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Original Research

Environmental cadmium exposure and experimental cardiovascular toxicity: protective role of erythropoietin with public health implications

Environmental cadmium ⟳ heart damage: epo shields

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Abstract

Aim: Cadmium (Cd) is an environmental heavy metal that accumulates in cardiac tissue and contributes to cardiovascular disease. Erythropoietin (EPO), traditionally recognized for its role in erythropoiesis, also exhibits potent cytoprotective properties. This study examined whether EPO can mitigate Cd-induced cardiac injury and explored the underlying molecular mechanisms.

Methods: Adult male rats were assigned to four groups: control, EPO alone, cadmium chloride alone, and EPO plus cadmium. Cardiac injury was evaluated through serum biomarkers, oxidative stress indices, inflammatory mediators, and markers of ferroptosis and apoptosis. Key signaling pathways were assessed using ELISA and quantitative gene expression analysis.

Results: Cadmium exposure significantly increased cardiac injury markers, elevated reactive oxygen species and lipid peroxidation, and depleted endogenous antioxidant defenses. It also activated NF-κB–mediated inflammation and induced both ferroptotic and apoptotic cell death. These alterations were accompanied by marked suppression of the PI3K/AKT survival pathway. EPO co-treatment substantially reduced oxidative damage, reduced inflammatory cytokine levels, restored antioxidant enzyme activities, and inhibited cell death pathways. Importantly, EPO was associated with improved PI3K/AKT signaling, which was associated with enhanced Nrf2-mediated antioxidant responses and reduced NF-κB-driven inflammation.

Conclusion: Erythropoietin effectively attenuates cadmium-induced cardiotoxicity by restoring survival signaling, strengthening antioxidant defenses, suppressing inflammation, and limiting multiple forms of cell death.

Keywords

cadmium, erythropoietin, cardiomyocyte, oxidative injury, ferroptosis

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Introduction

Cadmium (Cd) is a highly toxic environmental and industrial pollutant that poses a growing global health concern. Human exposure has increased substantially due to expanding industrialization and lifestyle-related sources. Cigarette smoke, occupational environments, contaminated food, and polluted water are major contributors to Cd intake. At the same time, additional contamination arises from activities such as mining, oil extraction, plastics manufacturing, battery production, welding, and soldering.[1] The persistence of Cd in soil, water, and air underscores its significance as a long-term public health hazard.

Among the organs affected by Cd, the heart is particularly vulnerable. Cd disrupts cardiovascular homeostasis by interfering with cytochrome P450 enzymes, disturbing redox balance, and accumulating within cardiac tissue, leading to oxidative stress, DNA damage, and transcriptional dysregulation.[2] The resulting oxidative imbalance activates inflammatory signaling pathways and stimulates the release of pro-inflammatory cytokines.[3] Cd also disrupts sulfhydryl homeostasis, suppresses antioxidant capacity, and promotes apoptotic cell death, collectively contributing to progressive cardiac injury.[4] Because oxidative stress and inflammation are central drivers of Cd-induced cardiotoxicity, antioxidant-based interventions have gained increasing attention as potential strategies to mitigate metal-induced organ damage.

Erythropoietin (EPO), a hematopoietic cytokine whose receptors are expressed in several non-hematopoietic tissues, including cardiomyocytes, has emerged as a potent cytoprotective molecule.[5] Experimental studies demonstrate that EPO confers cardioprotection independent of its erythropoietic function by reducing inflammatory mediators, attenuating apoptosis, and limiting oxidative damage in models of cardiac stress.[6] Despite extensive research, the full mechanistic spectrum of EPO's protective actions remains incompletely defined, reflecting its multifaceted biological activity. In the context of environmental Cd exposure and its cardiovascular consequences, the present study was designed to evaluate the cardioprotective effects of EPO and elucidate the underlying mechanisms.

Materials and Methods

Animals

Forty adult male Wistar rats weighing 210–330 g were used in this study. The animals were housed under controlled laboratory conditions, including a 12-hour light/12-hour dark cycle (lights on from 08:00 to 20:00) and an ambient temperature of 22 ± 2 °C. All rats had free access to standard chow and water throughout the experimental period.

