Acta Scientific Microbiology (ISSN: 2581-3226)

Volume 9 Issue 1 January 2026

Review Article

Exosome Therapeutics: Global Advances and Strategic Implications for Biomedical Research in Tanzania

Joel John Rutta*

Department of Sciences, Mathematics and Education, St. Joseph University in Tanzania, Tanzania

***Corresponding Author:** Joel John Rutta, Department of Sciences, Mathematics and Education, St. Joseph University in Tanzania, Tanzania.

Received: November 25, 2025

Published: December 31, 2025

Abstract

Exosomes, nanoscale extracellular vesicles, have transitioned from being perceived as cellular debris to being recognized as pivotal mediators of intercellular communication and promising therapeutic agents. This review aimed to synthesize global advancements in exosome therapeutics, analyze the associated translational challenges, and evaluate the specific potential for integrating this technology within Tanzania's biomedical research and healthcare framework. This review utilized peer-reviewed literature from PubMed and Google Scholar, complemented by grey literature including regulatory agency reports and Tanzanian health policy documents, to provide a comprehensive systematic analysis. Studies were selected based on their focus on exosome biology, therapeutic applications (drug delivery, regenerative medicine, diagnostics), manufacturing challenges, regulatory considerations, and/or biomedical research capacity building in low-resource settings. The analysis confirms the significant therapeutic potential of exosomes but highlights major hurdles in standardization, manufacturing, and regulation. For Tanzania, key opportunities include developing exosome-based diagnostics for endemic diseases and leveraging international collaborations, while primary challenges encompass infrastructural deficits and a shortage of specialized expertise. We posit that with strategic investment, exosome technology represents a viable avenue for Tanzanian researchers to engage with cutting-edge biomedicine and develop context-specific solutions to public health challenges.

Keywords: Exosomes; Extracellular Vesicles; Therapeutics; Drug Delivery; Precision Medicine; Global Health; Tanzania; Biomedical Research; Capacity Building

Introduction

Exosomes were first discovered in 1983 by Stahl's group in maturing mammalian reticulocytes. Exosomes are bio-vesicles sized around 30-200 nm, which are endosomal derived and released into surrounding body fluids by almost all the eukaryotic cells [1]. A typical exosome can contain membrane, cytosolic and nuclear proteins, metabolites, lipids, and nucleic acids (mRNA, ncRNAs, DNA) enclosed within a double membrane structure and are found to help in cellular responses, signal transduction, and even immunological responses by exploiting their capability to deliver their molecular cargo in various cells [2,3]. Exosomes, natural lipid bilayer nanoparticles secreted by cells, are a promising frontier in precision medicine, which aims to develop highly effective, minimally invasive, and individually tailored therapies.

Extracellular vesicles (EVs) are lipid-bound particles secreted by cells into the extracellular space and include three main subtypes microvesicles, exosomes, and apoptotic bodies which differ in their biogenesis, release pathways, size, molecular content, and functions [4]. Gor and Nema, [5] EVs, including microvesicles, exosomes, oncosomes, and apoptotic bodies, are categorized based on their release mechanisms and play roles in various biological processes like pathogenicity, gene transfer, stress response, and detoxification.

In therapeutic Extracellular vesicle (EV) carried potential due to their involvement in treating various diseases. One remarkable feature of extracellular vesicles (EVs) is their capacity to transport molecular signatures from their parent cells, enabling precise tar-

geting and interaction with recipient cells. These vesicles can encapsulate a wide array of molecules including proteins, RNAs, and lipids making them versatile carriers for delivering a range of therapeutic agents, from small molecules to large nucleic acids [4,6].

