercellular communication (Ahmed and Xiang, 2011). In order to maintain organismal homeostasis, these interactions allow cells to react to changes in the internal and external environment in a coordinated way (Su *et al.*, 2024). Recent studies have demonstrated that extracellular vesicles are essential mediators of more intricate and dynamic intercellular communication in addition to traditional communication pathways like cytokine-based signals, hormones, and cell-to-cell contact (Primorac *et al.*, 2026; Sheng *et al.*, 2025).

Nearly all cell types release extracellular vesicles, which are lipid membrane structures that range in size from nanoscale to microscopic, into the extracellular environment (Verweij *et al.*, 2021). These vesicles are divided into many categories, including as exosomes, microvesicles, and apoptotic bodies, according to their size and biogenesis mechanism (Li *et al.*, 2026). Exosomes are a subtype of extracellular vesicles that originate from the endosomal pathway through the development of multivesicular bodies (MVBs) and range in size from 30 to 150 nm (Doyle and Wang, 2019). The intraluminal vesicles are discharged into the extracellular environment as exosomes when MVBs fuse with the plasma membrane (Ju *et al.*, 2025). These structures reflect the physiological condition of the cells from which they emerge by carrying a range of molecular payloads, such as proteins, lipids, and nucleic acids (Chigozie, 2026).

Through a process that includes both surface contacts and the di-

rect transport of regulatory chemicals into target cells, exosomes serve as a physiological mode of biological information transfer between cells (Kalluri and LeBleu, 2020). Exosomes can shield their molecular cargo from enzymatic destruction during transport, which improves the durability and efficacy of signal delivery in contrast to traditional soluble signals (Adedokun *et al.*, 2026). Additionally, by influencing gene expression and intracellular signaling pathways, exosomes can alter a number of biological processes, such as proliferation, differentiation, immunological responses, and metabolism (Wei *et al.*, 2025a).

Exosomes have advantages in terms of complexity and selectivity when compared to other communication channels like hormones and cytokines (Huda *et al.*, 2021). Typically, hormones and cytokines work by interacting with particular receptors, which causes quick but constrained reactions within particular signaling pathways (Altan-Bonnet and Mukherjee, 2019). Exosomes, on the other hand, can transport several different kinds of chemicals at once, allowing for multi-level control of target cell activity (Si *et al.*, 2024). Additionally, the effectiveness of intercellular communication within complex tissues is improved by the selective detection of particular target cells made possible by the presence of particular surface molecules on exosomes (Ghaffari *et al.*, 2023).

Even though we have learned a lot about exosomes in the last few decades, there are still a lot of unanswered questions. There is still much to learn about the mechanisms of cargo selection into exosomes, particularly what influences molecular loading specificity (Aldarmahi *et al.*, 2025). Additionally, more research is needed to understand the dynamics of in-

teractions between exosomes and target cells in various physiological settings (Yadav *et al.*, 2024). The diversity of exosome populations and the limitations of analytical techniques that can identify vesicle subpopulations with different functions are further difficulties (Zhang *et al.*, 2025a).

Against this background, this review article aimed to provide a comprehensive synthesis of exosome-mediated intercellular communication mechanisms in physiological systems. Exosome biogenesis, molecular makeup, target cell contact mechanisms, and the function of exosomes in many biological systems are the primary topics of discussion. Additionally, this article discusses the difficulties encountered in exosome research as well as potential future growth paths to enhance their comprehension and application in biological settings.

Biogenesis and molecular composition of exosomes

The biogenesis and molecular composition of exosomes are key aspects that determine their function and role in intercellular communication in physiological systems.

Biogenesis of exosomes

Exosome biogenesis is a systematic process that involves the creation of intricate intracellular vesicular structures via the endosomal pathway (Kalluri and LeBleu, 2020). Early endosomes are produced by plasma membrane invagination at the start of this process, and these endosomes subsequently develop into late endosomes (Huotari and Helenius, 2011). MVBs, endosomal organelles with several intraluminal vesicles (ILVs) inside their lumen, are subsequently formed as a result of this process (Wang *et al.*, 2023a). After the MVB unites with the plasma membrane, these ILVs are eventually discharged as exosomes into the extracellular environment (Kar *et al.*, 2023).

The endosomal sorting complex required for transport (ESCRT)-dependent and ESCRT-independent pathways are the two primary mechanisms that regulate ILV development within MVBs (Verma and Marchese, 2015). A number of multiprotein complexes (ESCRT-0, ESCRT-I, ESCRT-II, and ESCRT-III) are involved in the ESCRT-dependent pathway and are involved in vesicle separation from the endosomal membrane, cargo selection, and membrane deformation (Wang *et al.*, 2023b). Ubiquitinated proteins are recognized and bound by ESCRT-0, after which they are drawn to particular membrane domains (Shields *et al.*, 2009). While ESCRT-III facilitates membrane scission, which produces ILVs, ESCRT-I and ESCRT-II aid in membrane invagination (Johnson *et al.*, 2017). Additionally, accessory proteins like vacuolar protein sorting 4 (VPS4) and ALG-2-interacting protein X (ALIX) are essential for the intricate stability and recycling of ESCRT components (Wang *et al.*, 2023b).

On the other hand, ILV production is facilitated by an ESCRT-independent pathway that does not directly involve the ESCRT complex (Ju *et al.*, 2021). This process often depends on lipid components produced by the enzyme neutral sphingomyelinase, especially ceramide (Wang *et al.*, 2025a). Ceramide causes endosomal membrane invagination by aiding in the development of negative membrane curvature (Stancevic and Kolesnick, 2010). Moreover, membrane microdominants that facilitate the loading of certain cargo into vesicles are organized by tetraspanin proteins like cluster of differentiation 9 (CD9), CD63, and CD81 (Rubinstein *et al.*, 2025).

MVBs can either fuse with the plasma membrane to release ILVs as exosomes into the extracellular environment or fuse with lysosomes to degrade their contents (Xu *et al.*, 2022). Several Rab GTPase proteins, including RAS-associated binding protein 27A (Rab27a) and Rab27b, which govern vesicle trafficking and docking to the plasma membrane, regulate this secretion process (Menaceur *et al.*, 2023). An overview of exosome biogenesis through the endosomal pathway is illustrated in Figure 1.