Experimental Layout

After the acclimation period, the animals were randomly assigned to four experimental groups, each consisting of ten rats:

- Group I (Control): Received 0.5% carboxymethyl cellulose (CMC; Sigma, USA) orally for seven consecutive days.
- Group II (EPO): Administered erythropoietin (EPO) at 6000 IU/kg/day via intraperitoneal (i.p.) injection for seven days. The selected dose and route followed the hepatoprotective protocol described by Saddam et al. [7]
- Group III (Cd): Given oral 0.5% CMC for 7 days and injected intraperitoneally with cadmium chloride ($CdCl_2$; Sigma, USA) at 1.2 mg/kg on day seven.
- Group IV (EPO + Cd): Treated with EPO at 6000 IU/kg/day i.p. for six days, followed by a single i.p. injection of $CdCl_2$ (1.2 mg/kg) on day seven.

The Cd dose and administration method were selected according to previously published studies investigating cadmium-induced toxicity.[8]

At the end of the experimental period, blood samples were collected under ketamine anesthesia. Serum was separated by centrifugation and used to determine the activities of AST, CK-MB, and LDH. Following blood collection, the rats were euthanized, and the hearts were excised, rinsed, and dissected to isolate the left ventricle. Ventricular tissue was homogenized in 10% (w/v) Tris HCl buffer and centrifuged; the resulting supernatant was stored for biochemical analyses. Additional tissue samples were fixed in 10% formalin for histological evaluation or stored at –80 °C for molecular studies.

Biochemical Assay

SOD activity was measured using a standard colorimetric assay based on the enzyme's ability to inhibit the reduction of nitroblue tetrazolium. GSH levels were quantified using a conventional spectrophotometric method involving the formation of a yellow chromophore with Ellman's reagent. Lipid peroxidation was assessed by determining MDA concentrations using the TBARS method. ROS generation was evaluated fluorometrically by measuring the oxidation of a non-fluorescent probe to its fluorescent product.

Histopathological Examination

Heart tissues fixed in 10% neutral buffered formalin were thoroughly washed, dehydrated through a graded ethanol series, cleared in xylene, and embedded in paraffin wax. The paraffin blocks were sectioned, and the resulting tissue slices were stained with H&E to be examined under a light microscope.

ELISA Measurements

The ELISA kits used in this study and their corresponding detection ranges were as follows: CK-MB (MBS2515061, 31.25–2000 pg/mL), AST (MBS264975, 3.12–200 U/L), LDH (MBS2018912, 1.56-100 ng/mL), Nrf2 (RK13241, 78.13–5000 pg/mL), (HO-1; ab279414, 15.63–1000 pg/mL), (NF-κB; ER1186, 0.156–10 ng/mL), TNF-α (MBS282960, 6.25 pg/mL - 400 pg/mL), IL-6 (MBS269892, 15.6–1000 pg/mL), (IL-1β; MBS2023030, 15.6–1000 pg/mL), SLC7A11 (ABIN6959628, 1.56–100 ng/mL), (GPX4; MBS934198, 7.8–500 pg/mL), caspase-3 (MBS261814, 1.56–100 ng/mL), Bax (ER0512, 0.313–20 ng/mL), and Bcl 2 (ERBCL2L2, 0.41–100 ng/mL).

qRT-PCR Analysis

Quantitative real-time PCR (qRT-PCR) was performed to evaluate gene expression levels in cardiac tissue. Approximately 100 ng of ventricular tissue was homogenized in QIAzol reagent for total RNA extraction, and cDNA was synthesized using a MultiScribe reverse transcriptase kit. qRT-PCR amplification was carried out on a 7500 Real-Time PCR System using SYBR Green PCR Master Mix. Relative gene expression was calculated using the $2^{-\Delta\Delta CT}$ method, with β-actin serving as the internal reference gene. Expression differences were determined based on relative CT values. The primer sequences used were as follows. PI3K forward 5′ AACACAGAAGACCAATACTC 3′ and reverse 5′ TTCGCCATCTACCACTAC 3′; Akt forward 5′ GTGGCAAGATGTGTATGAG3′andreverse5′CTGGCTGAGTAGGAGAAC 3′; and β-actin forward 5′ CCTGGAGAAGAGCTATGAGC 3′ and reverse 5′ ACAGGATTCCATACCCAGG 3′.