Drug Delivery methods like liposomes, micelles, dendrimers, polymeric nanoparticles, and inorganic nanoparticles enhance the efficacy and safety of therapeutic molecules, reducing off-target side effects and drug-related toxicity. Exosomes as drug delivery produced by various cells in the body, play a crucial role in intercellular communication and inducing physiological responses. Their biocompatibility, minimal toxicity, increased circulation, and specificity make them optimal drug delivery systems through cellular membranes [7]. Exosomes from a patient's own cells offer higher biocompatibility and lower toxicity compared to synthetic drug carriers, can penetrate tissues, diffuse to the blood, and cross the BBB [8]. Precision medicine EV-based therapies could revolutionize drug delivery to specific targets, shifting from a single treatment for all patients to a personalized, individualized approach [9]. Advancements in precision medicine offer the potential to introduce drug-containing EVs to specific tissues or cells, reducing toxicity and enabling higher therapeutic doses [10].

Global research community revealed that exosomes, due to their biocompatibility, low immunogenicity, and ability to cross biological barriers, are being explored for next-generation drug delivery systems, regenerative therapies, and vaccines [11].

However, research and development in high-income countries is asymmetric, presenting challenges for low- and middle-income countries like Tanzania, who face dual burdens of infectious and non-communicable diseases, necessitating innovative, cost-effective technologies (e.g., HIV/AIDS, tuberculosis, malaria) and a rising incidence of non-communicable diseases (e.g., cancer, diabetes) [12].

This review synthesizes global advances in exosome biology and therapeutics, critically appraises translational challenges, and analyzes Tanzania's potential to harness this technology. It proposes a strategic framework for building sustainable research capacity in exosome science, arguing that targeted engagement could accelerate Tanzania's progress in biomedical research and healthcare innovation.

Methods

Search strategy

We performing Systematic Literature Review on PubMed, Scopus, and Web of Science for publications between January 2018 and December 2025. The search strategy used keywords and MeSH terms related to exosomes, therapeutics, and the global health context, specifically focusing on Africa and low- and middle-income countries.

Eligibility criteria

This review including primary research and review articles focusing on the therapeutic or diagnostic applications of exosomes/extracellular vesicles, published in English. Studies are excluding if they focused on fundamental exosome biology without therapeutic context, or if they are conference abstracts, editorials, books, or inaccessible in full text.

Study selection and data charting

The review, following PRISMA-ScR guidelines, used a two-stage screening process to assess articles, with title/abstract screening followed by full-text examination against eligibility criteria. Data extraction, performed using a piloted Excel form and cross-checked for accuracy, captured study characteristics, exosome details, applications, challenges, regulatory aspects, and relevance to LMICs/Tanzania. A narrative synthesis framework was then applied to interpret the evidence in relation to Tanzania's biomedical context.

Synthesis of results

The study utilizes a narrative synthesis approach to map global advances, identify challenges, and analyze Tanzania's potential, using quantitative data to provide a descriptive overview.

Results

Study selection

The initial database search returning 2,150 records. After removing duplicates, 1,650 titles and abstracts were reviewed. Of these, 285 full-text articles were evaluated for eligibility, with 185 studies included in the final synthesis.

Characteristics of included studies

Preclinical research (70%, n = 130) was the most common type of study included, followed by review articles (25%, n = 46) and clinical trial reports (5%, n = 9). The corresponding authors were primarily from high-income countries in North America (40%), Europe (35%), and Asia (20%). Only two studies (~1%) had primary authorship from institutions in Sub-Saharan Africa (South Africa and Nigeria), with none from Tanzania.

Thematic analysis

Global applications of exosome therapeutics

Exosomes, nano-sized extracellular vesicles, transport bioactive substances and participate in physiological and pathological pro-

cesses. Their endogeneity and heterogeneity offer advantages over synthetic carriers for disease applications. However, limitations such as storage stability, low yield and purity, and weak targeting hinder their clinical use. Addressing these issues is crucial for advancing exosome research [13]. In plant also exosome, specifically plant-derived exosome-like nanoparticles (PELNs), are gaining attention as drug delivery systems due to their ability to transfer biological materials, low immunogenicity, and targetability [14].

