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SELECTIVE DESORPTION OF HEAVY METAL IONS FROM POLYMER-HYBRID NANOADSORBENTS: ELUENT SPECIFICITY AND MECHANISM

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Abstract: This article examines the selective desorption behavior of heavy metal ions (Zn^{2+}, Cd^{2+}, Hg^{2+}, Pb^{2+}, Cu^{2+}, and Au) from polymer-hybrid nanoadsorbents, focusing on the relationship between eluent chemistry and desorption mechanism. Regeneration of nanoadsorbents is a critical determinant of their industrial and economic viability, yet no single eluent achieves uniformly high selectivity across different metal species. The study analyzes three principal desorption mechanisms — proton (ion) exchange by mineral acids (HCl, HNO_3, H_2SO_4, H_3PO_4), complexation by chelating agents (EDTA, thiourea), and alkaline hydrolysis/deprotonation (NaOH) — and evaluates how each mechanism governs ion-specific release from functionalized polymer-hybrid surfaces. Comparative data show that acidic eluents such as HCl and HNO_3 achieve high desorption efficiency for certain divalent cations but can compromise nanocomposite structural integrity over repeated cycles, whereas chelating agents provide milder, more selective ion recovery with better preservation of adsorbent reusability. The influence of eluent concentration, metal-ion affinity, and competing ionic species on desorption selectivity is also discussed. The findings underscore that eluent specificity — rather than desorption strength alone — is the key parameter for designing regeneration protocols that combine high selectivity, structural durability, and industrial applicability of polymer-hybrid nanoadsorbents.

Keywords: selective desorption, eluent specificity, heavy metal ions, polymer-hybrid nanoadsorbent, chelating agent, regeneration mechanism.

INTRODUCTION: The industrial application of polymer-hybrid nanoadsorbents for heavy metal remediation depends not only on their initial adsorption capacity but, critically, on their ability to undergo efficient and reproducible regeneration. The central step of this process — desorption — governs whether a sorbent can be reused economically over multiple treatment cycles rather than being discarded as hazardous waste after a single application. While desorption efficiency has been widely studied, a narrower and arguably more consequential question has received comparatively less systematic attention: eluent specificity, i.e., why a given elution reagent releases one metal ion efficiently while leaving another only partially recovered from the same adsorbent surface. Heavy metal ions differ substantially in their coordination chemistry, ionic radius, charge density, and affinity for the functional groups (–COOH, $–NH_2$, –SH, –OH) typically grafted onto polymer-hybrid nanoadsorbents. As a result, the same functional site that binds one metal through a strong, kinetically stable complex may bind another through a weaker, more labile interaction. This difference in binding strength directly determines which eluent — and under what mechanism — can most effectively reverse the adsorption process. Experimental comparisons of multiple eluents applied to the same nanocomposite have shown that no single reagent performs optimally across all

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target ions: for example, in a thiol-lignocellulose–bentonite nanocomposite, hydrochloric acid achieved the highest desorption for zinc and cadmium, while mercury required a different eluent to reach comparable recovery. Such findings demonstrate that eluent selection cannot be generalized across metal species and must instead be guided by an understanding of ion-specific binding mechanisms. Three broad mechanistic pathways dominate the desorption of heavy metals from polymer-hybrid nanoadsorbents. Proton (ion) exchange, driven by mineral acids such as HCl, HNO_3, H_2SO_4, and H_3PO_4, displaces bound cations through competitive protonation of surface functional groups. Complexation (chelation), mediated by agents such as EDTA or thiourea, forms soluble, thermodynamically stable metal complexes that are selectively extracted from the adsorbent surface, often at lower reagent concentrations and under milder conditions than acid-based systems. Alkaline hydrolysis and deprotonation, typically achieved with NaOH, alters the surface charge state of the adsorbent and can promote the release of specific metal-hydroxide species. Each mechanism interacts differently with a given metal ion's coordination chemistry, meaning that the choice of mechanism — not merely reagent strength — determines both the efficiency and the selectivity of the desorption process.Selectivity in desorption carries direct practical consequences beyond simple regeneration efficiency. In multi-metal industrial effluents, a non-selective eluent recovers a mixture of metals that is difficult and costly to separate for resource recovery or safe disposal, whereas a selective eluent can sequentially strip target metals, enabling metal-specific recovery — an increasingly important goal in circular-economy-oriented wastewater treatment. Moreover, aggressive, non-selective acidic conditions capable of stripping multiple ions simultaneously often accelerate structural degradation of the polymer matrix, reducing the adsorbent's reusability over successive cycles. This creates a practical tension between achieving broad, high-efficiency desorption and preserving the selective, structurally gentle conditions needed for long-term nanoadsorbent performance. Despite this practical importance, the mechanistic basis of eluent specificity — how binding chemistry, functional group identity, and eluent structure jointly determine selective ion release — remains fragmented across individual case studies rather than synthesized into a coherent framework.

MATERIALS AND EXPERIMENTAL METHODS: This study was conducted as a systematic comparative analysis of experimental data reported in peer-reviewed literature on the desorption and regeneration of polymer-hybrid nanoadsorbents loaded with heavy metal ions. The methodology combines (a) structured literature retrieval, (b) mechanistic classification of eluents, and (c) quantitative cross-study comparison of desorption efficiency, selectivity, and structural stability outcomes. Relevant publications were identified through systematic searches of scientific databases, including ScienceDirect, Springer Nature, ACS Publications, PMC/PubMed Central, and Nature Scientific Reports, using combinations of the following keywords: "eluent," "desorption," "heavy metal," "nanoadsorbent," "polymer-hybrid nanocomposite," "regeneration," "EDTA," "chelating agent," "selective recovery." Studies published within approximately the last ten years were prioritized to ensure methodological and technological relevance, though foundational mechanistic studies were also included where necessary.Studies reporting quantitative desorption efficiency (%) for at least one heavy metal ion from a polymer-based or polymer-hybrid nanoadsorbent; Studies specifying eluent type, concentration, and experimental conditions (contact time, temperature, adsorbent dosage); Studies reporting multi-cycle regeneration data (≥2 adsorption–desorption cycles), where available.

Exclusion criteria: Studies lacking quantitative desorption data or eluent specification; Studies focused exclusively on non-metal target pollutants (e.g., dyes, pharmaceuticals) without comparative metal-desorption data; Non-peer-reviewed sources (theses, unreviewed preprints), except where used for general contextual background only.Extracted data were classified according to three principal desorption mechanisms, consistent with established mechanistic categories in the sorption–desorption

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literature: Mechanism category, Representative eluents, Mechanistic basis,Proton (ion) exchange,HCl, HNO_3, H_2SO_4, H_3PO_4 . Competitive protonation of surface functional groups, displacing bound metal cations.

CONCLUSION: In summary, achieving selective desorption in polymer-hybrid nanoadsorbents requires moving beyond the conventional focus on maximizing single-pass desorption efficiency toward a more nuanced, mechanism-informed selection of eluents that balances selectivity, structural preservation, and economic-environmental sustainability. Future research should prioritize systematic, single-protocol comparative studies across standardized adsorbent systems, as well as the development of predictive models linking metal-ion coordination chemistry to optimal eluent choice — enabling the rational design of selective, multi-cycle regeneration strategies for industrial-scale heavy metal remediation.

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