Ethical Approval

This study was approved by the Ethics Committee of Umm Al-Qura University, Makkah, Saudi Arabia (Date: 03.01.2026; Decision No.: HAPO-02-K-012-2026-05-3436).

Statistical Analysis

Data were expressed as mean ± SD and analyzed using GraphPad Prism software (version 8.0). Differences among groups were assessed using one-way ANOVA, followed by the Newman–Keuls post hoc test for multiple comparisons. A P value < .05 was considered statistically significant.

Reporting Guidelines

This study was reported in accordance with the ARRIVE 2.0 guidelines.

Results

EPO Improves Cardiac Morphology and Normalizes Serum Cardiac Enzymes

Figure 1A–H presents the histological examination of cardiac tissues. Healthy cardiomyocytes were observed in the control group, while the cadmium (Cd) group showed marked vascular congestion and cardiac muscle vacuolations. These abnormalities were ameliorated in the combined treatment group (EPO + Cd).

Consistent with the histological preservation observed in the EPO-treated group, biochemical markers of myocardial injury showed substantial improvement. Cadmium exposure caused a dramatic rise in circulating CK-MB, increasing from 55.1 ± 23.2 in control rats to 395.6 ± 124.7 pg/mL (P < .05). Similarly, AST levels escalated from 48.7 ± 4.6 to 172.8 ± 6.9 U/L (P < .05), while LDH surged from 3.14 ± 0.73 to 81.7 ± 7.4 ng/mL (P < .05). These elevations confirm substantial cardiomyocyte membrane damage following Cd administration.

Co-treatment with EPO (6000 IU/kg) markedly reduced these enzyme elevations. CK-MB declined to 117.0 ± 38.7 (P < .05 vs. Cd), AST decreased to 98.0 ± 17.4 (P < .05), and LDH fell to 37.4 ± 6.2 (P < .05). Although values did not fully return to baseline, the substantial reductions indicate a cardioprotective effect (Figure 1 I-K).

These biochemical improvements parallel the structural preservation observed histologically, reinforcing that EPO effectively limits Cd-induced myocardial injury by stabilizing cardiomyocyte membranes and reducing leakage of intracellular enzymes.

EPO Attenuates Cd-Induced Cardiac Oxidative Disturbances

Cadmium exposure (1.2 mg/kg, i.p.) produced a pronounced oxidative burden in cardiac tissue, as reflected by a marked rise in MDA (8.06 ± 0.92 vs. 1.04 ± 0.23 μmol/mg protein in controls, P < .05) and elevated ROS (3.47 ± 0.29 vs. 0.48 ± 0.07, P < .05). This oxidative escalation coincided with a sharp collapse in antioxidant defenses, where SOD declined to 1.54 ± 0.22 from 14.66 ± 0.94 U/mg (P < .05), and CAT dropped to 7.52 ± 0.87 compared with 22.71 ± 1.01 U/mg (P < .05).

These biochemical disruptions were paralleled by suppression of the Nrf2/HO-1 axis, with Nrf2 reduced to 82.9 ± 3.5 vs. 229.4 ± 25.1 pg/mg (P < .05). HO-1 fell to 248.9 ± 68.1 vs. 897.1 ± 33.4 pg/mg (P < .05), confirming a profound impairment of endogenous