Oncology

In cancer researcher engineered exosomes, modified extracellular vesicles, show promise as therapeutic tools for delivering antitumor drugs to tumor sites with fewer adverse effects [15]. In the liquid biopsy exosomes, extracellular vesicles mediating intercellular communication, show promise as biomarkers in liquid biopsy due to their abundance in body fluids and involvement in physiological processes. However, clinical application is hindered by limitations in exosome isolation and analysis methods [16]. For instance, in Lung cancer carcinogenesis studies show that often diagnosed late and having a poor prognosis, lacks effective treatments for metastatic disease due to the absence of suitable drug carriers for identified molecular targets [17]. Recent studies suggest that exosomes derived from natural killer (NK) cells may represent a promising therapeutic strategy for pancreatic cancer [18]. Another study shows that breast cancer is a prevalent malignancy in women, with triple-negative breast cancer (TNBC) exhibiting the poorest prognosis. Recent research explores exosome-based platforms as innovative therapeutic strategies [18].

Regenerative medicines

Studies using MSC-derived exosomes are the second largest area of research (30%), focusing on conditions such as myocardial infarction, stroke, and wound healing. The study by Odehnalová., *et al*. [19] Exosomes, nanosized extracellular vesicles, hold significant promise in diagnosing and treating cancer and neurodegenerative diseases, as well as in regenerative medicine despite of challenges in standardization and scalability. Another by Muthu., *et al*. [20] recent advances in translational and nanomedicine have accelerated the development of targeted drug delivery systems, with exosomes emerging as a promising cell-free delivery method due to their native characteristics. Exosomal cargo, secreted by mesenchymal stem cells (MSCs), has shown safety and efficacy in various diseases, demonstrating potential in regenerative medicine, a promising approach to restore normal function [21]. Another study by Popowski., *et al*. [22] Exosomes, extracellular vesicles secreted by cells, are gaining recognition for therapeutic potential in regenerative medicine, but challenges remain in standardizing production, regulatory compliance, and high-purity isolation.

Despite of advantages Rezabakhsh., *et al*. [23] discuss advances in stem cell identification and application have provided alternative therapeutic approaches to direct cell transplantation. However, isolation and purification are challenging due to heterogeneity in exosomal size and cargo. The lack of standard GMP-grade protocols limits Exo application in clinical settings.

Infectious diseases and vaccinology

The study by Huda and Nurunnabi, [24] explores the role of exosomes in immune modulation, cell-cell communication, and inflammation response, particularly in cancer and infectious diseases. It highlights their impact on tissue regeneration, tumor microenvironment, and disease progression, and their potential as vaccine delivery vehicle. Another study by Schorey and Harding, [25] exosomes and extracellular microvesicles (ExMVs) are vital in infection communication, transferring pathogen molecules. They induce immunity and regulate host defense, but also contribute to immune evasion in chronic infections. Their immunogenicity holds potential for vaccine development. For instance the study by Feng., *et al*. [26] exosomes, small extracellular vesicles involved in cell-to-cell communication, have shown promise in treating various disorders, including respiratory infectious diseases. These vesicles participate in physiological processes like blood coagulation, immune response, and tissue regeneration.

Diagnostic

The currently, studies and research show that exosome-based diagnostics are promising for detecting biomarkers across a range of diseases, including cancer, neurological disorders, and infectious diseases [27]. On the study by Chen., *et al*. [28] exosomes in bio-fluids offer non-invasive monitoring of cell status, aiding in diagnosis, prognosis, disease progression, and chemoresistance in clinical trials and diagnostic applications. Zhou., *et al*. [29] liquid biopsy, a noninvasive method for cancer diagnosis and treatment, offers a noninvasive alternative to solid biopsies, which are invasive and fail to capture tumor heterogeneity, and is promising for tumor progression and metastasis. Maja Petkovic, [30] extracellular vesicle (EVs) offer diagnostic potential for non-invasive prostate cancer screening, with research into EVs as biomarkers for disease microenvironments, providing insights into drug efficacy and precise medical treatments. Another study by Delshad., *et al*. [31] exosomes offer potential diagnostic tools for diseases due to their ability to reflect genetic profiles, making them ideal for real-time, noninvasive monitoring, especially for early cancer detection and personalized treatment strategies.