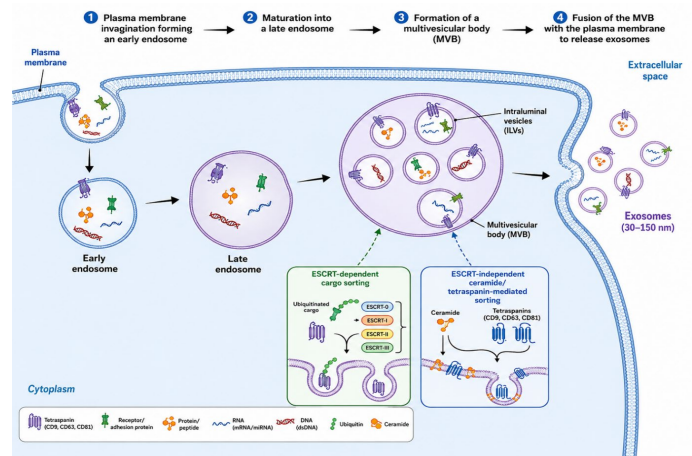


Figure 1. Exosome biogenesis through the endosomal pathway.

Molecular cargo

Exosomes function as particular and focused intercellular communication mediators by carrying a range of active biomolecules that represent the physiological condition and origin of their host cells (Spinelli *et al.*, 2025). During vesicle creation, the molecular cargo inside exosomes is packaged through a regulated selection mechanism rather than at random, indicating intricate cargo loading regulation (Lee *et al.*, 2024a).

One of the components of exosomes that has been studied the most is protein (Hu *et al.*, 2020). These proteins include membrane proteins including tetraspanins (CD9, CD63, and CD81), which are frequently employed as distinctive exosome identifiers because of their prevalence on the vesicle surface (Andreu and Yáñez-Mó, 2014). Moreover, proteins involved in vesicle trafficking (like Rab GTPases), membrane fusion (like annexins), and cytoskeleton organization are also present in exosomes (Villarroya-Beltri *et al.*, 2014). Exosomes may be able to directly alter signaling pathways in target cells upon transfer since they contain enzymes, receptors, and signaling mediators (Corrado *et al.*, 2013).

The form and function of vesicles are also significantly influenced by the lipid composition of exosomes (Ghadami and Dellinger, 2023). Certain lipids, including ceramide, phosphatidylserine, cholesterol, and sphingomyelin, are abundant in exosome membranes (Donoso-Quezada *et al.*, 2021). Membrane integrity, curvature creation, and effective contact with recipient cells are all facilitated by these lipids (Torres *et al.*, 2021). Certain lipids serve as signaling molecules in addition to their structural role, which can affect target cells' biological reactions (Horn and Jaiswal, 2019).

The primary functional elements of exosomes are nucleic acids, especially ribonucleic acid (RNA) (Chen *et al.*, 2024). Because they can post-transcriptionally control gene expression in recipient cells, microRNAs (miRNAs) have been the subject of the greatest research (Ratti *et al.*, 2020). Exosomes can also contain long non-coding RNA (lncRNA), which is involved in transcriptional and epigenetic regulation, and messenger RNA (mRNA), which may be translated into functional proteins after transfer (Han *et al.*, 2021). It is believed that RNA-binding proteins and certain sequence patterns that control loading selectivity are involved in the process of RNA selection into exosomes (Wang and Zhang, 2024).

Deoxyribonucleic acid (DNA), including pieces of mitochondrial DNA and double-stranded genomic DNA, has also been found in exosomes in recent studies (Li *et al.*, 2026). Exosomal DNA is believed to be involved in the transmission of genetic information between cells and the activation of immunological responses through DNA recognition pathways in recipient cells, while its biological function is still unclear (Schorey *et al.*, 2015).

Mechanisms of exosome-mediated intercellular communication

The mechanism of exosome-mediated intercellular communication involves a series of coordinated processes that enable the specific trans-

fer of signals and bioactive molecules from the host cell to the target cell. Table 1 summarizes the main mechanisms of exosome-mediated intercellular communication, which include the stages of recognition and uptake by the target cell, activation of signal transduction pathways, and genetic and epigenetic regulation.

Target cell recognition and uptake

An important factor in assessing the efficacy of intercellular communication is the interaction between exosomes and target cells (Ginini *et al.*, 2022). To ensure the focused and selective transfer of biological information, this procedure starts with a particular recognition mechanism mediated by exosome surface molecules and receptors on the receiving cell (Serrano *et al.*, 2025).

Target cell recognition typically entails receptor-ligand interactions between certain receptors on the target cell surface and exosomal membrane proteins such tetraspanins, integrins, and proteoglycans (He *et al.*, 2022). Without requiring vesicle internalization, this contact can activate early signaling pathways in addition to acting as a docking mechanism (Lau and Yam, 2023). The tropism of exosomes for particular cell types, which is dependent on the cell's origin and molecular makeup, is influenced by this recognition specificity (Gurunathan *et al.*, 2021).

Exosomes can enter target cells via a number of internalization mechanisms after the identification process (McKelvey *et al.*, 2015). Endocytosis, which comes in a variety of forms such clathrin-mediated endocytosis, caveolin-dependent uptake, macropinocytosis, and phagocytosis, is one of the primary mechanisms (Kumari *et al.*, 2010). The type of cell, the microenvironment, and the properties of the exosome itself all influence the pathway that is employed (Saad *et al.*, 2025). Exosomes are ingested

into endosomal vesicles by this mechanism, allowing their contents to be released into the cytoplasm (Kalluri and LeBleu, 2020).

Exosomes can transmit their cargo by direct fusion with the target cell's plasma membrane in addition to endocytosis (Joshi *et al.*, 2020). By avoiding the endosomal pathway and releasing vesicle contents straight into the cytoplasm, this method speeds up cellular reactions (Kim *et al.*, 2024). The lipid composition of the exosome, especially the presence of lipids like phosphatidylserine and cholesterol, and the physiochemical parameters of the surrounding environment, including pH, have an impact on membrane fusion (Skotland *et al.*, 2019).

Exosomes can interact with the cell surface in some situations without internalizing, but they can still affect cell activity by activating surface receptors (Jella *et al.*, 2018). This implies that exosomes serve as both biologically active signaling units and vehicles for the transfer of cargo (Huda *et al.*, 2021). The major routes by which exosomes interact with and deliver signals to recipient cells are summarized in Figure 2.

Signal transduction pathways

Exosomes serve as active mediators in the initiation and modulation of signal transduction pathways in target cells in addition to being vehicles for the transfer of biomolecules (Duan *et al.*, 2019). Exosomal cargo can initiate a number of intracellular signaling cascades that alter cellular function after connecting with recipient cells through internalization or binding to surface receptors (Zeng *et al.*, 2023).

The phosphoinositide 3-kinase / protein kinase B (PI3K/AKT) pathway is one that is often engaged and is essential for controlling metabolism, cell survival, and proliferation (Hemmings and Restuccia, 2012). Transferring proteins or microRNAs from exosomes can activate this pathway

Table 1. Mechanisms of exosome-mediated intercellular communication in physiological systems.

