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Review

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Podocyte dysfunction in kidney diseases: Mechanisms and therapeutic advances

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Abstract

Podocytes are terminally differentiated visceral epithelial cells that form the outermost layer of the glomerular filtration barrier. Through their foot processes and slit diaphragm structures, podocytes confer selective permeability to the glomerular filtration barrier and play a critical role in maintaining kidney function. Podocyte damage is characterized by foot process effacement, loss of slit diaphragm proteins, reorganization of the actin cytoskeleton, and apoptosis, and plays a central role in the pathogenesis of proteinuric glomerular diseases such as minimal change disease, focal segmental glomerulosclerosis, membranous nephropathy, and diabetic nephropathy. This narrative review examines podocyte biology, the main molecular pathways of podocyte damage (RhoA/ROCK, TGF-β, mTOR, and oxidative stress), the clinical presentations of podocytopathies, and treatment strategies ranging from RAAS blockade, SGLT2 inhibitors, cytoskeletal stabilizers, gene therapy, to regenerative medicine approaches. By highlighting recent findings and translational challenges, the importance of podocyte-focused therapies in glomerular diseases is emphasized. Future studies aim to preserve podocyte integrity and prevent progressive kidney disease through personalized molecular therapies and multidisciplinary research.

Keywords

podocyte, podocytopathy, glomerular filtration barrier dysfunction, proteinuria, nephrotic syndrome, gene therapy, regenerative medicine

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1. Introduction

The kidneys are vital organs that regulate water, electrolyte, and metabolite balance and eliminate toxic waste products. This function relies on the glomerular filtration barrier. This barrier consists of podocytes, glomerular endothelial cells, and the glomerular basement membrane (GBM).[1] As visceral epithelial cells, podocytes play a critical role in maintaining the selective permeability of the filtration barrier through their complex foot processes (FP) and slit diaphragm structures.[2] These cells dynamically regulate glomerular filtration through their cytoskeletal architecture and slit diaphragm (SD) proteins such

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as nephrin and podosin. Beyond their structural roles, they also actively participate in signal transduction, mechanotransduction, and cellular response mechanisms.[3]

Podocyte damage or dysfunction disrupts the integrity of the glomerular barrier, leading to proteinuria, nephrotic syndrome (NS), and progressive kidney failure. These pathological changes underlie the pathogenesis of many glomerulopathies, including minimal change disease (MCD), focal segmental glomerulosclerosis (FSGS), membranous nephropathy (MN), and diabetic nephropathy (DN).[1,4,5] A thorough understanding of podocyte biology and pathology is of great importance for the development of early diagnosis and targeted therapies.

This study is a narrative review and was prepared in accordance with the Scale for the Assessment of Narrative Review Articles (SANRA) guidelines.[6] The literature search was conducted in the PubMed, Web of Science, and Scopus databases between 2020 and 2026 using the keywords "podocyte," "podocytopathy," "glomerular disease," "podocyte injury," and "podocyte therapy."

A preprint version of this review has been published on SSRN (Ismayilova et al., 2026, SSRN Abstract ID: 6099546).

This review aims to comprehensively address the structural and functional characteristics of podocytes, mechanisms of injury, clinical podocytopathies, and current podocyte-targeted treatment strategies.

2. Podocyte biology and glomerular filtration

Podocytes are highly specialized, terminally differentiated visceral epithelial cells that form the outermost layer of the glomerular filtration barrier (GFB).[1] They wrap around the glomerular capillaries and attach to the GBM via complex foot processes; these foot processes are interconnected with SDs.[3] This unique architecture is of fundamental importance for the selective permeability of the glomerular filtration barrier.[2]

The primary structural components of the SD include proteins such as nephrin (NPHS1), podosin (NPHS2), CD2AP, Neph1, and FAT1; these proteins not only provide mechanical support but also initiate critical intracellular signaling.[3,7] The actin cytoskeleton, composed of F-actin, α-actinin-4, synaptopodin, and myosin, maintains the dynamic architecture of foot processes and enables them to respond to mechanical stress.[8]

Podocytes are metabolically active cells with high energy demands and are highly dependent on mitochondrial function.[9,10] Importantly, because they are terminally differentiated cells, they have very limited proliferative capacity under normal conditions; this makes them particularly vulnerable to injury and leads to irreversible loss.[1]

Podocytes also contribute to the maintenance of the GBM by synthesizing type IV collagen and laminin, and secrete vascular endothelial growth factor (VEGF) to preserve endothelial fenestrations.[1]

Recent technological advancements, such as glomerulus-on-a-chip models and super-resolution microscopy, have provided deeper insights into podocyte biology and their interactions with neighboring cells.[11,12]

