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Nanoparticle-Based Drug Delivery in Renal Ischemia-Reperfusion Injury: Insights into Molecular Signaling Pathways: A Systematic Review

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A B S T R A C T

Objective: Renal ischemia-reperfusion injury (RIRI) is a major cause of acute kidney damage following surgery, trauma, organ transplantation, and thrombotic events, primary due to oxidative stress and cellular injury. Nanoparticles (NPs) have emerged as promising therapeutic tools by enabling targeted drug delivery, controlled release, and reduced systemic toxicity. This systematic review evaluates the effects of NP-based therapies on RIRI, with a focus on their modulation of key molecular signaling pathways.

Methods: A systematic search was performed in PubMed, Scopus, and Web of Science, ScienceDirect, and Google Scholar for studies published between 1990 and 2024. After applying predefined inclusion and exclusion criteria, 14 studies were included in the final analysis.

Results: NP-based interventions consistently have improved experimental RIRI outcomes by reducing oxidative stress, preserving renal function markers, attenuating inflammation and fibrosis, and modulating immune and gene-expression responses. These effects were observed across different nanoformulations and therapeutic cargoes.

Conclusion: Current evidence supportsthe the use of nanoparticles as promising candidates for the prevention and treatment of RIRI, with clear potential for translation into advanced renal drug delivery and renoprotective strategies.

Keywords: Nanoparticle exposure, Renal ischemia-reperfusion injury, Signaling pathways

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Introduction

Renal ischemia-reperfusion injury (RIRI) is a leading cause of acute kidney injury, particularly during kidney transplantation, major vascular surgeries, and resuscitation after severe hypotension. Despite advances in supportive care, current therapies are unable to adequately suppress the intense oxidative stress, inflammation, and cell death triggered during ischemia and reperfusion. This therapeutic gap highlights an urgent need for novel strategies capable of neutralizing reactive oxygen species (ROS) and modulating dysregulated molecular pathways in RIRI [1, 2].

Nanoparticles have recently emerged as promising candidates due to their ability to deliver therapeutic agents directly to injured renal tissue, enhance drug stability, and reduce systemic toxicity. In addition, several nanomaterials exhibit intrinsic antioxidant or "nanozyme-like" activity, enabling direct scavenging of ROS and attenuation of inflammatory responses [3-5]. Metal-oxide and polymer-based nanoparticles have demonstrated strong biological activities relevant to renal protection, including antioxidative, anti-inflammatory, and anti-fibrotic effects [6] including antioxidant, antimicrobial, anti-cancer, anti-diabetic, anti- inflammatory, and wound-healing effects [7].

Considering the limited effectiveness of current treatments and the growing evidence supporting nanoscale therapeutics, this review examines how nanoparticle-based interventions modulate key signaling pathways associated with RIRI and highlights their potential for future clinical application.

Study design

Systematic review

This systematic review was developed in accordance with widely accepted guidelines for reporting systematic reviews [8]. The methodology employed in this work builds upon protocols established in earlier publications by our research team [9, 10].

Databases and search strategy

An extensive search was performed across multiple English-language academic databases, including PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar, to identify studies relevant to the topic. A detailed search strategy was initially designed in PubMed using a combination of carefully selected keywords, Boolean operators, and search fields. This search syntax was subsequently tailored for compatibility with the other databases. The literature search was conducted comprehensively and without temporal limitations, covering studies published up to the end of 2024. A concise overview of the individual search approaches used across each database is presented in Table 1.

Table 1: Search Syntax

Database	Search strategy	Records retrieved (n)
PubMed	(("Nanoparticles"[Mesh] OR nanoparticle*[Title/Abstract] OR "Titanium dioxide nanoparticle*"[Title/Abstract] OR "Gold nanoparticle*"[Title/Abstract] OR "Zinc oxide nanoparticle*"[Title/Abstract] OR "Iron nanoparticle*"[Title/Abstract] OR nanocapsule*[Title/Abstract] OR "Metal nanoparticle*"[Title/Abstract]) AND ("Renal ischemia-reperfusion injury"[Title/Abstract] OR "Kidney ischemia-reperfusion injury"[Title/Abstract] OR ((renal OR kidney)[Title/Abstract] AND ("ischemia-reperfusion"[Title/Abstract] OR "I/R injury"[Title/Abstract]))))	22
Scopus	TITLE-ABS (nanoparticle* OR "Titanium dioxide nanoparticle*" OR "Gold nanoparticle*" OR "Zinc oxide nanoparticle*" OR "Iron nanoparticle*" OR nanocapsule* OR "Metal nanoparticle*") AND TITLE-ABS ("Renal ischemia-reperfusion injury" OR "Kidney ischemia-reperfusion injury" OR ((renal OR kidney) AND ("ischemia-reperfusion" OR "I/R injury")))	28
Web of Science Core Collection	TS=(nanoparticle* OR "Titanium dioxide nanoparticle*" OR "Gold nanoparticle*" OR "Zinc oxide nanoparticle*" OR "Iron nanoparticle*" OR nanocapsule* OR "Metal nanoparticle*") AND TS=("Renal ischemia-reperfusion injury" OR "Kidney ischemia-reperfusion injury" OR ((renal OR kidney) AND ("ischemia-reperfusion" OR "I/R injury")))	32
Other database		5