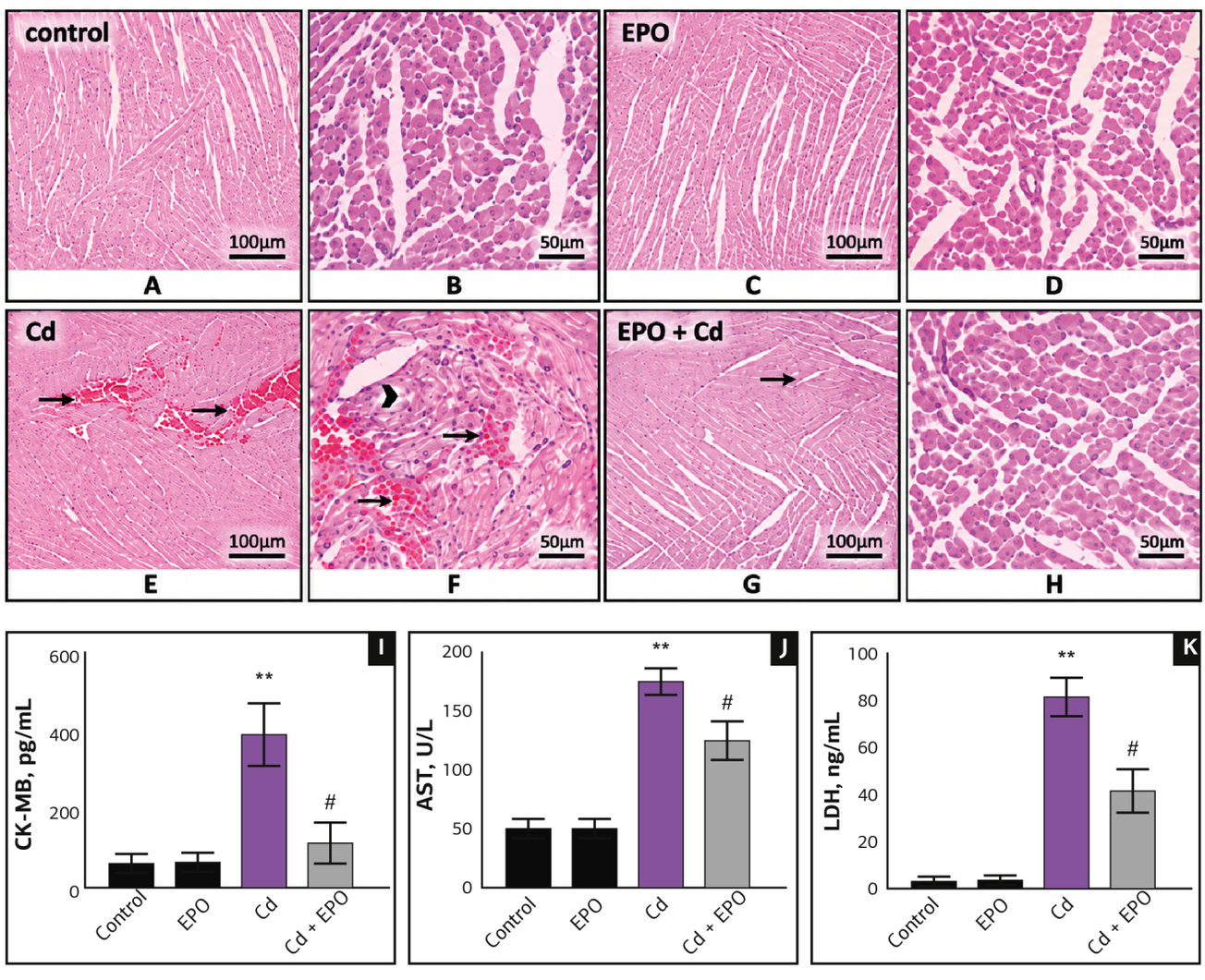

Figure 1. *Effects of Erythropoietin Treatment on Cadmium-Induced Cardiac Histopathological Damage and Serum Cardiac Injury Biomarkers*

cytoprotective signaling.

Co-administration of EPO (6000 IU/kg) substantially counteracted these Cd-driven alterations. EPO lowered MDA to 4.66 ± 0.96 ($P < .001$ vs. Cd) and reduced ROS to 1.47 ± 0.54 ($P < .05$), indicating a clear decline in lipid peroxidation and free radical accumulation. Antioxidant enzymes exhibited notable recovery, with SOD rising to 5.64 ± 0.93 and CAT increasing to 16.82 ± 1.55 (both $P < .05$ vs. Cd).

Importantly, EPO reactivated Nrf2 signaling, elevating Nrf2 to 147.7 ± 13.0 and HO-1 to 524.8 ± 72.4 (both $P < .05$ vs. Cd), demonstrating restoration of the transcriptional antioxidant machinery (Figure 1A-F). These findings demonstrate that EPO mitigates Cd-evoked oxidative injury by curbing ROS generation, stabilizing enzymatic defenses, and re-engaging the Nrf2/HO 1 cytoprotective pathway.