3. Podocyte damage pathways

Podocyte damage is a central event in the pathogenesis of proteinuric glomerular diseases such as MCD, FSGS, and DN.[1,4] Since podocytes are terminally differentiated cells, their capacity for proliferation and regeneration is very limited; therefore, damage typically results in podocyte loss (podocytopenia) and progresses to progressive glomerular sclerosis and kidney failure.[13,14] Podocyte damage mechanisms are closely interlinked and primarily involve slit diaphragm disruption, actin cytoskeleton reorganization, mitochondrial dysfunction and oxidative stress, activation of profibrotic signaling pathways (TGF-β and mTOR), as well as apoptosis and detachment processes.[5,15] These pathological changes, along with the dynamic processes in the healthy and damaged glomerular filtration barrier, are illustrated in Figure 3, while the ultrastructural and cytoskeletal organization is shown in Figures 1 and 2.

The structural integrity of the SD is critical for podocyte function. Mutations, downregulation, or acquired damage in major slit diaphragm proteins such as nephrin (NPHS1), podosin (NPHS2), CD2AP, and NEPH1 lead to diaphragm fragmentation, foot process effacement, and loss of selective permeability of the filtration barrier, resulting in massive proteinuria.[16–18] While genetic defects, particularly in hereditary podocytopathies, lead to an early and severe clinical presentation, in acquired diseases, immune-mediated damage, toxins, or hemodynamic stress reduce the expression of these proteins.[1]

Reorganization of the actin cytoskeleton is one of the earliest and most common signs of podocyte damage. Overexpression of the RhoA/ROCK signaling pathway leads to dysfunction of actin-binding proteins such as α-actinin-4 and synaptopodin, resulting in foot process effacement and detachment of podocytes from the GBM.[19,20] This process is triggered by hyperglycemia, mechanical stress, and inflammatory signals; cytoskeletal instability disrupts podocyte contractility, significantly reducing the mechanical stability of the filtration barrier.[21]

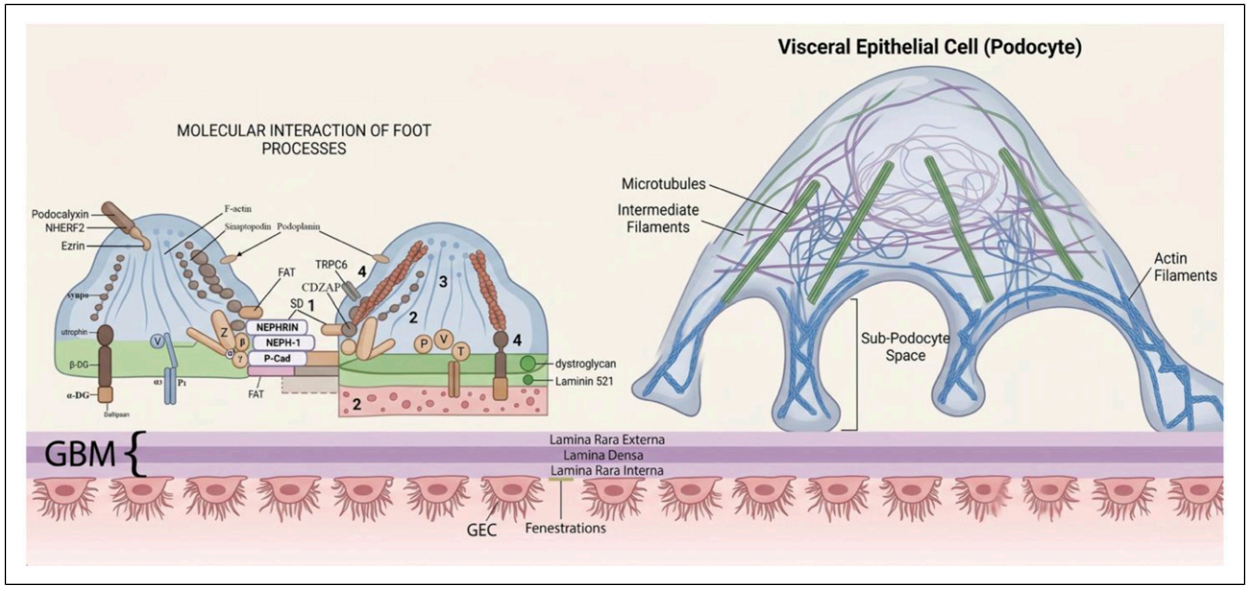


Figure 1. Molecular architecture of the glomerular filtration barrier and podocyte foot processes.
Schematic illustration showing the detailed molecular interactions within podocyte foot processes, including key slit diaphragm proteins (Nephrin, Podocin, CD2AP), cytoskeletal components (actin filaments, microtubules), adaptor proteins, and their connections to the glomerular basement membrane (GBM). The fenestrated glomerular endothelial cells (GEC) and the layered structure of the GBM are also depicted. (Created by the authors).