Study selection

Figure 1. illustrated the Summary of a standard four-step protocol for literature review based on legitimate keywords. we manually examined the references list of the included studies to gather any additional pertinent papers in order to collect all potentially relevant research. The inclusion criteria were on the association of nanoparticle with Renal ischemia/reperfusion injury (RIRI) in English. Studies were excluded if they were Review articles, duplicate articles, editorials, brief communications, rules, theses, oral presentations, book chapters, conference abstracts, comments, white papers, and technical reports.

Data extraction

Data were independently collected by two reviewers (MM, MKh) on the following aspects: author names, research model, publication year, type of disease, types of nanoparticles used, results obtained, agents involved, exposure duration, receptors/pathways studied, assessment periods, therapeutic interventions related to nanoparticle exposure and ischemia/reperfusion injury, protective effects observed, and molecular pathways involved. Disagreements between the two reviewers during this process were resolved with the assistance of a third researcher.

Results

After literature search in the data resources, 87 articles were found. Then, 74 articles were discarded because some were unrelated to the association of nanoparticle exposure with RIRI, duplicate articles, review articles, letters to the editor, and progress articles. Finally, after reviewing the full texts of the articles, 14 articles published between 2016 and 2024 that met the inclusion/exclusion criteria were selected for this SR (Figure. 1).

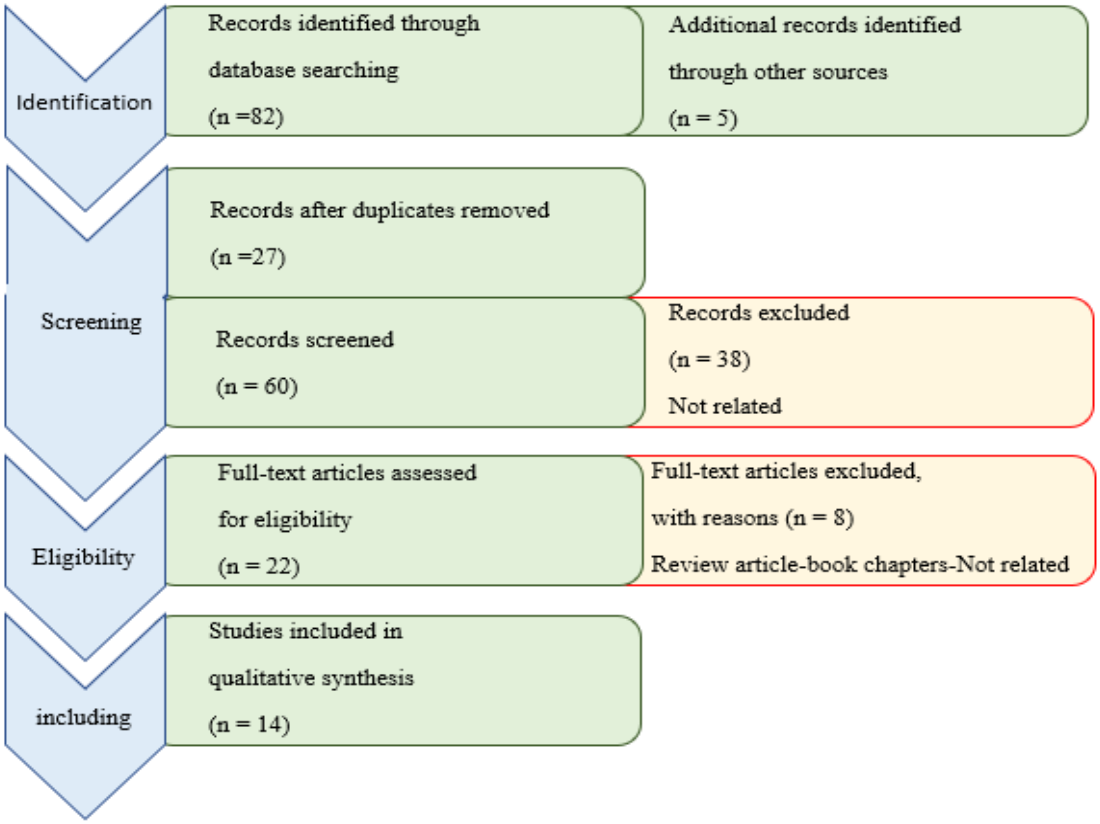


Figure 1: Summary of a standard four-step protocol for literature review

Table 2 displays the 14 articles' complete descriptions and a summary of their characteristics. Characteristics of studies conducted on the relationship between NPs utilization and RIRI are indicated in Table 3.

