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Review article

Regenerative Performance and Stability of Metal-Organic Frameworks following Heavy Metal Adsorption from Aqueous Solutions: A Mini Review

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Abstract

Metal-organic frameworks (MOFs) have attracted considerable research attention as a promising class of emerging adsorbents. MOFs possess exceptionally high surface areas, tunable pore structures and chemically tailored environments, making them well-suited for heavy metal selectivity. In this context, this review examines the regenerative performance and structural stability of pristine, functionalised, composite and MOF-derived materials following heavy metal adsorption. Across the reviewed studies, MOF-based systems generally exhibited favourable regenerative performance, particularly composite and selected functionalised systems, with losses in adsorption capacity typically below 10-15% after several cycles. These observations suggest that with appropriate MOF design, performance requirements for practical water treatment are attainable. Performance and stability depended mainly on the regeneration strategy and the type of MOF employed, particularly the framework composition, the metal node and the linker chemistry. Various regeneration techniques have been successfully reported, including chemical elution with acid or alkaline solutions, chelation-assisted desorption, electrochemically-assisted regeneration, photoregeneration and hybrid chemical-thermal strategies. Combined regeneration approaches showed strong potential to improve desorption efficiency while preserving structural integrity. MOF composites such as polymer-supported MOF beads, magnetic core-shell composites and MOF-oxide hybrid demonstrated enhanced recovery, stability and separation efficiency. Functionalisation with amines, thiols, sulfonates, and chelating agents improved selectivity in many systems. However, depending on the target metal, functionalisation can either facilitate or hinder regeneration due to strong coordination interactions. Despite these advances, most studies remain limited to batch-scale laboratory experiments with low regeneration cycles. Future work should prioritise increased regeneration cycles, leaching studies, stability evaluations, and continuous-flow systems to facilitate the practical implementation of MOF-based technology in water treatment.

Keywords: adsorption; desorption; heavy metal; metal-organic framework; regeneration

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1. Introduction

Owing to their persistence, bioaccumulation potential, and high toxicity in biological systems, heavy metals have been widely associated with acute and chronic health effects (Jomova et al., 2025; Pathak et al., 2026). Advances in nano-scale analytical detection have enabled the identification of trace metals at concentrations previously undetectable. This has led to the introduction of stricter environmental regulations. Unfortunately, attaining these new limits can become a financial burden to small- and medium-sized industries (Sutherland et al., 2017). Metallic contaminants such as Hg(II), Pb(II), Cd(II), Cu(II), and Cr(VI) have been reported to pose a threat to human and aquatic species (Shang et al., 2019; Cheng et al., 2025; Kochmar & Karabyn, 2025). Exposure has been linked to adverse effects, including neurological impairment, renal dysfunction, and carcinogenic outcomes, while simultaneously disrupting aquatic ecosystems (Sutherland et al., 2019; Ohiagu et al., 2022). Unlike organic contaminants, heavy metals do not undergo microbial degradation; thus, physical and chemical treatment technologies are usually required (Wuana & Okieimen, 2011).

Environmental contamination arising from industrial and mining residues can also lead to the mobilisation of dissolved salts and associated heavy metals into surrounding hydrological systems (Karabyn et al., 2026). Given that ecological safety is largely determined by the efficiency of treatment technologies (Kuzyk et al., 2023), the limitations of conventional strategies highlight the need for more effective treatment alternatives. Conventional treatment technologies such as chemical precipitation, membrane filtration, and ion exchange are widely used for heavy metal remediation (Shofia et al., 2025). However, these technologies possess inherent disadvantages such as secondary sludge generation, high operational costs, limited selectivity, and poor treatment levels (Azmi et al., 2025; Liu et al., 2026). As a consequence, adsorption has emerged as a promising technology due to its simplicity, economy, and ability to achieve low effluent treatment levels (Sutherland et al., 2023). It is noteworthy that the sustainability of adsorption systems is strongly dependent on the ability of adsorbents to be regenerated and reused without significant structural degradation (Gkika & Kyzas, 2026). If an adsorbent cannot be effectively regenerated, its value diminishes, and large-scale implementation can lead to secondary environmental burdens associated with the disposal of spent adsorbents.