Since podocytes are cells with high energy demands, they are highly sensitive to mitochondrial dysfunction and oxidative stress. Hyperglycemia, lipotoxicity, and hemodynamic stress increase the production of reactive oxygen species (ROS); this leads to a collapse of the mitochondrial membrane potential, reduced ATP production, mtDNA damage, and apoptosis.[5,22] Oxidative stress also weakens cellular defense by suppressing the Nrf2 antioxidant pathway and accelerates disease progression, particularly in DN.[23]

Profibrotic signaling pathways are key mechanisms that perpetuate chronic damage. The TGF-β pathway promotes epithelial-mesenchymal transition (EMT)-like dedifferentiation, excessive production of matrix proteins, and apoptosis in podocytes.[24,25] mTORC1 hyperactivation, in turn, increases podocyte hypertrophy, inhibits autophagy, and promotes detachment under metabolic stress; the Wnt/β-catenin pathway also exacerbates injury in association with oxidative stress.[1,26] The intersection of these pathways amplifies podocyte damage, leading to glomerular sclerosis and interstitial fibrosis.[15]

Molecular crosstalk among these four core pathways plays a central role in driving podocyte damage toward a chronic state, forming a signaling network far more complex than a simple "intersection." Recent studies have demonstrated that the RhoA/ROCK pathway directly activates TGF-β/Smad signaling through mechanotransduction and MYPT1 phosphorylation. This interaction exacerbates fibrosis secondary to podocyte injury, particularly in hypertensive nephropathy and diabetic nephropathy.[20]

mTORC1 hyperactivation, under condition of oxidative stress, triggers mitochondrial fragmentation and impairs fatty acid metabolism, which in turn further activates RhoA/ROCK1. This cascade results in cytoskeleton remodeling and subsequent podocyte loss.[27] TGF-β signaling, via mTORC1promotes podocyte hypertrophy and inhibits autophagy while simultaneously activating the Wnt/β-catenin pathway, thereby sustaining epithelial-mesenchymal transition (EMT)-like dedifferentiation.[26]

Oxidative stress directly activates both RhoA and mTORC1 through excessive ROS production while suppressing the Nrf2 antioxidant pathway. This creates a self-reinforcing vicious cycle among the pathways. This integration accelerates the progression to glomerular sclerosis and interstitial fibrosis by amplifying podocyte damage, particularly under conditions of hyperglycemia and mechanical stress.[5,15]

This integrated molecular network indicates that targeting a single pathway is likely insufficient. Therefore, multi-target therapeutic approaches, such as the combination of RhoA/ROCK inhibitors with mTOR modulators, may be more effective in future treatment strategies. Understanding this complex signaling landscape is essential for the development of personalized and combination therapies in podocytopathies.