Table 2: Characteristics of studies conducted on the relationship between nanoparticles and renal ischemia-reperfusion injury (RIRI)

Year	Ref.	Model (Animal/Human) In vivo/ In vitro	Injury/disease	Nanoparticle(s)	Investigation	Brief Results
2021	Awadalla et al [1]	Male Sprague Dawley rats	RIRI	ZnO-NPs	Effects of FA and ZnO-NPs and a combination of both on RIRI	FA and ZnO-NPs showed protective effects on cells against RIRI, with their combination offering enhanced kidney protection.
2022	Zhou et al. [11]	In vivo (mouse)	In vivo RIRI	CNPs	Effects of CNPs prophylactic in RIRI	CNPs show promise as a treatment or preventive approach for RIRI and kidney fibrosis.
		In vitro (HK2, RTEC cells)	In vitro hypoxia			

2023	Embaby et al. [12]	Male Sprague Dawley albino rats	RIRI	ZnO-NPs	Efficacy of ZnO-NPs and/or MIL on RIRI	ZnO-NPs and MIL also provided cellular protection in acute RIRI cases, and their combination proved even more effective.
2021	Liu et al. [13]	In vivo (C57BL/6 male mice)	RIRI	T-NPCoQ10	Efficacy of mitochondria-targeted nanocarrier to delivery of CoQ10 for RIRI	Delivering CoQ10 directly to mitochondria presents a highly effective strategy for controlling inflammation and oxidative damage in RIRI.
		In vitro (HK-2 cells)	(In vitro) oxygen-glucose deprivation			
2021	Xie et al. [14]	Male mice	RIRI	PHD2 siRNA G5-FA	Effects of PHD2 siRNA G5-FA on RIRI	G5-FA functions as a reliable carrier for delivering siRNA to the kidney. Suppressing PHD2 in renal tissues may help manage RIRI.
2022	Hou et al. [15]	In vivo mice)	In vivo: RIRI		Effects of NPs targeting TSP-1 on RIRI	LSKL/NPs can reduce and deactivate TSP-1, presenting a viable therapeutic method for RIRI.

		In vitro (HK-2 cells)	In vitro TSP-1 induced human renal tubular epithelial cell apoptosis	LSKL/NPs		
2020	Liu et.al. [16]	In vivo (mice)	RIRI	N-NP CoQ10	Efficacy of a N-NP CoQ10 strategy for RIRI treatment.	Administering N-NP CoQ10 may represent a promising approach in RIRI treatment.
		In vitro (human, HK-2 cells)				
2022	Xu et al [17]	In vivo (male BALB/c mice)	RIRI	NP-IGF-1C	Effects of NP-IGF-1C on preventing RIRI	NP-IGF-1C have demonstrated a protective effect during RIRI progression.
		In vitro (HEK293 cells)	In vitro Oxygen-glucose deprivation/reperfusion			
2016	Xu et al [18]	In vitro (HK-2 cells)	HK-2 cells IRI	Cur-NPs	Effect of Cur-NPs on HK-2 cells exposed to IRI	Cur-NPs helped safeguard HK-2 cells exposed to IRI.

2017	Xie et al [19]	Sprague-Dawley rats	RIRI	BBR-NPs	Effects of BBR-NP on the IRI renal cells	BBR-NP were more effective than berberine alone in preventing kidney injury caused by IRI.
2022	Saleh et al [20]	Male diabetic mice	RIRI induced AKI	PEG-AuNPs	Effect of PEG-AuNPs on RIRI induced AKI	PEG-AuNPs are a potential treatment for diabetic AKI triggered by IRI.
2024	Karimi et al [21]	Sprague–Dawley rats	RIRI induced AKI	Chitosan - NPs	Effects of a combination (TNG and chitosan – NPs) on RIRI induced AKI	A combination of TNG and Chitosan – NPs offered kidney protection from RIRI-induced AKI.
2024	Saiz et al [22]	In vivo Mice	In vivo Bilateral ischemia reperfusion injury(clamping both renal pedicles) In vitro	JQ1- NPs	Effects of BET inhibitor nanotherapy on kidney damage and CKD progression after RIRI	BET inhibitor-based nanotherapy showed protective effects against kidney damage and slowed the progression of CKD following RIRI.