Mechanism component	Subprocess	Main mechanism	Key molecules/Characteristics	Physiological impact	References
Target cell recognition and uptake	Target cell recognition	Receptor–ligand interactions between exosomes and target cells	Tetraspanins (CD9, CD63, CD81), integrins, proteoglycans	Target specificity and initiation of early signaling pathways	Ginini <i>et al.</i> (2022); Serrano <i>et al.</i> (2025); He <i>et al.</i> (2022); Lau and Yam (2023); Gurunathan <i>et al.</i> (2021)
	Internalization	Endocytosis (clathrin-mediated, caveolin-dependent, macropinocytosis, phagocytosis)	Membrane proteins, microenvironmental conditions	Cargo transfer into recipient cells through endosomal vesicles	McKelvey <i>et al.</i> (2015); Kumari <i>et al.</i> (2010); Saad <i>et al.</i> (2025); Kalluri and LeBleu (2020)
	Membrane fusion	Direct fusion with the plasma membrane	Phosphatidylserine, cholesterol, environmental pH	Rapid release of exosomal cargo into the cytosol	Joshi <i>et al.</i> (2020); Kim <i>et al.</i> (2024); Skotland <i>et al.</i> (2019)
	Surface interaction	Activation of target cell receptors without internalization	Exosomal ligand proteins	Signal activation without cargo transfer	Jella <i>et al.</i> (2018); Huda <i>et al.</i> (2021)
Signal transduction pathways	PI3K/AKT pathway	Activation of cellular proliferation, survival, and metabolism	Proteins, miRNAs, growth factors	Enhanced cell viability and metabolic adaptation	Duan <i>et al.</i> (2019); Zeng <i>et al.</i> (2023); Hemmings and Restuccia (2012); Huang <i>et al.</i> (2025a); Aheget <i>et al.</i> (2020)
	MAPK/ERK pathway	Regulation of proliferation, differentiation, and cellular responses	Signaling proteins, regulatory RNAs	Activation of growth-related gene expression	Wang <i>et al.</i> (2022a); Greenblatt <i>et al.</i> (2022); Tomuleasa <i>et al.</i> (2024); Hikita <i>et al.</i> (2022)
	NF-κB pathway	Regulation of immune and inflammatory responses	miRNAs, cytokines, adaptor proteins	Modulation of immune function and inflammatory signaling	Marca <i>et al.</i> (2025); Oeckinghaus and Ghosh (2009); Gangadaran <i>et al.</i> (2023)
	Pathway crosstalk	Integration of multiple signaling pathways	Combination of exosomal cargo molecules	Complex and context-dependent cellular responses	Muraleedharan <i>et al.</i> (2026); Mukerjee <i>et al.</i> (2025)
Genetic and epigenetic regulation	Post-transcriptional regulation	Transfer of miRNAs that suppress target mRNA	miRNAs	Selective suppression of gene expression	Chigozie (2026); O'Brien <i>et al.</i> (2018); Oveili <i>et al.</i> (2023); Lorite <i>et al.</i> (2024)
	Transcriptional regulation	Activity of lncRNAs and circRNAs affecting transcription	lncRNAs, circRNAs	Modulation of gene activity through protein interactions and chromatin remodeling	Wang <i>et al.</i> (2025b); Weinhouse (2021); Tsai <i>et al.</i> (2010)
	Epigenetic modification	Regulation of DNA methylation	DNA methyltransferases (DNMTs), demethylating enzymes	Long-term alteration of gene expression patterns	Papakonstantinou <i>et al.</i> (2024); Zhang <i>et al.</i> (2026a); Eichten <i>et al.</i> (2014)
	DNA transfer	Delivery of exosomal DNA	Genomic DNA, mitochondrial DNA	Potential horizontal genetic communication	Takahashi <i>et al.</i> (2017); Di Bella (2022)

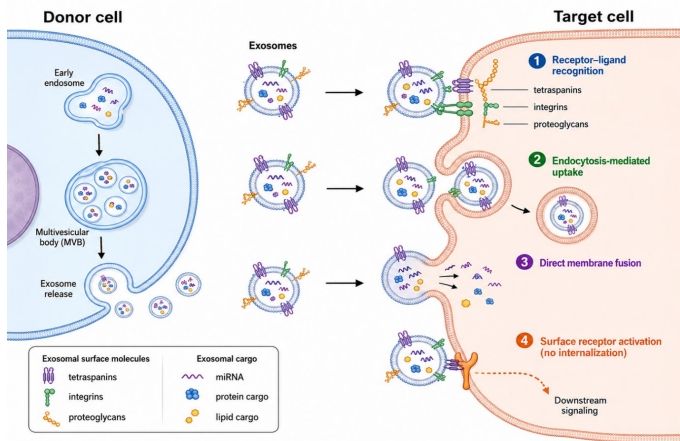


Figure 2. Mechanisms of exosome-mediated communication with target cells

by altering the expression or activity of important pathway components (Huang *et al.*, 2025a). Exosomes that contain growth factors or negative regulators of apoptosis, for instance, can boost AKT phosphorylation,

promoting cell survival and stress adaptability (Aheget *et al.*, 2020).

Additionally, one important target for exosome regulation is the mitogen-activated protein kinase / extracellular signal-regulated kinase (MAPK/ERK) pathway (Wang *et al.*, 2022a). This circuit controls proliferation, differentiation, and reactions to outside stimuli (Greenblatt *et al.*, 2022). Through interactions with tyrosine kinase receptors or by affecting the expression of genes that control the pathway, exosomal components such as signaling proteins and regulatory RNAs can initiate the mitogen-activated protein kinase (MAPK) cascade (Tomuleasa *et al.*, 2024). Increased transcriptional activity of genes supporting growth and tissue-specific functions is frequently linked to exosome-induced ERK activation (Hikita *et al.*, 2022).

Exosomes also influence the nuclear factor kappa-light-chain-enhancer of activated B cells (NF- κ B) pathway, which is a crucial modulator of inflammatory and immunological responses (Marca *et al.*, 2025). By controlling the breakdown of inhibitors or promoting the translocation of these transcription factors into the nucleus, exosomal cargo, such as miRNAs, cytokines, or adaptor proteins, can affect the activation of the NF- κ B complex (Oeckinghaus and Ghosh, 2009). Exosomes can control

Table 2. Physiological roles of exosomes across biological systems.