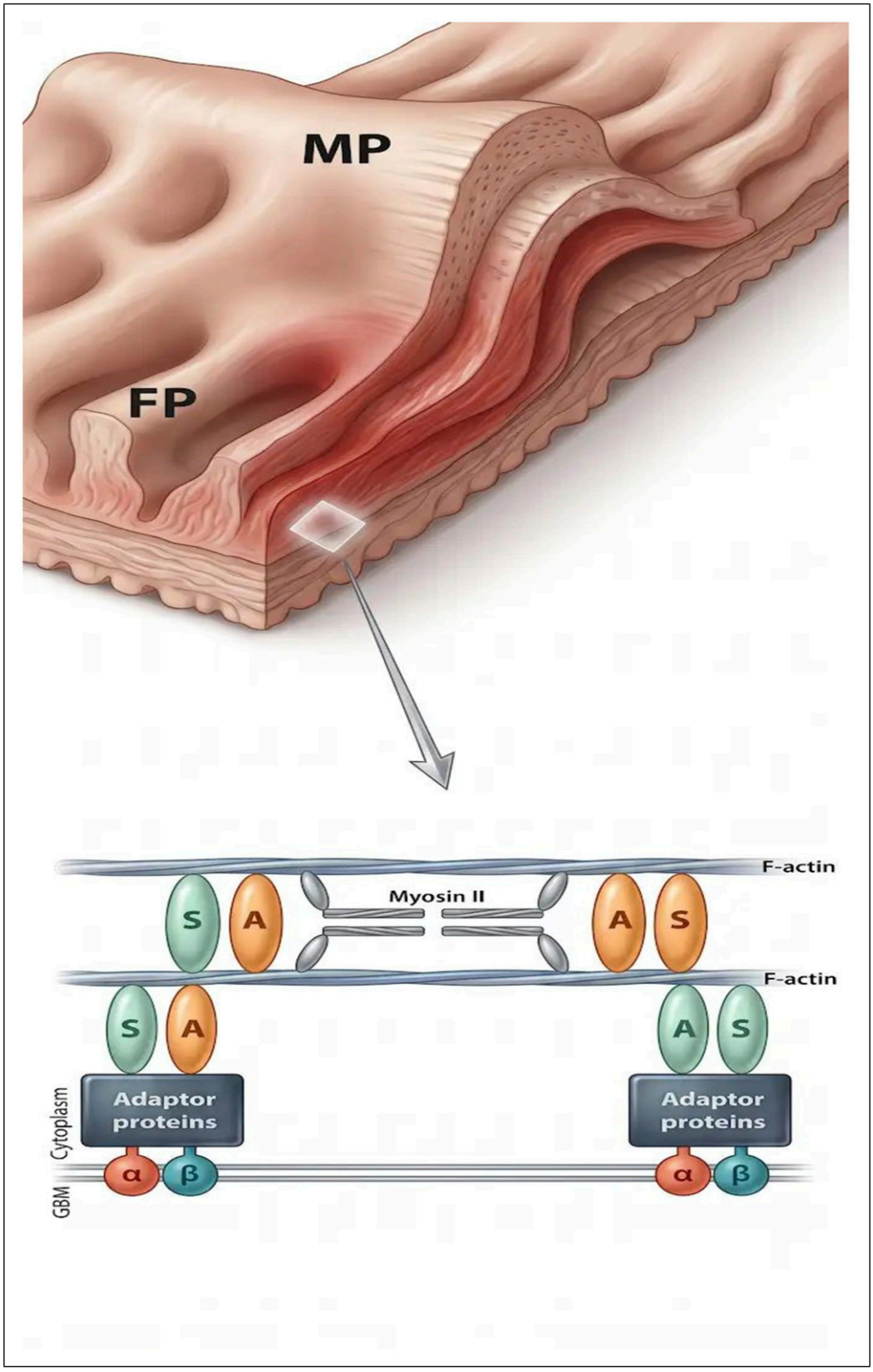


Figure 2. Actin-myosin cytoskeletal organization in podocyte foot processes.
(a) Three-dimensional view of podocyte major process (MP) and foot process (FP) attached to the glomerular basement membrane (GBM). (b) Schematic representation of the molecular architecture showing parallel F-actin bundles crosslinked by α-actinin-4 (A) and synaptopodin (S), contractile myosin II, adaptor proteins, and integrin (αβ) linkage to the GBM.
(Created by the authors).

Damaged podocytes are lost through apoptosis, anoikis, or detachment. Because they are terminally differentiated, their proliferative capacity is limited, leading to the development of podocytopenia.[13,27] The detection of podocyte markers (nephrin, podocalcin, podosin) in urine provides valuable non-invasive biomarkers for monitoring active disease, progression, and treatment response.[14,28]

These mechanisms are typically activated by common triggers (hyperglycemia, mechanical stress, immune-mediated damage, toxins) and overlap with one another.[5,21] A detailed understanding of the molecular basis of podocyte damage provides a strong foundation for the development of targeted therapies such as RhoA/ROCK inhibitors, mTOR modulators, antioxidants, and TGF-β inhibitors.[20,25]

4. Clinical podocytopathies

Podocyte damage is the common pathological basis of many primary and secondary glomerular diseases and is the primary cause of proteinuria and progressive kidney failure.[1,15] Podocytopathies can arise from genetic, immune-mediated, metabolic, or toxic factors and are clinically classified as MCD, MN, FSGS, and hereditary nephrotic syndromes.

MCD is the most common cause of nephrotic syndrome in childhood. It is characterized by widespread effacement of the podocyte foot processes, although persistent structural changes in the SD proteins are generally not observed. The disease is associated with T-cell-mediated factors affecting glomerular permeability and responds very well to immunomodulatory therapies (steroids, calcineurin inhibitors).[28,29]

FSGS can occur in either a primary or secondary form. In primary FSGS, genetic mutations in podocytes (NPHS1, NPHS2, WT1, TRPC6, etc.) or immune-mediated damage play a role. Secondary FSGS, on the other hand, develops as a result of adaptive hyperfiltration caused by conditions such as obesity, reflux nephropathy, viral infections, or drug toxicity. It is characterized by foot process effacement, podocyte detachment, and segmental sclerosis. The prognosis is relatively poor, with up to 50% of cases progressing to end-stage renal disease.[5,30]

MN is the most common cause of primary nephrotic syndrome in adults. In most cases, autoantibodies develop against podocyte surface antigens (PLA2R, THSD7A). These antigen-antibody complexes lead to subepithelial immune complex deposition, causing podocyte damage and proteinuria.[31,32]