		In vitro HK-2 cell	-			
2024	Guo et al [23]	In vivo (Male C57/B6 mice)	In vivo (RIRI)	Albumin - NPs	Effects of the Albumin - NPs on RIRI	Prolonged retention of albumin - NPs alleviates RIRI
		In vitro (TCMK-1 cells)	In vitro Hypoxia-Reoxygenation Model			

Nanoparticles(NPs), Renal ischemia/reperfusion injury (RIRI), Ischemia/reperfusion injury (IRI) ,Acute kidney injuri (AKI) Ferulic acid (FA) ,Zinc oxide nanoparticles (ZnO-NPs), Human kidney tubular epithelial cells (HK2), Renal tubular epithelial cells (RTEC), Thrombospondin-1(TSP-1), Ceria-NPs(CNPs), Milrinone (MIL), Mitochondria-targeted TPP CoQ10 nanoparticles (T-NPCoQ10), Small interfering RNA (siRNA), Folic acid (FA)-decorated polyamidoamine dendrimer generation 5 (G5-FA), Prolyl Hydroxylase Domain Protein 2(PHD2), Thrombospondin-1(TSP-1), Peptide which inhibits TSP-1 activation (LSKL), Neutrophil membrane-enveloped Coenzyme Q (N-NP CoQ10), insulin-like growth factor-1C nanoparticles (NP-IGF-1C), curcumin-carrying distearoy lphosphatidylethanolamine -polyethylene glycol nanoparticles (Cur-NPs), Berberine nanoparticles (BBR-NP), Polyethylene glycol capped gold nanoparticles (PEG-AuNPs), Adenosine5′ monophosphate–activated protein kinase nuclear factor erythroid-2-related factor- 2 (AMPK-Nrf2), Acute kidney injury (AKI), trinitroglycerine (TNG), Human Embryonic Kidney (HEK), Mouse proximal tubular epithelial cells (TCMK-1), Chronic kidney disease (CKD), Extra-Terminal motif (BET).

Table3: Characteristics of studies that show the positive point of treatment by nanoparticles for renal ischemia-reperfusion injury (RIRI)

Year	Ref.	Model of ischemia	Time of ischemia	Nanoparticle (dose or size)	Effective size/dose	Treatment duration by Nanoparticle	Measurement/ assayed factor(s)	Final Results	(Probable) Physiological/ pharmacological route(s) of action
2021	Awadalla et al [1]	Occlusion of left renal pedicle and Right nephrectomy 5 min before removal of the clamp	45 min	ZnO-NP 5 mg/Kg, i.p.	5 mg/Kg i.p.	2 hrs before ischemia	Cr, BUN, MDA, TNF-α, Bax, caspase-3, CAT, SOD, Expression of Nrf2, HO-1, HIF-1α genes and ki67	↓Cr and BUN	↑ Cell proliferation, ↓ Oxidative stress, ↑ (ki67), upregulation of antioxidant genes and downregulation of inflammatory cytokine and apoptotic genes upregulation of (Nrf2, HO-1 and HIF-1α) and downregulation of (TNF-α and caspase-3 and Bax).
2022	Zhou et al. [11]	Unilateral nephrectomy and contralateral renal vascular clamping	40 min	In vivo Ceria -NP 10 mg/kg i.v.	NP118 nm	In vivo: 2 h before surgery	Cr, BUN, Histological analysis, Cytochrome c quantification, Flow cytometry, MDA, Nrf2, macrophage infiltration	↓Cr , BUN and MDA Improvement in Histological change. ↑Cytochrome c quantification	In vivo: ↓Oxidative stress, ↓ RIRI induced inflammatory response, ↓ macrophage infiltration and polarization to M1 phenotype, Regulating the Nrf2 pathway,
		In vitro		In vitro		In vitro: 12 h			

		serum-free condition followed by 2 h of standard condition (IR mimicking condition)		Ceria -NP 20 μg/mL					↓ pro-inflammatory cytokine and chemokine production. In vitro: ↓ Intracellular ROS production, ↓ lipopolysaccharide-induced inflammation in RAW264.7 cells
2023	Embaby et al. [12]	Unilateral RIRI and right nephrectomy	45 min	ZnO-NP (5, 7.5, and 10 mg/kg b.wt. i.p.)	10 mg/kg i.p.	2 h before RIRI induction	Cr, urea, GPx, CAT, and SOD activities, MDA and NO concentrations. TNF-α, NF-κB, KIM-1, NGAL, and caspase-3 Nrf2. renal lesions and fibrosis, vascular permeability	↓Cr and urea, Improvement in Histopathological change, Improvement in vascular permeability, renal lesions and fibrosis.	↓Oxidative stress, apoptosis ↑Antioxidant activity, ↑ GPx, CAT, and SOD activities, ↓ MDA and NO concentrations. ↓Renal expressions of TNF-α, NF-κB, KIM-1, NGAL, and caspase-3, ↑ Gene expressionNrf2 mRNA
2021	Liu et al. [13]	bilaterally Renal hilum clamping	40 min	T-NPCoQ10	In vivo: 50 mg/kg	In vivo: 24 h before I/R surgery	In vivo: Plasma Cr, BUN, tubular injury score	↓Cr, BUN and tubular injury score	In vivo: ↓Oxidative injury in both cell and animal models, ↓ mtDNA damage,