Physiological system	Primary role of exosomes	Key mechanism	Dominant molecules/Cargo	Physiological impact	References
Immune system	Modulation of immune responses	Transfer of immunostimulatory and immunosuppressive signals	Cytokines, immune proteins, miRNAs	Regulation of immune cell activation and maintenance of immune tolerance	Essola <i>et al.</i> (2023); Vučemić (2024); Kurywachak <i>et al.</i> (2018); Chahar <i>et al.</i> (2015); Chen <i>et al.</i> (2025); Shao <i>et al.</i> (2021); Yi <i>et al.</i> (2025)
	Antigen presentation	Transfer of MHC class I/II complexes and cross-presentation	MHC-peptide complexes, antigenic proteins	Activation and proliferation of antigen-specific T cells	Zhu (2025); Gorentla and Zhong (2012); Li <i>et al.</i> (2019a)
	Innate-adaptive immune integration	Communication among immune cell populations	Regulatory RNAs, signaling proteins	Coordinated and balanced immune responses	Gangadaran <i>et al.</i> (2023); Baquir and Hancock (2017); Essola <i>et al.</i> (2023)
Nervous system	Modulation of neurotransmission	Transfer of synaptic molecules between neurons and glial cells	Synaptic proteins, enzymes, miRNAs	Regulation of neuronal activity and synaptic plasticity	Zappulli <i>et al.</i> (2016); Desdín-Micó and Mittelbrunn (2017); Dyndał <i>et al.</i> (2026); Frühbeis <i>et al.</i> (2012); Song <i>et al.</i> (2024); Han <i>et al.</i> (2023)
	Neuroprotection	Delivery of protective bioactive factors	Anti-apoptotic proteins, antioxidant enzymes, miRNAs	Enhanced neuronal viability and resistance to stress	Kalani and Tyagi (2015); Chiaradia <i>et al.</i> (2021); Sun <i>et al.</i> (2025a); Weng <i>et al.</i> (2022)
	Proteostasis	Elimination and transport of abnormal proteins	Misfolded or aggregated proteins	Maintenance of neuronal homeostasis and intracellular stability	Takahashi <i>et al.</i> (2017); Khan <i>et al.</i> (2022); Fallahi <i>et al.</i> (2024)
	Angiogenesis	Activation of endothelial proliferation, migration, and differentiation	Growth factors, signaling proteins, miRNAs	Formation of new blood vessels and vascular remodeling	Ribeiro <i>et al.</i> (2013); Gu <i>et al.</i> (2023); Zarubova <i>et al.</i> (2022); Li <i>et al.</i> (2025a)
Cardiovascular system	Vascular homeostasis	Regulation of vascular tone and permeability	miRNAs, nitric oxide-related mediators	Maintenance of blood pressure and vascular flow stability	Chae <i>et al.</i> (2025); Dinc and Ardic (2026); Silva <i>et al.</i> (2025); Li <i>et al.</i> (2025a)
	Cardiac cell communication	Interactions between cardiomyocytes and surrounding cells	Signaling proteins, regulatory RNAs	Adaptation to mechanical and metabolic stress	Zhang <i>et al.</i> (2024); Mao <i>et al.</i> (2025); Yang <i>et al.</i> (2018)
	Gamete maturation	Transfer of regulatory molecules to germ cells	Proteins, lipids, miRNAs	Regulation of spermatogenesis, oogenesis, and gamete competence	Chen <i>et al.</i> (2023); Ebrahimi <i>et al.</i> (2025); Feng <i>et al.</i> (2025); Zhou <i>et al.</i> (2021); Voros <i>et al.</i> (2025); Ezzati and Izadpanah (2025)
Reproductive system	Embryo implantation	Embryo-endometrial communication	Growth factors, signaling RNAs	Enhancement of uterine receptivity and implantation success	(Czernek and Dächler (2020); Chen <i>et al.</i> (2022a); Sun <i>et al.</i> (2025b)
	Immune tolerance	Modulation of maternal immune responses	Immunomodulatory molecules	Prevention of embryo rejection and maintenance of pregnancy	(Mehdinejadi <i>et al.</i> (2025); Bai <i>et al.</i> (2022)
	Energy homeostasis	Regulation of metabolic signaling pathways	Enzymes, regulatory proteins, miRNAs	Control of glycolysis, lipid metabolism, and energy balance	Lee <i>et al.</i> (2016); Sanghvi and Singh (2026); Mohammed <i>et al.</i> (2025); Hernández-Gómez <i>et al.</i> (2023); Jiao <i>et al.</i> (2024); Liu <i>et al.</i> (2025)
Metabolic regulation	Inter-organ cross-talk	Communication across tissues and organs	Regulatory RNAs, signaling proteins	Coordination of systemic metabolism	Isaac <i>et al.</i> (2021); Wang <i>et al.</i> (2022b); Son <i>et al.</i> (2023); Chimal-Vega <i>et al.</i> (2025)
	Metabolic adaptation	Response to physiological and environmental changes	Dynamic exosomal cargo composition	Adjustment of cellular and systemic energy demands	Luo <i>et al.</i> (2024); Li <i>et al.</i> (2025b); Zhang <i>et al.</i> (2025b)

the expression of genes linked to tissue homeostasis, immunological defense, and inflammatory response through various pathways (Gangadaran *et al.*, 2023).

It's interesting to note that these pathways are frequently activated in an integrated and interactive way (crosstalk) rather than independently (Muraleedharan *et al.*, 2026). Because exosomes can coordinate several signaling pathways at once, they can provide more intricate and contextual cellular responses that are suited to physiological requirements (Mukerjee *et al.*, 2025).

Genetic and epigenetic regulation

Through the transmission of regulatory chemicals that can affect genetic and epigenetic processes, exosomes serve a critical function in controlling gene expression in target cells (Chigozie, 2026). This method provides flexibility in physiological responses to different stimuli by enabling changes in cellular phenotype without necessitating long-term modifications to the DNA sequence (Behbahani *et al.*, 2016).

The transfer of miRNAs, which are tiny non-coding RNA molecules involved in post-transcriptional control of gene expression, is one such pathway (O'Brien *et al.*, 2018). The miRNAs carried by exosomes can attach to particular mRNAs after they are absorbed by target cells, causing mRNA degradation or preventing translation (Oveili *et al.*, 2023). Exosomes can influence a variety of biological processes, including proliferation, differentiation, and stress responses, by selectively suppressing or regulating the expression of specific proteins (Lorite *et al.*, 2024).

Exosomes include a variety of non-coding RNAs in addition to miRNAs, such as circular RNAs (circRNAs) and lncRNAs, which are involved in epigenetic regulation (Wang *et al.*, 2025b). By affecting chromatin structure or interacting with transcription factors, these compounds can interact with protein complexes within target cells to modify gene transcriptional activity (Weinhouse, 2021). For instance, lncRNAs can operate as scaffolding to attract histone modification enzymes to particular gene locations, changing a gene's repressive or active state (Tsai *et al.*, 2010).

Moreover, exosomes have the ability to affect target cells' DNA methylation patterns (Papakonstantinou *et al.*, 2024). DNA methyltransferases (DNMTs) and demethylating enzymes are known to be regulated by certain exosomal payloads, such as regulatory RNAs and enzymatic proteins (Zhang *et al.*, 2026a). The long-term control of gene expression in a physiological setting is influenced by these variations in methylation levels, which also affect chromatin accessibility and gene transcription rates (Eichten *et al.*, 2014).