Hereditary podocytopathies begin in early childhood as a result of mutations in slit diaphragm (NPHS1, NPHS2), actin cytoskeletal (ACTN4, INF2, MYO1E), or glomerular basement membrane (GBM) proteins. Congenital nephrotic syndrome (Fin type) is the most severe form and is typically associated with an NPHS1 mutation. Steroid resistance is common in this group, and the rate of progression is high.[17,33]

In recent years, significant progress has been made in identifying new biomarkers that can be used in the diagnosis, classification, and monitoring of podocytopathies. Among these, circulating anti-nephrin autoantibodies have emerged as a particularly promising biomarker, especially in minimal change disease (MCD) and a subgroup of primary focal segmental glomerulosclerosis (FSGS). Using a novel immunoprecipitation-ELISA assay, anti-nephrin autoantibodies were detected in approximately 69% of adult with active MCD and in up to 90% of children with idiopathic nephrotic syndrome before the initation of immunosuppressive therapy. These autoantibodies show a strong correlation with disease activity; their levels decrease during remission and rise again during relapse. Furthermore, passive transfer and active immunization studies in animal models have shown that anti-nephrin autoantibodies can induce an MCD-like phenotype.[34,35] These findings may aid in distinguishing anti-nephrin-positive podocytopathies from other proteinuric glomerular diseases and have the potential to reduce the need for renal biopsy in selected cases.

Urinary podocyte-derived biomarkers also provide valuable non-invasive information. Podocalixin levels measured in the urinary supernatant are elevated in non-proliferative glomerular diseases such as membranous nephropathy, podosin and nephrin mRNA levels in urine sediment increase more markedly in proliferative or rapidly progressive forms. When combined with clinical parameters, these biomarkers can enhance the monitoring of disease activity and treatment response.[14] In primary membranous nephropathy, anti-PLA2R antibody titers remain the most established serological biomarker and correlate with disease activity and prognosis. In addition, tests for anti-THSD7A and newly identified podocyte antigens improve diagnostic accuracy.[31] In hereditary podocytopathies, while genetic analysis of NPHS1, NPHS2, WT1, and ACTN4 mutations remains the gold standard, urinary exosomal miRNAs and specific podocyte protein panels are being investigated as potential auxiliary biomarkers for monitoring disease progression and the risk of relapse following transplantation.

Collectively, these novel biomarkers not only improve diagnostic accuracy but also pave the way for personalized therapeutic approaches, such as B-cell-targeted therapies, in anti-nephrin-positive patients. Their integration into clinical practice is expected to significantly advance the early diagnosis and long-term management of podocytopathies.

A common feature of these clinical presentations is the strong correlation between the severity of podocyte damage, the level of proteinuria, and renal prognosis. In recent years, urinary podocyte markers (podocalcin, nephrin, podosin) and podocyturia have become important non-invasive biomarkers for monitoring disease activity and treatment response.[14,28]

5. Podocyte-targeted therapeutic innovations

In recent years, therapies targeting podocyte damage have led to a paradigm shift in the management of glomerular diseases. These therapies aim to protect existing podocytes, reverse damage, and promote regeneration.[1,25]

Renin-Angiotensin-Aldosterone System (RAAS) blockade remains a cornerstone of podocyte protection. Angiotensin II blockade (ACE inhibitors and ARBs) not only reduces intraglomerular pressure but also decreases podocyte apoptosis, protects slit diaphragm proteins (nephrin, podosin), and enhances actin cytoskeleton stability. It significantly slows renal progression, particularly in diabetic nephropathy and FSGS.[5,26]

Calcineurin Inhibitors (Cyclosporine, Tacrolimus) are among the most effective agents that directly target the podocyte cytoskeleton. Cyclosporine inhibits the RhoA/ROCK pathway by protecting synaptopodin from phosphorylation and can reverse foot process effacement. Although it achieves high remission rates in minimal change disease and primary FSGS, nephrotoxicity is a limiting factor with long-term use.[36]

SGLT2 inhibitors exert a dual metabolic and hemodynamic effect in podocyte protection. By reducing glomerular hyperfiltration, they lower mechanical stress, improve mitochondrial function, and suppress oxidative stress. Large studies such as DAPA-CKD and EMPA-KIDNEY have demonstrated that they slow podocyte loss and reduce renal endpoints in both diabetic and non-diabetic chronic kidney disease.[37,38]

Among new molecularly targeted therapies, RhoA/ROCK inhibitors, mTOR inhibitors (rapamycin analogs), and TGF-β pathway modulators are emerging as key options. Podocyte-specific RhoA/ROCK inhibition restores foot process architecture and reduces proteinuria.[19,20] Antioxidant agents and Nrf2 activators, on the other hand, prevent podocyte loss caused by oxidative stress by targeting mitochondrial dysfunction.[23]

In recent years, significant advances have been made in targeted therapies for podocyte damage. Among these, **Sparsentan** is one of the first agents to act as an antagonist of both the dual endothelin A receptor (ET_AR) and the angiotensin II type 1 receptor (AT_1R). In the Phase 3 DUPLEX trial conducted in patients with FSGS, Sparsentan significantly reduced proteinuria levels and slowed the decline in kidney function.[39] By exerting hemodynamic and antifibrotic effects, it reduces podocyte injury and is therefore considered a promising treatment option for podocytopathies.