Thematic Analysis 2: Reported challenges

Manufacturing and scalability

The most frequently cited hurdle in review articles (60%) involves challenges in reproducible isolation, purification, and large-scale GMP production. Exosome manufacturing scalability is a key challenge under active investigation by researchers who are exploring innovative solutions. The study by Ahn., *et al*. [32], Pharmaceutical companies are advancing exosome therapeutics, but challenges persist in producing clinical-grade exosomes. Whitford and Guterstam, [33] on their study emphasizing efficient exosome isolation faces challenges due to lack of understanding and scalable solutions, the need for generic production platforms. The article review by Zhao., *et al*. [34] traditional isolation methods for extracellular vesicles, such as ultracentrifugation, suffer from low yields, high equipment costs, and inconsistent purification, which limits their scalability.

Standardization and characterization

A major concern was the lack of uniform protocols for isolation and characterization, according to Minimal Information for Studies of Extracellular Vesicles (MISEV) guidelines (55%). The study by Yadav., *et al*. [35] extracellular vesicle research faces challenges like heterogeneity, complex isolation techniques, and lack of standardization, hindering reproducibility and clinical translation, and inconsistencies in exosomal preparations. Nelson., *et al*. [36] on their study also explored the challenges extracellular vesicles (EVs), including exosomes and microvesicles, lack a specific distinguishing marker despite originating from different biogenesis pathways. Moreover, exosome-based diagnostic assays and therapeutics development is challenging due to limitations in isolating and characterizing exosomes, over-lap between sub-types, similar size and density ranges, and sample preparation and characterization methods [37]. The study by Ludwig., *et al*. [38] technological advancements in exosome isolation have not resulted in universally accepted recommendations due to challenges in selecting and reproducing different isolation methodologies. This emphasizing more by literature indicates that different isolation methods can alter the concentration, purity, and size of exosomes, which can cause variations in mRNA sequence analysis [39]. Ludwig., *et al*. [38] different isolation methods have pros and cons, and absolute exosome purity is an unrealistic goal, partially achieved by SEC, which removes some contaminating plasma or medium components. Lee., *et al*. [40] on their study of exosome-based therapies face challenges in isolation, purification, characterization, and regulatory standardization, despite promising clinical trials results, necessitating further attention to improve clinical practice. H. Chen and Li, [41] on their study Recent advances in scalable exosome production Challenges and innovations, discuss that the potential application of EVs requires reproducible isolation, enrichment, and characterization due to their nano-size, heterogeneity, and biological origin, making proper methodologies lacking [42].

Regulatory pathways

The global regulatory framework for exosomes focuses on two main strategies: identifying the components within exosomes and studying the physiological effects of their secretion [43]. Exosomes present challenges for regulatory agencies in demonstrating their pharmacokinetics and therapeutic efficacy. Verma and Arora, [44] 0n their paper discuss the complex global regulatory frameworks governing EV-based therapies, highlighting challenges such as intracellular mechanisms and diverse manufacturing processes. Q. Li., *et al*. [45] advancement is hindered by complex technological and regulatory challenges. Furthermore, key challenges include the development of standardized production protocols, a clearer understanding of therapeutic mechanisms, and resolving complex regulatory issues.

Drug loading and targeting efficiency

The engineering of exosomes for effective cargo loading and targeted delivery continues to pose a significant technical challenge. As it have been reviewed by other authors for instance, Ilgın Kımız Geboloğlu, [46] describe exosomes offer significant advantages over other delivery systems like liposomes and polymeric nanoparticles, but their optimal therapeutic use still presents challenges. The study by Serrano., *et al*. [47] efficient cargo loading into vesicles is challenging, with passive methods yielding low encapsulation rates and active methods like electroporation and sonication improving loading but introducing problems. The study by Hussen., *et al*. [48] exosomes hold promise as drug delivery vehicles to inhibit tumor growth, but a limited understanding of their contents and loading mechanisms hinders clinical translation. The primary obstacle to utilizing exosomes in medicine is the absence of standardized loading strategies. Palakurthi., *et al*. [48] efficiently loading active materials into exosomes without compromising drug integrity and stability is a major challenge. Exosomal drug products' loading is crucial, influenced by exosome source, drug properties, and loading methods; clinical application faces challenges, including efficient drug import methods [49].