Additionally, there is proof that DNA fragments carried by exosomes may aid in the genetic information transfer between cells (Takahashi *et al.*, 2017). The existence of exosomal DNA raises the prospect of a more intricate type of horizontal genetic communication than previously thought, even though the mechanics and biological significance are still being investigated (Di Bella, 2022).

Physiological roles of exosomes

Exosomes play a crucial role in various physiological systems by facilitating intercellular communication through the coordinated transfer of bioactive molecules. Table 2 presents a summary of the physiological roles of exosomes in various biological systems, including the immune, nervous, cardiovascular, reproductive, and metabolic systems.

Immune system

Because exosomes can transport bioactive chemicals that alter immune cell interactions, they play a major role in immune system control (Essola *et al.*, 2023). Exosomes serve as physiological communication mediators that facilitate immune response coordination during both homeostatic and stimulated settings (Vučemilović, 2024).

Modulating immunological responses is one of exosomes' main roles (Kurywachak *et al.*, 2018). Proteins, cytokines, and regulatory RNAs that can affect target cell activity are carried by exosomes, which are produced by a variety of cell types, including immune cells such dendritic cells, macrophages, and lymphocytes (Chahar *et al.*, 2015). Depending on the source and makeup of their payload, exosomes can be either immunosuppressive or immunostimulatory (Chen *et al.*, 2025). Exosomes that carry costimulatory molecules or pro-inflammatory cytokines, for instance, can boost T cell activation and fortify the adaptive immune response (Shao *et al.*, 2021). On the other hand, exosomes containing particular miRNAs or anti-inflammatory compounds can inhibit immune cell activation, preserve immunological tolerance, and avoid overreaction (Yi *et al.*, 2025).

Exosomes also play a critical role in antigen presentation, which is the first stage of the adaptive immune response (Essola *et al.*, 2023). Major histocompatibility complex (MHC) class I and II complexes containing bound antigenic peptides can be found in exosomes generated from antigen-presenting cells, such as dendritic cells (Zhu, 2025). T-cell receptors on lymphocytes are able to identify these complexes, which leads to the activation and growth of antigen-specific T cells (Gorentla and Zhong, 2012). It's interesting to note that exosomes can exhibit antigens both directly and by transferring them to other antigen-presenting cells (a process known as cross-presentation), which increases the immune response's breadth and effectiveness (Li *et al.*, 2019a).

Additionally, exosomes facilitate communication between innate and adaptive immune system components (Gangadaran *et al.*, 2023). A coordinated and proportionate response to stimuli is produced by the integration of signals between different immune cell populations made possible by the transfer of chemicals via exosomes (Baqir and Hancock, 2017). This system is essential for preserving the equilibrium between immune activation and tolerance under physiological conditions, which is essential for avoiding diseases like autoimmunity or chronic inflammation (Essola *et al.*, 2023).

Nervous system

Because they facilitate communication between nerve cells and support cells in the neural environment, exosomes are essential for maintaining nervous system function (Zappulli *et al.*, 2016). Exosomes help transmit bioactive chemicals that promote signal integration, preserve homeostasis, and guard against cellular stress under physiological settings (Desdín-Micó and Mittelbrunn, 2017).

Exosomes serve as extra mediators that enhance traditional synaptic communication mechanisms in the setting of neurotransmission (Dyndał *et al.*, 2026). Exosomes carrying synaptic proteins, enzymes, and regulatory RNAs are actively released by neurons and glial cells, including astrocytes and oligodendrocytes (Frühbeis *et al.*, 2012). By affecting neurotransmitter release, synaptic plasticity, and receptor sensitivity, this cargo can alter the activity of receiving neurons (Song *et al.*, 2024). Additionally, exosomes facilitate the coordination of intricate neuronal networks without exclusively depending on direct synaptic transmission by facilitating the transfer of signaling molecules between neurons (Han *et al.*, 2023).

Additionally, exosomes are important for neuroprotection processes (Kalani and Tyagi, 2015). Anti-apoptotic proteins, antioxidant enzymes, and microRNAs that control reactions to oxidative stress and inflammation are just a few of the beneficial elements that these vesicles may include (Chiaradia *et al.*, 2021). Exosomes aid in maintaining neuronal survival in the face of shifting microenvironmental conditions and boosting nerve cell resilience to harm through the transfer of these components (Sun *et al.*, 2025a). Exosomes, which provide trophic factors and metabolic modulation to sustain neuronal survival, are known to be produced by glial cells, especially astrocytes (Weng *et al.*, 2022).

Exosomes also contribute to the removal of extraneous or potentially dangerous cellular constituents (Takahashi *et al.*, 2017). Exosomes sup-

port the nervous system's proteostasis processes by carrying misfolded or aggregated proteins (N.A. Khan *et al.*, 2022). Maintaining intracellular stability and promoting the best possible brain tissue function depend on this function (Fallahi *et al.*, 2024).

Cardiovascular system

Because they facilitate intercellular communication, especially between endothelial cells, vascular smooth muscle cells, and cardiomyocytes, exosomes are essential for preserving cardiovascular function (Li *et al.*, 2025a). Exosomes play a role in vascular balance, angiogenesis regulation, and hemodynamic environment adaption under physiological settings (Olejars *et al.*, 2020).

Exosomes serve as carriers of pro-angiogenic chemicals that can promote the development of new blood vessels during angiogenesis (Ribeiro *et al.*, 2013). Growth factors, signaling proteins, and microRNAs that can activate molecular pathways linked to endothelial cell proliferation, migration, and differentiation are found in exosomes released by endothelial cells and progenitor cells (Gu *et al.*, 2023). Increased gene expression that contributes to the development of new vascular structures is made possible by this cargo transfer, facilitating regulated tissue vascularization (Zarubova *et al.*, 2022). Additionally, the coordinated development of a functional blood vessel network depends on exosomes' ability to promote intercellular communication within the vascular milieu (Li *et al.*, 2025a).

By controlling endothelial function and interacting with smooth muscle cells, exosomes also help to maintain vascular homeostasis (Chae *et al.*, 2025). Molecules that can alter vascular tone, vascular permeability, and reactions to mechanical stress are carried by these vesicles (Dinc and Ardic, 2026). For instance, genes involved in the synthesis of nitric oxide, a crucial mediator of vasodilation, can have their expression regulated by microRNAs carried by exosomes (Silva *et al.*, 2025). Exosomes thereby contribute to the preservation of the equilibrium between vasodilation and vasoconstriction, which is necessary for steady blood pressure and blood flow (Li *et al.*, 2025a).