Another emerging agent**, Apecotrep** (BI 764198), a selective inhibitor of the transient receptor potential cation channel subfamily C member 6 (TRPC6). Overexpression of TRPC6 leads to calcium influx, cytoskeletal disruption, and cellular damage in podocytes. In the Phase 2 PODOMOUNT-pFSGS trial, data presented at the American Society of Nephrology (ASN) Kidney Week 2025 demonstrated that once-daily oral Apecotrep reduced proteinuria levels by approximately 40% in patients with primary FSGS, and the drug was well tolerated. The results of this study were subsequently published in *The Lancet*.[40] These findings indicate that TRPC6 inhibition may represent a new therapeutic strategy that directly targets podocyte damage.

Monoclonal antibodies are also playing an increasingly important role in the treatment of podocytopathies. In particular, B-cell-depleting therapies (rituximab and obinutuzumab) can be effective in controlling disease activity in cases of MCD and FSGS that are positive for anti-nephrin autoantibodies.[34] In membranous nephropathy, agents such as rituximab and the next-generation anti-CD38 monoclonal antibody felzartamab alleviate podocyte damage by reducing immune complex formation.[31] These biologic agents offer alternative or adjunctive treatment options to traditional immunosuppressive therapies, particularly in immune-mediated podocytopathies.

The ability of these novel agents (Sparsentan, Apecotrep, and monoclonal antibodies) to target distinct molecular pathways involved in podocyte injury supports the development of more personalized treatment approaches in the future. However, long-term efficacy and safety data from larger and longer-term studies are still required.

Regenerative and gene therapies represent the most promising approaches for the future. Induced pluripotent stem cell (iPSC)-derived podocytes and the paracrine effects of mesenchymal stem cells support podocyte regeneration in experimental FSGS models. CRISPR-Cas9-based gene editing strategies, on the other hand, hold the potential to provide a permanent solution for hereditary podocytopathies by correcting mutations in genes such as NPHS1, NPHS2, and ACTN4.[17]

The table below summarizes a comparison of the main podocyte-targeted therapies:

These innovations, coupled with a better understanding of podocyte biology, are paving the way for the development of disease-specific, personalized treatment strategies. Future studies should focus on combinations of these agents and podocyte-specific drug delivery systems (nanoparticles).[15,25]