Discussion

Interpretation of results

Exosome therapeutics research is progressing quickly but is geographically concentrated in high-income countries, focusing on diseases prevalent in those regions such as cancer and neurodegeneration, while neglecting conditions more common in low- and middle-income countries like malaria, HIV, neglected diseases and

other communicable diseases. The review highlights a significant lack of research leadership from Africa, specifically Tanzania, which emphasizes the existing disparities in global health research equity and translational capabilities.

Global challenges in scalability, standardization, safety, and regulatory clarity are exacerbated in resource-limited contexts, with high-income countries investing in GMP bio-manufacturing and harmonized standards, while LMICs (Low Middle Incoming Countries) face structural constraints in exosomes from research to production to manufacturing.

Tanzania faces potential fallout from exosome therapeutics, but strategic entry points include aligning national health priorities with therapeutic potential, forming international partnerships, investing in research, and strengthening regulatory preparedness to bridge the uneven benefits distribution.

Strategic implication for Tanzania

Tanzania's current lack of infrastructure presents a unique opportunity to strategically implement advanced technologies and standards from the beginning, avoiding common early-stage challenges. This can be achieved by, Tanzania should enter the exosome field using phased, high-feasibility approaches that align with the country's national disease priorities the followings are proposed priorities.

Proposed pilot activities

Pilot 1: Exosomes based TB diagnostics

The pilot will aim to develop diagnostic tests for tuberculosis in children and TB meningitis using exosomes. It will develop small-scale EV isolation and RNA profiling workflows at MUHAS/NIMR/TMDA/National Health Laboratory in Tanzania. The goal is to identify specific RNA molecules in exosomes as biomarkers.

Pilot 2: HIV/TB treatment monitoring

This pilot study will explore the potential of exosomal microRNAs as early biomarkers for monitoring treatment response in patients with HIV and tuberculosis (TB). The research will aim to identify microRNA signatures that can indicate how effectively patients are responding to treatment, potentially allowing for earlier intervention and improved outcomes.

Pilot 3: Capacity Building and Partnership Program

The Capacity-Building Partnership Program aims to establish project-based collaborations with global EV research hubs like Karolinska Institutet, NUS and Indian Extracellular Vesicle Society (INSEV) as well as leading South African laboratories. The program will focus on reciprocal training, protocol harmonization, and joint PhD mentorship to enhance research capabilities. The current gap in local exosome expertise necessitates structured "twinning" collaborations between Tanzanian institutions (such as MUHAS, NIMR, and university-based biomedical laboratories) and established international centers of excellence. Instead of broad, unfocused collaborations, these should be project-specific alliances formed to address clearly defined scientific questions about Tanzania's disease landscape. These collaborations would create a long-term cohort of Tanzanian scientists with expertise in extracellular vesicle biology, molecular biology, biochemistry, bioinformatics, and translational research through co-designed research projects, reciprocal training, and shared lab protocols. Such collaborations have the potential to develop into regional hubs of excellence capable of driving exosome innovation in Africa.

Pilot 4: TMDA regulatory sandbox

TMDA should launch a structure regulatory learning initiative that will allow to evaluate early-stage exosome diagnostics and create regulatory pathways that are appropriate for their purpose.