Additionally, in cardiac tissue, exosomes play a role in communication between cardiomyocytes and non-cardiomyocyte cells (Zhang *et al.*, 2024). Coordinated responses to mechanical and metabolic demands, including adaptability to variations in heart strain, are made possible by the interchange of chemicals via exosomes (Mao *et al.*, 2025). The structural and functional integrity of cardiac tissue can be supported by cardiomyocyte-derived exosomes, which can transmit signals that affect the activity of target cells including fibroblasts and endothelial cells (Yang *et al.*, 2018).

Reproductive system

Because they facilitate communication between cells involved in gametogenesis, fertilization, and embryo implantation, exosomes are essential to the reproductive system (Chen *et al.*, 2023). Exosomes serve as molecular signal carriers in the highly coordinated reproductive environment, supporting somatic cells and guaranteeing synchronized operation between germ cells (Mehdinejadi *et al.*, 2025).

Exosomes enable gamete growth and maturation in both the male and female reproductive systems within the framework of germ cell communication (Ebrahimi *et al.*, 2025). Proteins, lipids, and regulatory RNAs found in the exosomes secreted by Sertoli cells in the testes aid in the differentiation and maturation of spermatocytes (Chen *et al.*, 2023). This chemical transfer supports growing germ cells metabolically and protectively while assisting in the regulation of gene expression necessary for spermatogenesis (Feng *et al.*, 2025). Additionally, by transferring proteins and RNAs that improve motility and fertilization potential, exosomes in epididymal fluid contribute to sperm maturation (Zhou *et al.*, 2021).

Exosomes generated by cells surrounding the oocyte, such as gran-

ulosa and cumulus cells, help control oocyte maturation in the female reproductive system (Chen *et al.*, 2023). Exosomal cargo, which includes growth factors and miRNAs, contributes to the development of oocytes capable of fertilization by controlling communication between the oocyte and the follicular environment (Voros *et al.*, 2025). This process illustrates how crucial exosomes are in establishing the ideal milieu for gamete formation (Ezzati and Izadpanah, 2025).

Additionally, exosomes are essential for the early stage of pregnancy known as embryo implantation, which necessitates intricate coordination between the embryo and the endometrium (Czernek and D  chler, 2020). Endometrial cells release exosomes that contain signaling molecules that alter uterine receptivity, including controlling the expression of genes related to tissue remodeling, cell adhesion, and local immunological responses (Sun *et al.*, 2025b). On the other hand, the embryo also creates exosomes that have the ability to affect the endometrial environment, creating a two-way communication that is necessary for a successful implantation (Chen *et al.*, 2022a).

Additionally, after implantation, exosomes contribute to the preservation of immunological equilibrium in the reproductive environment (Mehdinejadi *et al.*, 2025). Exosomes aid in the development of immunological tolerance, which permits the maternal immune system to tolerate a genetically semi-allogeneic embryo without inciting a rejection response, by delivering immunomodulatory chemicals (Bai *et al.*, 2022).

Metabolic regulation

Because they make it easier for cells and organs to share molecular information, exosomes are essential for metabolic regulation (Lee *et al.*, 2016). The equilibrium of energy metabolism in physiological systems is dependent on coordinated communication across tissues, which is partially mediated by exosomes, in addition to intracellular regulation (Sanghvi and Singh, 2026).

Through the transfer of bioactive substances including enzymes, regulatory proteins, and non-coding RNAs, exosomes contribute to the regulation of homeostasis in the context of energy metabolism (Mohammed *et al.*, 2025). Genes linked to important metabolic pathways, including as glycolysis, fatty acid oxidation, and oxidative phosphorylation, can have their expression modulated by exosomal cargo, especially microRNAs (Hern  ndez-G  mez *et al.*, 2023). For instance, by controlling the expression of glucose transporters and metabolic enzymes, exosomes produced from metabolically active tissues might affect target cell sensitivity to insulin (Jiao *et al.*, 2024). Cellular responses can be modified in response to shifting energy requirements and dietary circumstances thanks to this mechanism (Liu *et al.*, 2025).

Additionally, exosomes provide inter-organ crosstalk, which is an essential component of systemic metabolic coordination (Isaac *et al.*, 2021). To preserve metabolic balance, organs like the pancreas, skeletal muscle, adipose tissue, and liver communicate with one another via exosome-mediated signals (Wang *et al.*, 2022b). For instance, chemicals that affect the liver's and muscles' metabolism of fats and carbohydrates can be carried by exosomes that are discharged from adipose tissue (Son *et al.*, 2023). On the other hand, by transferring regulatory RNAs that alter particular metabolic pathways, liver exosomes can control peripheral tissue function (Chimal-Vega *et al.*, 2025).

Additionally, exosomes are involved in the metabolic response to physiological changes like fasting, exercise, or dietary alterations (Luo *et al.*, 2024). In these circumstances, the exosome cargo's composition may dynamically alter, reflecting the host cell's metabolic state and triggering adaptive reactions in target cells (Li *et al.*, 2025b). This implies that exosomes serve as a communication mechanism that is sensitive to the inside environment of the organism (Zhang *et al.*, 2025b). The broad physiological contribution of exosomes in maintaining intercellular coordination across organ systems is presented in Figure 3.

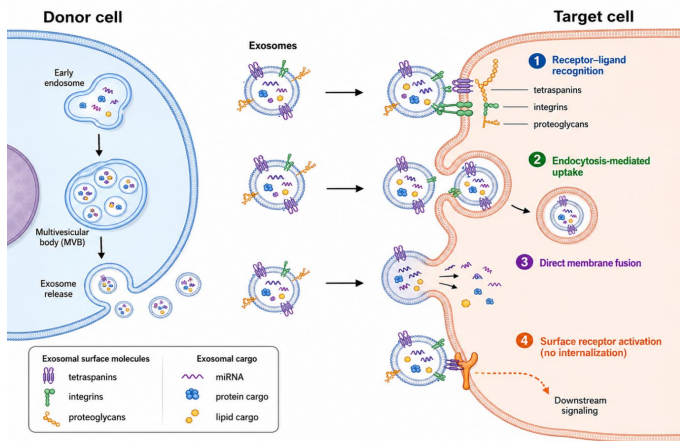


Figure 3. Physiological roles of exosomes across major biological systems

Comparison with other intercellular communication mechanisms

Exosomes, cytokines, hormones, and gap junctions are just a few of the complimentary processes that allow cells in physiological systems to communicate with one another (Zhang *et al.*, 2019). Regarding the form of signal transmission, target specificity, duration, and spectrum of biological effects, each mechanism is distinct (Isaac *et al.*, 2021). Table 3 compares the main characteristics of various communication mechanisms between cells, namely exosomes, cytokines, hormones, and gap junctions, based on aspects of signal transmission, specificity, range, and complexity of biological effects.