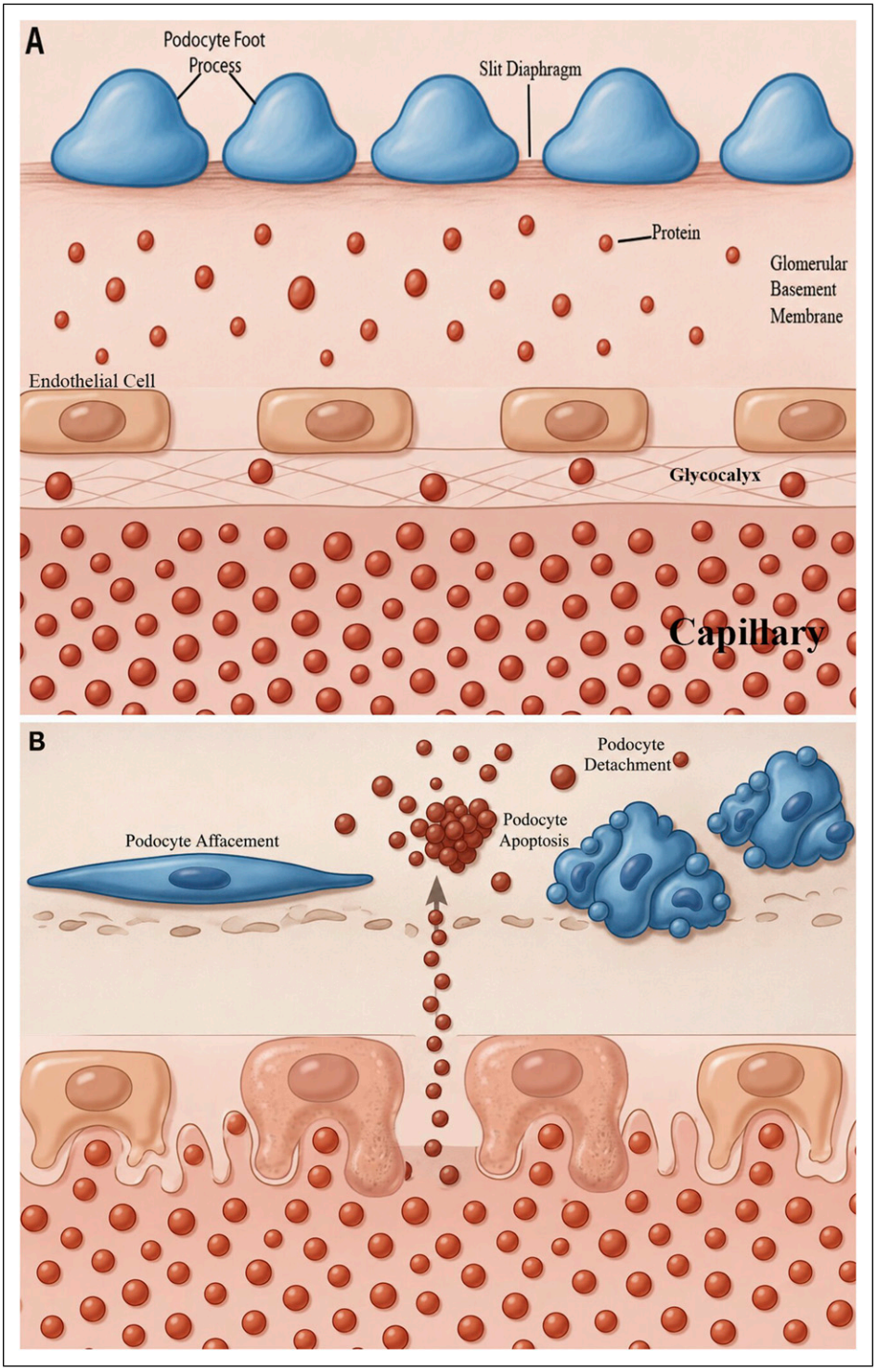


Figure 3. Healthy and injured glomerular filtration barrier structure and podocyte injury.
(a) Normal glomerular filtration barrier. Podocytes display intact interdigitating foot processes connected by slit diaphragms. The glomerular basement membrane (GBM) exhibits normal thickness and architecture, while fenestrated glomerular endothelial cells with an intact glycocalyx layer are preserved. Small proteins are retained within the filtration barrier under physiological conditions. (b) Injured glomerular filtration barrier. Podocyte injury is characterized by foot process effacement, detachment, and apoptosis. Endothelial injury is illustrated by swelling, loss of fenestrations, and disruption of the glycocalyx, while the GBM exhibits pathological thickening and structural irregularity. These combined alterations compromise the integrity of the glomerular filtration barrier, resulting in increased protein leakage into the urinary space. A podocyte with preserved attachment is shown on the left for comparison.
(Created by the authors.)

Table 1. Comparative Overview of current and emerging podocyte-targeted therapeutic approaches.

Therapeutic class	Target mechanism	Clinical efficacy	Limitations
RAAS Blockade	Hemodynamic modulation and anti-apoptatic effects	High	Hyperkalemia, hypotension
Calcineurin Inhibitors	Cytoskeletal stabilization	Very high (particularly in MCD/FSGS)	Nephrotoxicity
SGLT2 Inhibitors	Metabolic and hemodynamic protection	High (in both DKD and non-DKD)	Genitourinary infections
Rhoa/ROCK Inhibitors	Regulation of actin cysoskeletal dynamics	Experimental → Clinical translation underway	Limited clinical evidence to date
Spersentan	Dual ET_AR and AT_1R antagonism	High (significant proteinuria reduction in FSGS)	Limited long-term data
Gene/CRISPR Based Therapies	Genetic correction	Early-stage development	Safety and delivery challenges
Apecotrep (TRPC6 Inhibitor)	TRPC6 channel inhibition	Promising (Phase 2: ~40% proteinuria reduction in primary FSGS)	Early-stage development, long-term data pending

6. Discussion

This narrative review provides a comprehensive synthesis of podocyte biology, fundamental mechanisms of injury, clinical podocytopathies, and emerging targeted therapeutic strategies. Compared to previous reviews[1,4,5,7] this study brings together recent advancements from 2024–2026 regarding mitochondrial dysfunction, the RhoA/ROCK signaling pathway, and regenerative approaches such as iPSC-derived podocytes and CRISPR-based gene therapies. While most previous studies have focused either on fundamental mechanisms or on a specific group of diseases, this review offers a broader translational perspective by linking molecular pathways to current and developing therapies.