							Protein carbonyl content, mtDNA damage, BAX, Caspase- 3, Bcl-2, and IL-1β, TNF-α, and IL-6,	↓Protein carbonyl content	↓ inflammatory and apoptotic responses, ↓BAX, Caspase- 3, Bcl-2, and IL-1β, TNF-α, and IL-6
		In vitro Oxygen-glucose deprivation	8-h		In vitro 5 μM	In vitro: incubation with T-NPCoQ10 for 2 h (according to methods)			In vitro: ↓ROS generation
							In vitro: ROS generation		
2021	Xie et al. [14]	Right kidney was removed, and the renal pedicle of left kidney was clipped by microvascular clamp	30 min	PHD2 siRNA G5-FA	7 mg siRNA/1 7.5 mg G5-FA per 10 g b.wt.	24 hours prior to I/R surgery.	PHD2 and GLUT1 mRNA, PHD2 protein, Cr /BUN Kidney Injury Molecule-1, Neutrophil Gelatinase-Associated Lipocalin, Histologic study, Hypoxia	Improved Renal Function in RIRI, Mice. ↓ BUN and Cr in RIRI with PHD2 siRNA G5-FA group ↓Ttubular dilation, ↓loss of brush border, ↓vacuolar degeneration,	G5-FA is a vector to deliver siRNA for local gene knock-down in kidney. ↓Majority of PHD2 expression in the kidney by G5-FA–mediated siRNA delivery due to selective targeting to the proximal tubules (↓ PHD2 mRNA and protein) ↑mRNA Expression of HIF-1(Target Gene GLUT1) by silencing of PHD2 in Kidney ↓NGAL, KIM-1, and IL-1b levels

								↓tubular necrosis, ↓cast formation in RIRI with PHD2 siRNA G5-FA group	in RIRI 1 PHD2 siRNA G5-FA group
2022	Hou et al. [15]	Left renal pedicle clamping for 28 min immediately following surgical removal of the right kidney	28 min Invitro	LSKL/NP	In vivo: 0.12 g/kg /bw In vitro:	In vivo: 3h after RIRI In vitro: 72 h	In vivo: renal lesion scoring, histology, IL-6 concentration, Cr	In vivo: ↓serum Cr, ↓Renal histologic lesions ↓Renal pathological scores	↓TSP-1production in the kidneys by LSKL/NPs (probably TSP-1 protein adsorbed on LSKL/NPs were rapidly taken up, and it failed to induce tubular epithelial cell death. TSP-1 adsorbed on LSKL/NPs and neutralized was incapable of signaling through CD47. ↓ TSP-1proteins out of the tissue, ↓TSP-1 concentration in IR kidneys by LSKL/NP recirculation ↓Renal cell apoptosis

		Invitro: TSP-1 induced human renal tubular epithelial cell apoptosis					In vitro: Apoptosis	In vitro: ↓Apoptosis	↓ IL-6 In vitro: ↓Total apoptotic cell
2020	Liu et.al. [16]	Bilaterally renal hilum clamping	40 min	N-NP CoQ10	In vivo: 50 mg/kg	In vivo: 24 h before I/R surgery	In vivo: Cr, BUN, IL-1 β, TNF- α, IL-6, BAX, Bcl-2, Caspase-3, SOD, GSH and MDA	In vivo: Improve renal function, ↓ Cr, BUN	In vivo: ↓Oxidative damage, ↓ Renal cell apoptosis, ↓ Inflammatory response, ↓IL-1 β, TNF- α, IL-6, MDA and BAX, Caspase-3, ↑ SOD, GSH, Bcl-2 protein
		Oxygen-glucose deprivation/reperfusion	In vitro 8 h.		In vitro:5 μM	In vitro: 24 h	In vitro: Apoptosis, mtDNA damage, Protein carbonyl content	In vitro: ↓Protein carbonyl content and mtDNA damage	In vitro: ↓Oxidative damage, ↓Cell apoptosis