Because exosomes may transport multiple biomolecules at once, such as proteins, lipids, and nucleic acids, they provide a more sophisticated transfer mechanism than cytokines (Hu *et al.*, 2024). Generally speaking, cytokines function as soluble signaling molecules that attach to particular receptors on the surface of target cells, causing a comparatively quick reaction that is restricted to the activation of a particular signaling

pathway (Levine, 2008). Exosomes, on the other hand, carry cargo inside target cells in addition to activating surface receptors, enabling more significant alterations like long-term gene expression regulation and cellular function modification (Lee *et al.*, 2024a).

Exosomes have distinct distribution and selectivity from hormones (Kita and Shimomura, 2022). With effects that are typically widespread and endocrine coordinated, hormones are produced into the systemic circulation and can travel to distant target organs (Guo and Yuan, 2022). Exosomes can circulate in bodily fluids as well, but because of their cellular origin and surface molecular makeup, they typically have a more selective tropism towards particular target cells (Batrakova and Kim, 2015). Furthermore, whereas exosomes can influence target cells through a variety of methods, such as the direct transfer of regulatory molecules, hormones often cause a reaction by activating particular receptors (Yadav *et al.*, 2024).

Gap junctions, on the other hand, are a type of direct cell-to-cell communication via protein channels that join the cytoplasm of two nearby cells (Dbouk *et al.*, 2009). This mechanism, which is restricted to cells in direct physical touch, permits the quick and effective exchange of ions and tiny molecules (Goodenough and Paul, 2009). Exosomes, as opposed to gap junctions, allow long-distance communication between cells without necessitating physical touch, increasing the variety of interactions between bodily tissues (Kalluri and LeBleu, 2020).

Exosomes have the advantage of being able to transport a variety of molecular cargo at once, which allows for flexibility in modifying many elements of cellular function (Mukerjee *et al.*, 2025). Another significant benefit is the capacity to shield the cargo from enzymatic deterioration while in transit, particularly in the dynamic extracellular environment (Huang *et al.*, 2025b). Additionally, compared to traditional soluble signals, the tropism characteristics of exosomes allow for more selective transmission (Gurunathan *et al.*, 2021).

Exosomes do have certain restrictions, though. It can differ greatly amongst tissues because its generation and secretion are dependent on the physiological circumstances of the cells (Zhang *et al.*, 2025c). Consis-

Table 3. Comparison of intercellular communication mechanisms: exosomes, cytokines, hormones, and gap junctions.

Parameter	Exosomes	Cytokines	Hormones	Gap junctions	References
Signal form	Membrane-bound vesicles (30–150 nm)	Soluble protein signaling molecules	Chemical messengers (peptides, steroids, amines)	Intercellular protein channels	Zhang <i>et al.</i> (2019); Isaac <i>et al.</i> (2021)
Cargo type	Proteins, lipids, RNA (miRNA, mRNA, lncRNA), DNA	Specific proteins/cytokines	Single signaling molecules	Ions and small molecules	Hu <i>et al.</i> (2024); Levine (2008); Goodenough and Paul (2009)
Mechanism of action	Receptor interaction, internalization, and direct cargo transfer	Binding to surface receptors	Activation of specific receptors (endocrine/paracrine signaling)	Direct diffusion between adjacent cytoplasm	Lee <i>et al.</i> (2024a); Guo and Yuan (2022); Dbouk <i>et al.</i> (2009)
Target specificity	High (tropism determined by cellular origin and exosomal surface composition)	Moderate (receptor-dependent)	High but broadly distributed (specific target organs)	Very high (restricted to adjacent cells)	Kita and Shimomura (2022); Batrakova and Kim (2015); Gurunathan <i>et al.</i> (2021)
Communication range	Local to systemic	Primarily local (paracrine/autocrine)	Systemic (via blood circulation)	Extremely local (direct cell–cell contact)	Guo and Yuan (2022); Kalluri and LeBleu (2020)
Response speed	Moderate	Rapid	Relatively slow to moderate	Very rapid	Levine (2008); Goodenough and Paul (2009); Yadav <i>et al.</i> (2024)
Duration of effect	Long-term (gene regulation and functional reprogramming)	Short-term	Intermediate to long-term	Very transient	Lee <i>et al.</i> (2024a); Guo and Yuan (2022)
Effect complexity	High (multi-cargo and multi-pathway regulation)	Limited (pathway-specific signaling)	Coordinated systemic regulation	Limited to direct molecular exchange	Mukerjee <i>et al.</i> (2025); Levine (2008)
Cargo protection	High (protected by lipid membrane encapsulation)	Low	Moderate	Not applicable	Huang <i>et al.</i> (2025b)
Limitations	Heterogeneity, variable biogenesis, and incompletely understood mechanisms	Limited signaling scope	Slower response and broad distribution	Restricted to physically adjacent cells	Zhang <i>et al.</i> (2025c); Gandham <i>et al.</i> (2020); Escudero-Cernuda <i>et al.</i> (2025)

tent characterization of exosomes is especially challenging due to their heterogeneity in size, composition, and origin (Gandham *et al.*, 2020). Furthermore, it is difficult to interpret the biological functions of cargo selection and target cell recognition since the precise mechanisms driving these processes are still poorly known (Escudero-Cernuda *et al.*, 2025).

Clinical and translational perspectives

Despite being essential to physiological functions, exosomes have a lot of potential for clinical and translational uses due to their special qualities (Lee *et al.*, 2024b). Opportunities for their application in diagnosis, treatment, and the development of biomedical technologies are made possible by their capacity to carry a wide range of bioactive compounds steadily and their relative biocompatibility (Mukerjee *et al.*, 2025).

Biomarkers are among the most promising uses (Mosquera-Heredia *et al.*, 2021). Exosomes, whose molecular payload reflects the condition of their host cells, are present in a variety of biological fluids, including blood, urine, and cerebrospinal fluid (Shen *et al.*, 2025). Exosome profiles of proteins, lipids, and particularly non-coding RNAs can be utilized to detect physiological alterations and early indicators of a disease prior to the emergence of overt clinical symptoms (Wei *et al.*, 2025b). Exosomes' persistence in circulation and capacity to shield their cargo from enzymatic breakdown make them advantageous as biomarkers, allowing for more precise and sensitive detection (S.U. Khan *et al.*, 2022).

Exosomes may also be used as novel medicine delivery methods (Chen *et al.*, 2022b). Exosomes can connect effectively with target cells thanks to their natural membrane shape, and their cargo can be altered to contain therapeutic substances like medications, proteins, or RNA (Di Bella, 2022). Exosomes have benefits over traditional delivery methods in terms of biocompatibility, immune evasion, and the ability to modify their surface to target particular targets (Serrano *et al.*, 2025). Exosomes are therefore a viable option for more targeted, molecularly based treatments (Basyoni *et al.*, 2025).