6.1. Contribution to the literature and innovative aspects

The primary strength and innovative aspect of this review lies in its focus on podocyte-specific therapeutic approaches such as RhoA/ROCK inhibitors, Nrf2 activators, podocyte-targeted nanocarrier systems, and gene editing technologies in addition to established treatments like RAAS blockade, SGLT2 inhibitors, and calcineurin inhibitors. Additionally, the schematic figures prepared by the authors (Figures 1–3), which illustrate the molecular details of both normal and damaged podocyte architecture, contribute to a better visual understanding of the subject. Furthermore, the comparative presentation of the efficacy and limitations of current and emerging treatments in Table 1 provides a practical summary for clinical applications.

6.2. Limitations

As this study is a narrative review, it has certain inherent limitations. First, since a systematic review methodology was not followed, it is possible that some relevant studies were overlooked despite extensive database searches. Second, a significant portion of the promising treatments discussed (particularly RhoA/ROCK inhibitors, gene therapies, and stem cell-based approaches) are still in the preclinical or early clinical research phase; this limits the strength of current clinical recommendations. Third, due to the rapidly evolving nature of the field, studies published after April 2026 could not be included in this review. Finally, it is acknowledged that, by the nature of narrative reviews, studies reporting positive outcomes may have been given greater prominence, whereas negative or conflicting findings may have been underrepresented.

Despite these limitations, the review highlights existing knowledge gaps in the management of podocyte damage and underscores the urgent need for podocyte-protective and regenerative therapies capable of halting the progression of glomerular diseases.

7. Conclusion

Podocytes play an indispensable role in maintaining the selective permeability of the glomerular basement membrane (GBM) and ensuring the continuity of renal function. Due to their structural complexity and functional characteristics, podocytes are highly sensitive to various intrinsic and environmental factors; disruption of their integrity constitutes the fundamental pathophysiological mechanism underlying glomerular diseases such as membranous nephropathy (MCD), focal segmental glomerulosclerosis (FSGS), and diabetic nephropathy (DN).

Mechanisms such as serum protein loss, reorganization of the actin cytoskeleton, and podocyte apoptosis are the primary drivers of progressive proteinuria and renal failure. Significant progress has been made in strategies targeting podocyte damage through immunomodulation, cytoskeletal stabilization, molecularly targeted therapies, and regenerative medicine approaches. However, the efficacy of current treatments remains limited.

In the future, a better understanding of the molecular regulatory pathways of podocytes will facilitate the development of personalized treatment approaches. Significant advancements are anticipated in podocyte-related glomerular diseases with the clinical implementation of innovative methods such as gene therapy, cellular engineering, and biological agents. The promotion of translational research, the identification of new therapeutic targets, and multidisciplinary collaborations are key elements that will improve clinical outcomes in this field.

In short, strategies to preserve the structural and functional integrity of podocytes will remain a key focus in the management of glomerular diseases.

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Author contributions

Shams Ismayilova conceived the review topic, conducted the literature review, synthesized the findings, and wrote the manuscript.
Afig Berdeli supervised the study and critically reviewed the manuscript for scientific accuracy and intellectual content.
Onur Mutlu contributed to figure preparation, participated in manuscript revision and editing, and approved the final version.
Jamila Bayramova contributed to reference organization, participated in manuscript revision and editing, and approved the final version.
All authors reviewed and approved the final version of the manuscript.

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Data Availability Statement

This article is a review of previously published studies and does not contain any new datasets generated or analyzed by the authors.

Supplemental Material

Supplemental material for this article is available online.

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Appendix

Abbreviations

GBM:	Glomerular Basement Membrane
FP:	Foot Process
SD:	Slit Diaphragm
GFB:	Glomerular Filtration Barrier
NS:	Nephrotic Syndrome
MCD:	Minimal Change Disease
FSGS:	Focal Segmental Glomerulosclerosis
MN:	Membranous Nephropathy
DN:	Diabetic Nephropathy
DKD:	Diabetic Kidney Disease
MP:	Major Process
RAAS:	Renin–Angiotensin–Aldosterone System
SGLT2:	Sodium–Glucose Cotransporter 2
ROCK:	Rho-associated Coiled-Coil Containing Protein Kinase
TGF-β:	Transforming Growth Factor Beta
mTOR:	Mechanistic Target of Rapamycin
ROS:	Reactive Oxygen Species
EMT:	Epithelial-Mesenchymal Transition
iPSC:	Induced Pluripotent Stem Cell
Nrf2:	Nuclear factor erythroid 2-related factor 2
NPHS1:	Nephrin
NPHS2:	Podocin
ACTN4:	α-Actinin-4
MYO1E-	Miyosin-1e
PLA2R:	Phospholipase A2 Receptor
THSD7A:	Thrombospondin Type-1 Domain-Containing 7A.