2022	Xu et al [17]	Both renal arteries clamping	45 min	NP-IGF-1C	In vivo: 200 µl	In vivo: 2 h before the operation and 24 h and 48 h after the operation	In vivo: serum Cr, BUN, KIM-1 and NAGL, CAT, MDA, GSH-Px, IL-6 and IL-10, Histopathological evaluation, Bax and Bcl-2	In vivo: ↑renal function, ↓serum Cr, BUN, Improved Histopathological evaluation,	In vivo: ↓ Inflammatory factors, oxidative stress, apoptosis and biomarkers of renal injury, ↓KIM-1 and NAGL, MDA, IL-6 and IL-10, ↑Antioxidant enzyme levels, ↑ CAT, GSH-Px, ↓Bax and ↑Bcl-2
		Oxygen-glucose deprivation/reperfusion	8 h		In vitro: …	In vitro: 24 h	In vitro: oxidative damage	In vitro: ↑Cell viability	In vitro: ↑Live-dead %
2016	Xu et al [18]	Cell cultured under ischemia and hypoxia	24 h	Cur-NP (81.93 ± 0.5 nm)	50 µM	24 h	Cell viability, caspase-3 and Bax, Bcl-2, increased SOD, apoptotic rate, reactive oxygen species level, and MDA	Improved cell viability	Downregulated protein expression levels of caspase-3 and Bax, upregulated expression of Bcl-2 protein, ↑ Antioxidant enzyme (↑SOD level), ↓ Apoptotic rate, ↓Reactive oxygen species level, and MDA

2017	Xie et al [19]	Right nephrectomy and left renal artery occlusion	In vivo 45 min	BBR-NP	4mg/kg	Six and 24 hours before RIRI	BUN and Cr, neutrophil infiltrations and tubular necrosis, MDA, cytoplasm Cyt-C, mitochondria Cyt-C, Caspase-3 and MMP,	↓BUN and Cr levels and neutrophil infiltrations and tubular necrosis	↓ Oxidative stress and apoptosis, Caspase-3 and MMP, MDA, cytoplasm Cyt-C, ↑ mitochondria Cyt- C
2022	Saleh et al [20]	Bilateral vascular pedicles clamping	30 min	PEG-AuNP 40 µg/kg 150 µg/kg 400 µg/kg	40 µg/kg 150 µg/kg 400 µg/kg	30 min earlier to ischemia and 5 min prior to reperfusion for 3 consecutive days	BUN, Cr, MDA, GSH, GPx, SOD, AMPK, PI3K, AKT, Nrf2, HO-1, IL-1β, and TNF-α	↓BUN, Cr and Histological damage. ↓renal fibrosis ↑recovering of damaged renal cells, ↓Renal tubular atrophy, glomerular damage, mitochondrial damage, and necrotic area.	↓ Inflammatory cytokines, ↑ antioxidant system. ↓ Apoptosis ↓ MDA, TNF-α and IL-1β, upregulated the AMPK-Nrf2 pathway.

2024	Karimi et al. [21]	Bilateral renal pedicles occlusion	60 min	Chitosan nanoparticles	60 (mg/kg)	30 min before renal ischemia	Oxidative stress, TAC, histopathological examination, Cr and BUN, GFR, urine flow rate	↑TAC ↓BUN and Cr ↓urine flow rate	Attenuated oxidative stress ↑GFR Corrected the renal histopathological changes
2024	Saiz et al. [22]	In vivo Bilateral IRI (clamping both renal pedicles)	In vivo 45 or 30 min (depending on the experimental set)	In vivo JQ1- NPs 10, 20, 30, and 40 mg/kg In vitro JQ1- NPs 10,50,	In vivo 40 mg/kg	In vivo 1 h after surgery	In vivo BUN and Cr, Lcn2 and NGAL gene, KIM-1 Immune cells (neutrophils and monocytes) infiltration, Expression of proinflammatory cytokines genes In vitro	In vivo ↓BUN and Cr ↓neutrophils and monocytes In vitro ↓IL6 and CCL2	In vivo: ↓Lcn2 and NGAL gene, ↓KIM-1 ↓Immune cells infiltration ↓Expression of proinflammatory cytokines genes In vitro: ↓ Pro-inflammatory genes

				250 and 500 nm	In vitro 500 nm	In vitro 1, 3, 6, 18, and 24 h	IL6 and CCL2		
		In vitro -	In vitro -						
2024	Guo et al. [23]	In vivo: Bilateral Ischemia-Reperfusion Surgery (pedicle was clamped with an artery clamp)	In vivo: 35 min	Albumin - NPs	In vivo: 10 mg/kg	In vivo: NP injection:1h After ischemia-reperfusion surgery Sampling: At 48 h postreperfusion	In vivo: BUN Cytokine Levels (IL-1β, IL-18) and LDH levels Pyroptosis effector molecule GSDMD and KIM-1 Histopathological examination	↓BUN ↓Cytokine Levels (IL-1β, IL-18) ↓LDH levels	↓Pyroptosis effector molecule GSDMD ↓KIM-1 Corrected the renal histopathological changes
		In vitro: Hypoxia-Reoxygenation Model	In vitro: 12 h.		In vitro:	In vitro:	In vitro:		

					long-lasting NP (BSA@ DSF NPs) (1 μM)	2h	Oxidative Stress GSDMD IL-1β and IL-18	In vitro: ↓IL-1β, IL-18	In vitro: ↓Pyroptosis cells ↓ GSDMD ↓Oxidative Stress