Leveraging diagnostic potential as an entry point

Tanzania's potential for exosome science lies in diagnostic applications, focusing on rapid, non-invasive, and sensitive exosomal biomarker discovery platforms that could transform detection of conditions that remain difficult to diagnose with existing tools such as tuberculous meningitis, pediatric tuberculosis, or HIV/TB co-infection treatment monitoring. Prioritizing exosomal RNA and protein biomarker discovery aligns both. This aligns with the country's epidemiological realities and research capacity, and establishing a national diagnostic-research pipeline would lay the groundwork for future therapeutic development.

Early and proactive regulatory engagement

To ensure Tanzania's readiness for exosome diagnostics and therapeutics, the Tanzania Medicines and Medical Devices Authority (TMDA) should be involved from the beginning of scientific capacity building. Early engagement through workshops, forums, and joint policy development will help TMDA anticipate regulatory needs, develop appropriate frameworks, reduce uncertainty for researchers, and ensure safe, ethical adoption of exosome science aligned with global standards.

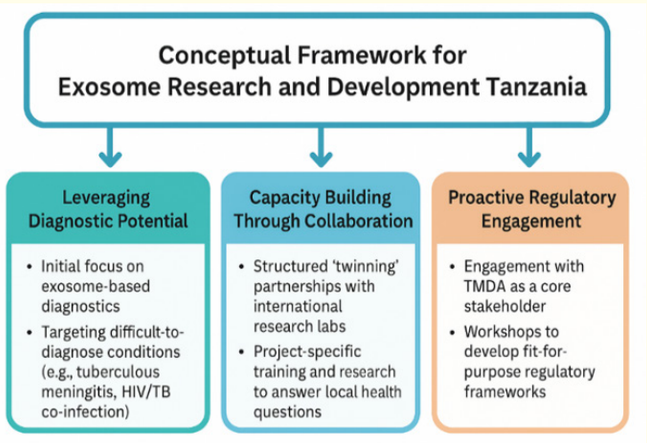

Figure 1: Concept Framework for Exosome Research and Development Tanzania.

Conclusion

Exosome therapeutics are progressing worldwide, presenting translational opportunities for Tanzania. To realize this potential, Tanzania needs to establish regulatory frameworks, infrastructure, and collaborations. Strategic investments, robust regulations, and regional partnerships are crucial for Tanzania to responsibly participate in the advancement of exosome technology.

Acknowledgement

I acknowledge St. Joseph University in Tanzania for the technical support. I thank the anonymous reviewers for their careful reading of our manuscript and their many insightful comments and suggestions.

Limitation of the Review

This scoping review is limited by its restriction to English-language publications, potentially missing relevant studies. As a scoping review, it maps the breadth of evidence without critically appraising the quality of individual studies, which is a focus of systematic reviews.

Future Direction

Future research needs to implement the proposed strategic framework, beginning with pilot projects to prove that exosome isolation and analysis are feasible in Tanzanian labs.

Conflict of Interest

The author declares no conflicts of interest.

Funding

No fund agencies in public, private, government.

Bibliography

1. Satheeshan G., *et al*. "Exosome theranostics: Comparative analysis of P body and exosome proteins and their mutations for clinical applications". *Functional and Integrative Genomics* 24.4 (2024): 124.

2. Batrakova EV and Kim MS. "Using exosomes, naturally-equipped nanocarriers, for drug delivery". *Journal of Controlled Release* 219 (2015): 396-405.

3. Kim MS., *et al*. "Development of exosome-encapsulated paclitaxel to overcome MDR in cancer cells". *Nanomedicine: Nanotechnology, Biology and Medicine* 12.3 (2016): 655-664.

4. Doyle L and Wang M. "Overview of Extracellular Vesicles, Their Origin, Composition, Purpose, and Methods for Exosome Isolation and Analysis". *Cells* 8.7 (2019): 727.

5. Gor H and Nema V. "Exosomes and Extracellular vesicles, potential tools in the effective management of tuberculosis infection". *The Microbe* 8 (2025): 100520.

6. Manoochehri H., *et al*. "Extracellular Vesicles in Cancer Immunotherapy: Therapeutic, Challenges and Clinical Progress". *Asian Journal of Pharmaceutical Sciences* (2025): 101065.