Exosomes are gaining attention in the field of regenerative medicine due to their ability to promote tissue regeneration and repair (Odehnalová *et al.*, 2025). It is known that stem cell-derived exosomes include growth factors, cytokines, and regulatory RNAs that can promote angiogenesis, cell proliferation, and differentiation (Zhang *et al.*, 2025c). The use of exosomes provides a safer alternative to cell-based therapies by removing the dangers of cell transplantation, such as immunological responses or possible carcinogenesis (Li *et al.*, 2025c). Exosomes are therefore viewed as a viable substitute in the creation of cell-free regenerative treatments (Ana *et al.*, 2021).

However, there are still a number of obstacles to the therapeutic use of exosomes, such as characterisation, quality control of large-scale production, and standardization of isolation techniques (Serrano *et al.*, 2025). Furthermore, before exosomes are widely used in clinical practice, a better understanding of their biodistribution, long-term safety, and mechanisms of action is required (Dal'Forno-Dini *et al.*, 2025).

Current challenges and limitations

Even though exosome research has advanced quickly, there are still a number of conceptual and methodological issues that prevent a thorough understanding of exosomes and their best application in both scientific and therapeutic settings (Hussen *et al.*, 2022). To produce reliable and repeatable results, a more standardized and integrated method is required due to the intricate biological characteristics of exosomes (Mukerjee *et al.*, 2025).

The absence of standardized exosome isolation techniques is a significant barrier (Gorgzadeh *et al.*, 2024). Numerous methods, including size-based filtration, ultracentrifugation, polymer precipitation, and size-exclusion chromatography, are frequently employed; however, each has pros and cons related to purity, efficiency, and scalability (Dilsiz,

2024). Because different techniques can result in vesicle populations with different features, it can be challenging to compare studies and interpret results universally (De Sousa *et al.*, 2023).

Additionally, a major obstacle in exosome study is the variability of extracellular vesicles (Zeng *et al.*, 2022). In terms of size and molecular makeup, exosomes are frequently hard to tell apart from other vesicle types including microvesicles and apoptotic bodies (Ståhl *et al.*, 2019). Variation reflects distinct cellular origins, physiological circumstances, and biogenesis pathways even within the exosome population (Yu *et al.*, 2024). Determining the precise function of exosomes in physiological processes is challenging due to their heterogeneity, which has implications for biological function variability (Chigozie, 2026).

Molecular characterisation challenges are another major barrier (Aljohani, 2025). Although exosome cargo has been identified using a variety of analytical techniques, including proteomics, lipidomics, and transcriptomics, the sensitivity and specificity of these approaches are still restricted (Li *et al.*, 2019b). To guarantee the identity and purity of the vesicles being examined, a variety of techniques are needed because not all exosome indicators are ubiquitous (Jia *et al.*, 2022). When sample numbers are small or come from diverse biological sources, this problem is made worse (Aljohani, 2025).

The lack of in vivo research that can accurately represent exosome dynamics in biological systems is another significant drawback (Li *et al.*, 2019b). The majority of research still uses in vitro models, which offer strong experimental control but fall short of accurately capturing the intricacy of cell-cell interactions in live things (Wang *et al.*, 2023c). Our knowledge of the biodistribution, half-life, and systemic impact of exosomes under healthy and pathological settings is limited by the absence of reliable in vivo models (Palakurthi *et al.*, 2024).

Future directions

The swift advancements in extracellular vesicle biology have created a plethora of avenues for additional investigation that could enhance our comprehension of the function of exosomes in physiological systems (Wang *et al.*, 2024a). However, a multidisciplinary strategy that combines state-of-the-art technologies with more thorough research designs is required to fully realize this promise (Li *et al.*, 2025d).

Utilizing omics tools, including as transcriptomics, proteomics, lipidomics, and genomes, to better describe exosome cargo is one important avenue (Choi *et al.*, 2013). This method makes it possible to identify exosome chemical profiles in a systemic, high-resolution manner, thereby illuminating the connection between biological function and cargo composition (Haraszti *et al.*, 2016). Additionally, a more comprehensive understanding of the function of exosomes in tissue and organ regulation may result from the integration of multi-omics data (Liu *et al.*, 2023).

Additionally, in order to overcome the constraints brought on by exosome heterogeneity, single-vesicle analytic approaches must be developed (Zhang *et al.*, 2026b). This method makes it possible to examine the size, molecular makeup, and biological activity of individual vesicles (Zhang *et al.*, 2025a). This method makes it possible for researchers to find exosome subpopulations with particular functions that were previously challenging to find using whole-population analysis (Li *et al.*, 2019b). It is anticipated that developments in nanotechnology-based platforms and high-resolution microscopy technology would hasten the field's growth (Gao *et al.*, 2023).

The creation of synthetic exosomes, also known as modified exosomes, is another exciting area of study (Kalluri and LeBleu, 2020). Exosomes that are synthetic or bioengineered can be made to convey particular cargoes more effectively and precisely (Kučuk *et al.*, 2021). This method offers substantial potential for therapeutic applications, especially in focused drug administration, in addition to enabling a more controlled investigation of exosome function (Sadeghi *et al.*, 2023). Optimizing production techniques, stability, and safety in biological systems

are major obstacles in the development of artificial exosomes (Ge *et al.*, 2026).

Furthermore, one of the most promising opportunities for the future is the integration of exosome research with the idea of precision medicine (Wang *et al.*, 2024b). Individual differences in exosome composition represent distinct biological circumstances, which may allow for more individualized approaches to diagnosis and treatment (Burtenshaw *et al.*, 2022). Exosomes could be used as biomarkers or as a customized therapeutic platform to improve the efficacy of medical treatments and lessen adverse effects (Dehghani *et al.*, 2025).

Conclusion

Through coordinated processes ranging from biogenesis and molecular cargo loading to contacts with target cells, exosomes play a critical role in intercellular communication. Their capacity to transmit proteins, lipids, and nucleic acids selectively allows for the regulation of gene expression and the manipulation of different signaling pathways, so dynamically affecting cellular function.

Exosomes integrate communication across tissues in physiological systems, such as the immunological, neurological, cardiovascular, reproductive, and metabolic systems, and help maintain homeostasis. This activity demonstrates that exosomes serve as active regulators of biological balance in addition to being molecular carriers.

Nevertheless, our knowledge of the precise mechanisms underlying exosomes is continuously developing. In order to better understand the intricacies of exosome activity and facilitate the advancement of their applications in the biomedical area, more research combining molecular techniques and state-of-the-art technology is required.

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Conflict of interest

The authors have declared no conflict of interest.

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