Anti-Inflammatory Impact of EPO on Cd-Induced Cardiac Inflammation

Cadmium administration triggered a substantial inflammatory response in cardiac tissue, as evidenced by significant elevations in NF-κB, TNF-α, IL-1β, and IL-6 compared with control animals (all $P < .05$). NF-κB increased sharply from 1.78 ± 0.27 in controls to 8.53 ± 0.71 in the Cd group, while TNF-α surged from 10.12 ± 2.33 to 235.0 ± 12.5 pg/mg. Similarly, IL-1β rose from 20.7 ± 3.5 to 143.6 ± 8.4 pg/mg, and IL-6 escalated from 196.5 ± 38.1 to 688.0 ± 92.4 pg/mg, confirming a robust pro-inflammatory shift.

Co-treatment with EPO (6000 IU/kg) markedly tempered this inflammatory activation. NF-κB levels declined to 4.93 ± 1.06 ($P < .05$ vs. Cd), while TNF-α dropped to 66.2 ± 18.3 ($P < .05$). IL-1β was reduced to 76.6 ± 14.1, and IL-6 decreased to 361.4 ± 43.7 (both $P < .05$ vs. Cd). These reductions indicate a strong inhibitory effect of EPO on Cd-driven cytokine release and transcriptional inflammatory signaling (Supplementary Figure 2G-J).

The attenuation of inflammatory mediators aligns with the previously described antioxidant restoration, suggesting that EPO not only limits oxidative stress but also re-establishes immune homeostasis, thereby contributing to the preservation of cardiac tissue structure and function.

EPO Suppresses Cd-Induced Ferroptotic and Apoptotic Activation

Cadmium exposure markedly disrupted ferroptosis-regulating proteins, as evidenced by a profound decline in SLC7A11 (3.1 ± 0.74 vs. 36.9 ± 3.7 in controls, $P < .001$) and GPX4 (9.7 ± 2.6 vs. 115.2 ± 10.1, $P < .05$. This suppression of cystine transport and lipid peroxide detoxification indicates a strong ferroptotic drive in Cd-treated myocardium.

Simultaneously, Cd provoked a robust apoptotic response. Bax increased sharply to 12.7 ± 1.2 compared with 0.80 ± 0.07 in controls ($P < .05$), while caspase-3 rose to 72.4 ± 14.3 from 10.6 ± 1.5 ($P < .05$). In contrast, the anti-apoptotic mediator Bcl-2 decreased dramatically to 0.57 ± 0.23, compared with 3.87 ± 0.83 in control rats ($P < .05$).

Co-administration of EPO (6000 IU/kg) substantially countered these molecular disturbances. EPO restored SLC7A11 to 20.6 ± 2.1 ($P < .05$ vs. Cd) and elevated GPX4 to 71.0 ± 12.1 ($P < .05$), indicating a strong reversal of ferroptotic signaling. Apoptotic markers were also markedly reduced: Bax decreased to 3.78 ± 0.55, and caspase-3 declined to 37.7 ± 5.1 (both $P < .05$ vs. Cd). Meanwhile, Bcl-2 increased to 2.19 ± 0.38 ($P < .05$), demonstrating reactivation of anti-apoptotic defenses (Supplementary Figure 3A-E).

EPO Restores PI3K/AKT Signaling Suppressed by Cd Exposure

Cadmium markedly inhibited the PI3K/AKT survival pathway, as reflected by a sharp reduction in PI3K expression from 1.00 ± 0.00 in control rats to 0.22 ± 0.02 ($P < .05$). A similar pattern was observed for AKT, which declined from 1.00 ± 0.00 to 0.12 ± 0.03 ($P < .05$). This coordinated suppression indicates a strong inhibitory effect of Cd on upstream prosurvival signaling.

Co-administration of EPO (6000 IU/kg) significantly counteracted this inhibition. PI3K levels increased to 0.55 ± 0.04 ($P < .05$ vs. Cd), while AKT rose to 0.63 ± 0.11 ($P < .05$ vs. Cd), demonstrating partial but meaningful reactivation of the pathway (Supplementary Figure 3F, G).

Reinstatement of PI3K/AKT signaling by EPO aligns with the previously described improvements in oxidative, inflammatory, and apoptotic markers. Since PI3K/AKT is known to enhance Nrf2 activation and suppress NF-κB, its restoration provides a mechanistic explanation for the broad cytoprotective effects observed in EPO-treated Cd-exposed myocardium.