7. Sharma V and Mukhopadhyay CD. "Exosome as drug delivery system: Current advancements". *Extracell Vesicle* 3 (2024): 100032.

8. Liang Y., *et al*. "Engineering exosomes for targeted drug delivery". *Theranostics* 11.7 (2021): 3183-3195.

9. de Jong B., *et al*. "Recent Advances in Extracellular Vesicles as Drug Delivery Systems and Their Potential in Precision Medicine". *Pharmaceutics* 12.11 (2020): 1006.

10. Carnino JM., *et al*. "Extracellular Vesicles: A Novel Opportunity for Precision Medicine in Respiratory Diseases". *Frontiers in Medicine* 8 (2021): 661679.

11. Omrani M., *et al*. "Global trend in exosome isolation and application: an update concept in management of diseases". *Molecular and Cellular Biochemistry* 479.3 (2024): 679-691.

12. MoHCDGEC. "Health Sector Strategic Plan July 2021-June 2026 (HSSP V)". (2021).

13. Yi Zhang and Jiayao Bi. "Exosome: A Review of Its Classification, Isolation Techniques, Storage, Diagnostic and Targeted Therapy Applications" (2021).

14. Barzin M., *et al*. "Application of plant-derived exosome-like nanoparticles in drug delivery". *Pharmaceutical Development and Technology* 28.5 (2023): 383-402.

15. Zhang M., *et al*. "Engineered exosomes from different sources for cancer-targeted therapy". *Signal Transduction and Targeted Therapy* 8.1 (2023): 124.

16. Yu D., *et al*. "Exosomes as a new frontier of cancer liquid biopsy". *Molecular Cancer* 21.1 (2022): 56.

17. Li MY., *et al*. "Progress on pivotal role and application of exosome in lung cancer carcinogenesis, diagnosis, therapy and prognosis". *Molecular Cancer* 20.1 (2021): 22.

18. Szwedowicz U., *et al*. "Exosomes and Other Extracellular Vesicles with High Therapeutic Potential: Their Applications in Oncology, Neurology, and Dermatology". *Molecules* 27.4 (2022): 1303.

19. Odehnalová N., *et al*. "The potential of exosomes in regenerative medicine and in the diagnosis and therapies of neurodegenerative diseases and cancer". *Frontiers in Medicine* 12 (2025): 1539714.

20. Muthu S., *et al*. "Exosomal therapy—a new frontier in regenerative medicine". *Stem Cell Investigation* 8 (2021): 7.

21. Adelipour M., *et al*. "Potential applications of mesenchymal stem cells and their derived exosomes in regenerative medicine". *Expert Opinion on Biological Therapy* 23.6 (2023): 491-507.

22. Popowski K., *et al*. "Exosome therapeutics for lung regenerative medicine". *Journal of Extracell Vesicles* 2 9.1 (2020): 1785161.

23. Rezabakhsh A., *et al*. "Applications, challenges and prospects of mesenchymal stem cell exosomes in regenerative medicine". *Stem Cell Research Therapy* 12.1 (2021): 521.

24. Huda MN and Nurunnabi M. "Potential Application of Exosomes in Vaccine Development and Delivery". *Pharm Research* 39.11 (2022): 2635-2671.

25. Schorey JS and Harding CV. "Extracellular vesicles and infectious diseases: new complexity to an old story". *Journal of Clinical Investigation* 126.4 (2020): 1181-1189.

26. Feng J., *et al*. "Exosomes: Applications in Respiratory Infectious Diseases and Prospects for Coronavirus Disease 2019 (COVID-19)". *Journal of Biomedical Nanotechnology* 16.4 (2020): 399-418.

27. Lee KWA., *et al*. "Clinical Applications of Exosomes: A Critical Review". *International Journal of Molecular Sciences* 25.14 (2024): 7794.

28. Chen YF., *et al*. "Exosomes: a review of biologic function, diagnostic and targeted therapy applications, and clinical trials". *Journal of Biomedical Sciences* 31.1 (2024): 67.