Nanoparticles (NPs), 46 nm (NP46), 81 nm (NP81), and 118 nm (NP118), Intravenous injection (i.v), Malondialdehyde (MDA), Total superoxide dismutase (T-SOD), Superoxide dismutase (SOD), Catalase (CAT) , Proliferation marker (ki67), Glutathione peroxidase (GSH-Px), kidney injury molecule-1 (KIM-1), Neutrophil gelatinase-associated lipocalin (NAGL), Blood Urea Nitrogen (BUN), Creatinine(Cr), Thrombospondin-1 (TSP-1), Inhibitor of TSP-1 (LSKL), Blood urea nitrogen (BUN), Creatinine (Cr), Apoptosis Regulator (BAX), glutathione(GSH), interleukin-1-beta (IL-1β), Tumor necrosis factor alpha (TNF-α), interleukin-6(IL-6), Nitric oxide (NO), Nuclear factor κ B (NF-κB), Hypoxia-inducible factor 1(HIF-1α), nuclear factor erythroid 2–related factor 2(Nrf2), Heme oxygenase 1(HO-1), hypoxia-inducible factor 1(HIF-1α), Mitochondrial DNA (mtDNA), Total antioxidative capacity (TAC), Neutrophil membrane-enveloped Coenzyme Q (N-NP CoQ10), Bovine serum albumin (BSA), Disulfiram (DSF). Folic acid (FA)-decorated polyamidoamine dendrimer generation 5 (G5-FA), Ischemia reperfusion injury (IRI), Lactate Dehydrogenase (LDH), Gasdermin D (GSDMD), Matrix metalloproteinase (MMP).

DISCUSSION

Renal ischemia-reperfusion injury (RIRI) has increasingly been recognized as a major complication in various clinical scenarios. Despite its clinical relevance, therapeutic options to prevent or manage this condition remain inadequate. Recent comprehensive analyses have pointed to the promise of nanoparticle (NP)-mediated drug delivery systems, which provide numerous advantages such as targeted delivery, controlled drug release, chemical stability, and reduced toxicity [24, 25]. This review analyzed a range of nanoparticles including Zinc oxide NPs (ZnO-NPs), Ceria-NPs, Mitochondria-targeted TPP CoQ10 NPs (T-NPCoQ10), Inhibitor of Thrombospondin (LSKL)/NP, Neutrophil membrane-enveloped Coenzyme Q (N-NP CoQ10), Insulin-like growth factor-1C NPs (NP-IGF-1C), Curcumin (Cur)-NPs, Berberine (BBR)-NPs, Polyethylene glycol capped gold NPs (PEG-AuNPs), Albumin-NPs, Chitosan-NPs, liposomes loaded with JQ1 (JQ1-NPs), and folic acid (FA)-decorated polyamidoamine dendrimer generation 5 (G5-FA) NPs carrying Prolyl Hydroxylase Domain Protein 2 (PHD2) Small interfering RNA (siRNA) that have been studied in the context of RIRI.

Due to their unique physicochemical characteristics, nanomaterials exhibit enhanced biological interactions compared to their bulk counterparts. Properties like high surface area-to-volume ratios (e.g., in ZnO-NPs) [26, 27], good solubility, and sustained drug release (as observed in Cur-NPs) make them ideal for biomedical applications. Certain nanoparticles, such as Ceria-NPs, also exhibit enzyme-mimicking behavior, and their efficacy in immune modulation can be influenced by particle size highlighting the need to fine-tune NP dimensions for optimal therapeutic outcomes [11, 28]. Nanoparticles serve as effective carriers for delivering otherwise unstable therapeutic agents such as small molecule drugs and peptides, which are often rapidly degraded or cleared from the system. By encapsulating these agents, NPs enhance their bioavailability, reduce systemic toxicity, and improve drug targeting [29] demonstrated in formulations like G5-FA/PHD2 siRNA, LSKL/NPs, and NPCoQ10 [13-15].

Another factor that changes in renal ischemia is plasma urea and creatinine levels. Furthermore, RIRI often leads to elevated plasma creatinine and urea levels. Studies show that treatment with LSKL/NPs, BBR-NPs, ZnO-NPs, Albumin-NPs, JQ1-NPs, and Chitosan-NPs can significantly reduce these markers, indicating potential for renal protection [1, 12, 15, 19, 21, 22].

RIRI contributes significantly to illness and death by impacting several biological mechanisms, including oxidative stress, antioxidant defenses, inflammation, fibrosis, immune regulation, apoptosis, and gene expression.