Discussion

Cadmium (Cd) remains a pervasive environmental contaminant due to its extensive use in industrial processes and incorporation into numerous consumer products. As a result, human exposure is common, particularly through cigarette smoke, contaminated food sources, and inhalation of polluted air in proximity to industrial facilities or hazardous waste sites.[9] Epidemiological investigations consistently demonstrate that elevated Cd burden is associated with increased mortality from cardiovascular disorders.[10] Experimental and clinical evidence further confirms that Cd accumulates within cardiac tissue, contributing directly to structural and functional myocardial injury in both humans and animal models.[11,12]

In this study, the cardioprotective potential of erythropoietin (EPO) against Cd-induced myocardial injury in rats was evaluated. Co-treatment with EPO preserved normal cardiac architecture and mitigated Cd-triggered pathological alterations. This protection was primarily attributed to activation of the Nrf2 signaling pathway, which enhanced antioxidant enzyme expression and reduced oxidative stress markers, including ROS and MDA. EPO administration also attenuated inflammatory signaling by suppressing NF-κB activation and downstream cytokine production. Furthermore, EPO maintained cardiomyocyte integrity by limiting both ferroptotic and apoptotic cell death pathways.

Evidence from the present study aligns with the observations of Alruhaimi et al.,[13] demonstrating that cadmium exposure produces clear biochemical and morphological signs of cardiac injury.

Previous investigations have shown that cadmium (Cd) toxicity is largely driven by its ability to trigger extensive peroxidation of membrane polyunsaturated fatty acids, generating free radical species and amplifying ROS formation, ultimately weakening endogenous antioxidant defenses.[14] These observations are consistent with our findings, where a single Cd dose markedly suppressed Nrf2 and (HO-1), reduced (SOD) and (CAT) activities, and simultaneously increased ROS and (MDA) levels. In contrast, co-treatment with EPO preserved cardiac architecture and improved cardiac enzyme profiles. This aligns with the cardioprotective effects reported by Rezaee et al.[15] in carbon monoxide–induced cardiac injury, and with Diab et al.,[16] who demonstrated EPO mediated modulation of CK-MB in myocardial infarction. Our results also parallel those of Liu et al.,[17] who showed that EPO enhances Nrf2 signaling in a model of cirrhotic cardiomyopathy.

Erythropoietin exerts potent antioxidant effects that extend beyond its classical hematopoietic role. Mechanistically, EPO activates the EPOR–JAK2 signaling axis, which subsequently stimulates downstream pathways such as PI3K/AKT and MAPK. Activation of PI3K/AKT is particularly important for redox regulation, as it promotes the nuclear translocation and transcriptional activity of Nrf2. Once activated, Nrf2 binds to antioxidant response elements (AREs) and enhances the expression of cytoprotective enzymes, including HO-1, SOD, CAT, and glutathione-related enzymes.

Reactive oxygen species (ROS) are known to activate several intracellular signaling cascades, including the TLR4/NF κB pathway, which drives the transcription of pro-inflammatory mediators. This activation not only enhances cytokine production but also perpetuates oxidative stress and contributes to cell death.[18] Our findings align with this mechanism, as Cd-exposed animals exhibited a pronounced inflammatory response characterized by elevated cardiac levels of NF-κB, IL-6, IL-1β, and TNF-α compared with normal controls. These results are consistent with the observations of Alruhaimi et al., [13] who demonstrated that cadmium activates the TLR4/NFκB axis and upregulates inflammatory markers such as TNF-α, IL-6, and COX-2. In contrast, animals receiving EPO alongside Cd showed a marked reduction in these inflammatory mediators, supporting the findings of Qin et al.,[19] who reported that EPO mitigates sepsis-related myocardial injury through suppression of NF-κB signaling. Erythropoietin exerts strong anti-inflammatory actions that complement its antioxidant properties.