29. Zhou B., *et al*. "Application of exosomes as liquid biopsy in clinical diagnosis". *Signal Transduction and Targeted Therapy* 5.1 (2020): 144.

30. Maja Petkovic. "Exosomes: A Promising New Tool for Diagnostic and Clinical Applications". *Amsbio* (2020).

31. Delshad M., *et al*. "Exosomal Biomarkers: A Comprehensive Overview of Diagnostic and Prognostic Applications in Malignant and Non-Malignant Disorders". *Biomolecules* 15.4 (2022): 587.

32. Ahn SH., *et al*. "Manufacturing Therapeutic Exosomes: from Bench to Industry". *Molecular Cells* 45.5 (2024): 284-290.

33. Whitford W and Guterstam P. "Exosome Manufacturing Status". *Future Medicinal Chemistry* 11.10 (2019): 1225-1236.

34. Zhao X., *et al*. "Scalable and cost-effective CAR-T exosome therapies: challenges and future directions". *Immunotherapy* 17.12 (2025): 891-898.

35. Yadav A., *et al*. "Standardized Reporting of Research on Exosomes to Ensure Rigor and Reproducibility". *Advance in Wound Care* 13.11 (2024): 584-599.

36. Nelson BC., *et al*. "Measurement and Standardization Challenges for Extracellular Vesicle Therapeutic Delivery Vectors". *Nanomedicine* 15.22 (2020): 2149-2170.

37. Lai JJ., *et al*. "Exosome Processing and Characterization Approaches for Research and Technology Development". *Advance in Science* 9.15 (2022): 2103222.

38. Ludwig N., *et al*. "Challenges in Exosome Isolation and Analysis in Health and Disease". *International Journal of Molecular Science* 20.19 (2019): 4684.

39. Tang YT., *et al*. "Comparison of isolation methods of exosomes and exosomal RNA from cell culture medium and serum". *International Journal of Molecular Medicine* 40.3 (2017): 834-844.

40. Chen H and Li Q. "Recent advances in scalable exosome production: Challenges and innovations". *Chinese Journal of Plastic and Reconstructive Surgery* 7.3 (2025): 149-163.

41. Escudero-Cernuda S., *et al*. "Limitations and challenges in the characterization of extracellular vesicles from stem cells and serum". *Microchime Acta* 192.5 (2025): 311.

42. Wang CK., *et al*. "Regulation of exosomes as biologic medicines: Regulatory challenges faced in exosome development and manufacturing processes". *Clinical and Translational Science* 17.8 (2025): e13904.

43. Verma N and Arora S. "Navigating the Global Regulatory Landscape for Exosome-Based Therapeutics: Challenges, Strategies, and Future Directions". *Pharmaceutics* 17.8 (2025): 990.

44. Li Q., *et al*. "Exploring Regulatory Frameworks for Exosome Therapy: Insights and Perspectives". *Health Care Science* 4.4 (2025): 299-309.

45. Ilgın Kımız Geboloğlu. "Exosomes: Large-scale production, isolation, drug loading efficiency, and biodistribution and uptake". (2022).

46. Serrano DR., *et al*. "Exosome-Based Drug Delivery: A Next-Generation Platform for Cancer, Infection, Neurological and Immunological Diseases, Gene Therapy and Regenerative Medicine". *Pharmaceutics* 17.10 (2025): 1336.

47. Hussen BM., *et al*. "Strategies to overcome the main challenges of the use of exosomes as drug carrier for cancer therapy". *Cancer Cell International* 22.1 (2018): 323.

48. Palakurthi SS., *et al*. "A comprehensive review of challenges and advances in exosome-based drug delivery systems". *Nanoscale Advances* 6.23 (2024): 5803-5826.

49. Xiao-Ming Xi XMX., *et al*. "Drug loading techniques for exosome-based drug delivery systems". *Pharmazie* 2/3 (2021): 61-67.