Ischemia-reperfusion (I/R) events lead to a marked rise in malondialdehyde (MDA), an indicator of lipid peroxidation, while significantly lowering the activities of antioxidant defenses like Total antioxidative capacity (TAC), Glutathione peroxidase (GPx), Catalase (CAT), and Superoxide dismutase (SOD) in kidney tissues, compared to healthy controls and sham groups [12]. Research has shown that treatments with various nanoparticles such as ZnO-NPs, CNPs, T-NPCoQ10, BBR-NPs, PEG-AuNPs, NP-IGF-1C, Albumin-NPs, and Chitosan-NPs [1, 11-13, 17, 20, 21, 23] enhance antioxidant defenses by boosting nuclear factor erythroid 2–related factor 2 (Nrf2) and Heme oxygenase 1(HO-1) levels, scavenging reactive oxygen species (ROS), and reducing MDA levels, thus offering renal protection from RIRI. Specifically, BBR-NPs inhibit the Matrix metalloproteinase-9 (MMP-9) pathway, helping to counter oxidative and mitochondrial stress [19]. Moreover, pretreatment with these nanoparticles helps mitigate oxidative stress and enhance renal protection by promoting Nrf2 activation and improving antioxidant enzyme activity.

RIRI triggers a heightened expression of inflammatory markers such as Tumor necrosis factor alpha (TNF-α), Nuclear factor κ B (NF-κB), interleukin-1-beta (IL-1β), and IL-18 in renal tissues.

Various nanoparticle treatments including PEG-AuNPs, NP-IGF-1C, LSKL/NPs, T-NPCoQ10, Albumin-NPs, JQ1-NPs, and ZnO-NPs have demonstrated anti-inflammatory properties in managing RIRI [1, 12, 13, 15, 17, 22, 23]. These nanoparticles reduce inflammation by decreasing macrophage infiltration, limiting the shift of macrophages to the M1 pro-inflammatory type, and lowering the production of inflammatory cytokines and chemokines, leading to functional kidney recovery [11]. Additionally, certain NPs selectively target neutrophil-associated molecules to effectively reduce inflammation and improve kidney function during RIRI.

Several studies have reported elevated levels of apoptotic markers like caspase-3 and Bax as well as kidney injury

indicators (kidney injury molecule-1 (KIM-1) and Neutrophil gelatinase-associated lipocalin (NAGL)) in tissues affected by RIRI.

Treatments with T-NPCoQ10, BBR-NPs, NP-IGF-1C, N-NP CoQ10, Cur-NPs, and ZnO-NPs show anti-apoptotic effects by suppressing pro-apoptotic genes (Caspase-3 and Bax (apoptosis regulator)), enhancing anti-apoptotic gene Bcl-2 expression, and reducing cellular apoptosis in kidney tissues [1, 12-14, 16-18]. Moreover, JQ1-NPs and ZnO-NPs significantly lower NGAL and KIM-1 levels [12, 22]. Pretreatment with PEG-AuNPs also helps mitigate severe tissue damage, including necrosis and apoptosis, by activating phosphorylated AMP-activated protein kinase (AMPK), which plays a key role in preventing mitochondrial dysfunction and limiting excessive mitochondrial ROS production after RIRI [20].

The use of nanoparticles in the treatment of RIRI requires a thorough safety assessment. There are concerns about the potential toxicity, metabolism, and long-term effects of nanoparticles in the kidney. Nanoparticle toxicity can result from oxidative stress, inflammation, and cellular damage, which are influenced by their type, size, and structure. How these nanoparticles are metabolized and cleared from the body, particularly by the kidneys, is critical to preventing accumulation and chronic renal toxicity. The long-term outcomes of RIRI treatment with nanoparticles are not yet fully understood, and further research is needed to ensure their long-term safety and efficacy.

Conclusion

This systematic review investigated the role of nanoparticles (NPs) in relation to RIRI. The reviewed studies consistently showed that RIRI is associated with increased inflammatory cytokines, heightened oxidative stress, elevated levels of serum creatinine and urea nitrogen, and suppressed antioxidant defense mechanisms. Various types of nanoparticles have been demonstrated to influence these pathological pathways, highlighting their potential therapeutic impact. These findings are crucial for informing policymakers about the benefits of integrating nanoparticle-based interventions in managing RIRI.

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Author Contribution

Planning and conducting the study, methodology, investigation, supervision, writing– review & editing were performed by MKh and MM. Writing – review & editing were performed by AA and MRK. All authors read and approved the final manuscript.

Ethical approval

This study was a systematic review and did not use laboratory animals or human data in a laboratory manner and has an ethical code (Ethics ID: IR. MEDILAM.REC.1402./240) from Ilam University of Medical Sciences.

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Informed consent

Not applicable.

Competing interest

The authors declare no conflict of interests in this study.

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