Ferroptosis is defined by excessive iron accumulation and lipid peroxidation, processes that ultimately compromise membrane integrity and promote regulated cell death.[20] Our findings demonstrate that Cd markedly suppresses the expression of GPX4 and SLC7A11, consistent with observations by Xiong et al.,[21] who reported Cd-induced inhibition of these key ferroptosis regulators. Cd exposure also enhanced apoptotic signaling in cardiac tissue, corroborating the results of Refaie et al.,[22] who identified a strong pro-apoptotic influence of Cd in experimental cardiotoxicity. Importantly, co-administration of EPO effectively reversed both ferroptotic and apoptotic alterations in cardiomyocytes. This protective action aligns with the findings of Kang et al.,[23] who demonstrated that EPO suppresses neuronal ferroptosis in spinal cord injury, and with Rezaee et al.,[15] who reported the anti-apoptotic effects of EPO in carbon monoxide-induced cardiac injury. Erythropoietin protects cardiomyocytes from ferroptosis and apoptosis through convergent antioxidant and survival pathways. By activating EPOR–JAK2–PI3K/AKT signaling, EPO restores GPX4 and SLC7A11 expression, enhances glutathione availability, and limits Fe^{2+} driven lipid peroxidation, thereby suppressing ferroptotic cell death. Simultaneously, EPO promotes anti-apoptotic signaling by stabilizing mitochondrial membranes, increasing Bcl-2, reducing Bax, and preventing caspase activation.

The present findings demonstrate that cadmium exposure markedly suppresses the PI3K/AKT survival pathway, as reflected by the significant reduction in both PI3K and AKT expression, consistent with earlier observations by Liu et al. [24] this inhibition is particularly detrimental because PI3K/AKT signaling is a central regulator of cell survival, redox homeostasis, and inflammatory responses. The substantial restoration of PI3K and AKT levels following EPO co-administration indicates that EPO's cardioprotective actions are mediated, at least in part, through reactivation of this pro-survival axis. Notably, the reinstatement of PI3K/AKT signaling by EPO, as also reported by Tóthová,[25] provides a mechanistic explanation for the observed improvements in oxidative stress, inflammation, and cell death. Given that PI3K/AKT serves as an upstream activator of Nrf2 and a suppressor of NF-κB, its restoration clarifies how EPO simultaneously enhances antioxidant defenses while attenuating inflammatory mediators.

Limitations

Limitations include: single acute cadmium dose (not chronic human exposure), high short-term EPO dose (6000 IU/kg), no pathway inhibitor validation, lack of functional cardiac measures, and male-only subjects. Future work requires chronic models, functional testing, mechanistic probes, and both sexes.

Conclusion

In summary, environmental cadmium induces experimental cardiotoxicity via oxidative stress, inflammation, and ferroptosis/apoptosis. Erythropoietin confers cardioprotection by modulating PI3K/AKT/Nrf2 signaling and suppressing the NF-κB pathway, supporting further investigation of its potential protective role in cadmium-related cardiovascular injury.

Declarations

Animal and Human Rights Statement

All procedures performed in this animal study were conducted in accordance with the ethical standards of the institutional animal research committee and applicable national guidelines for the care and use of laboratory animals.

Informed Consent

Not applicable.

Data Availability

The datasets used and/or analyzed in the current study are not publicly available but can be obtained from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

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None.

Author Contributions (CRediT Taxonomy)

Conceptualization: A.A.
Methodology: A.A.
Investigation: A.A.
Data Curation: A.A.
Formal Analysis: A.A.
Writing – Original Draft: A.A.
Writing – Review & Editing: A.A.
Supervision: A.A.

AI Usage Disclosure

The authors declare that no AI-assisted technologies were used.

Abbreviations

AKT: Protein kinase b
ANOVA: Analysis of variance
AST: Aspartate aminotransferase
CAT: Catalase
Cd: Cadmium
$CdCl_2$: Cadmium chloride
CK-MB: Creatine kinase mb
CMC: Carboxymethyl cellulose
ELISA: Enzyme-linked immunosorbent assay
EPO: Erythropoietin
GPX4: Glutathione peroxidase 4
GSH: Reduced glutathione
H&E: Hematoxylin and eosin
HO-1: Heme oxygenase-1
IL: Interleukin
i.p.: Intraperitoneal

LDH: Lactate dehydrogenase
MDA: Malondialdehyde
NF-κB: Nuclear factor kappa b
Nrf2: Nuclear factor erythroid 2-related factor 2
PI3K: Phosphoinositide 3-kinase
qRT-PCR: Quantitative real-time polymerase chain reaction
ROS: Reactive oxygen species
SLC7A11: Solute carrier family 7 member 11
SOD: Superoxide dismutase
TBARS: Thiobarbituric acid reactive substances
TNF-α: Tumor necrosis factor alpha

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