Metal-organic frameworks (MOFs) have attracted considerable research attention as next-generation adsorbents due to their tunable pore architecture, exceptionally high surface areas, and chemically tailored environments (Arif et al., 2026). These characteristics can facilitate strong and selective interactions with contaminants (Huang et al., 2021). Additionally, the structure of MOFs consists of metal nodes connected by organic linkers to form a network that is crystalline and porous in nature (Sutherland, 2025b). The modular nature of MOFs allows their structure to be tailored through ligand engineering and metal node selection, thus enabling the selective adsorption of heavy metal ions (Ma et al., 2023). Concerns regarding the hydrolytic stability and structural integrity of MOFs in aqueous solutions have directed research efforts towards the development of not only more robust pristine MOFs (such as high-valency metal nodes and stronger metal-oxygen bonds) but also MOF composites and MOF-derived materials (Yuan et al., 2018a; Huang et al., 2020).

MOF composites encompass a diverse range of hybrid systems that are designed to enhance MOF performance while retaining the original MOF structure (Rahman et al., 2026). Examples of these hybrid systems include MOF-magnetic assemblies, MOF-polymer matrices, MOF-carbon composites and MOF@MOF core-shell architectures

(Mourdikoudis et al., 2025). Such structural configurations can contribute to improved mechanical strength, reduced framework degradation and improved stability in aqueous solution (Nayak et al., 2025). In contrast, MOF-derived materials such as pyrolysed porous carbons, metal oxides and metal phosphates are produced through chemical or thermal transformation of the parent MOF framework (Ren et al., 2020). Since the MOF no longer relies on metal-ligand coordination bonds to maintain structural integrity, it can exhibit superior chemical and hydrolytic stability, particularly under harsh acidic conditions (Chai et al., 2025). Ligand engineering is another MOF-modification strategy that can improve performance and selectivity. These modifications are classified as pre-synthetic (in which functionalised linkers are directly incorporated during framework assembly) or post-synthetic (in which the framework is chemically modified after synthesis) (Khan et al., 2023). A major limitation in the practical implementation of MOF systems arises from their conventional preparation as fine crystalline powders (Xie et al., 2024). Despite their high surface area, the fine MOF particles present a challenge for large-scale implementation, which includes difficulties in handling, particle aggregation and adsorbent separation (Chakraborty et al., 2024). To overcome these limitations, approaches such as granulation, bead and microsphere formation, as well as fabrication of MOF monoliths and gels, have been increasingly reported (Sutherland, 2025b).

Strategies for regenerating adsorbents are generally classified into two broad categories. These categories include thermal processes (employing steam, inert gas or microwave radiation) and non-thermal methods (such as ultrasound treatment, solvent extraction and complexation reactions) (Omorogie et al., 2016). Several studies have reported that regeneration processes can compromise framework integrity (Gupta et al., 2021; Moaty et al., 2025). For instance, highly acidic or alkaline eluents can induce protonation of linkers, cleavage of metal-ligand bonds or the leaching of metal nodes, all of which can contribute to the degradation of the coordination framework (Yuan et al., 2018). Similarly, thermal regeneration treatments may induce partial structural collapse and loss of crystallinity in certain MOFs (Blanco-Brieva, 2013). Consequently, evaluation of regeneration behaviour is essential for determining the true long-term applicability of MOFs in water treatment systems (Sutherland, 2025a).

Non-thermal solvent-based regeneration strategies are the most commonly reported methods for MOFs. This may be largely due to the sensitivity of metal-ligand coordination frameworks to elevated temperatures. Gardea-Torresdey et al. (2004) described an eluent, or stripping agent, as a chemical mediator capable of recovering sorbed contaminants from an adsorbent. Thus, the selection of an appropriate eluent should ensure maximum recovery with minimal eluent volume, minimise physical damage to the sorbent, exhibit low toxicity, and preserve the adsorbent uptake capacity (Sutherland & Venkobachar, 2020). Acidic eluents (e.g., HCl, HNO_3) typically promote desorption through protonation of surface functional groups and competitive coordination with the sorbed metal ion (Khan & Shahbaz, 2026). Whereas alkali treatments (e.g., NaOH) often facilitate desorption through ion-exchange (Manousi et al., 2019). Chelating agents (e.g., EDTA, thiourea) promote desorption through selective complexation of sorbed metal ions, thereby reducing the need for aggressive protonation and potentially limiting chemical attack on the MOF framework (Ji et al., 2022). Thus, the judicious selection of eluent type is critical for achieving efficient regeneration while maintaining the long-term functionality of the MOF adsorbent.

This review examines the adsorption of heavy metals from aqueous solutions using MOFs, with particular emphasis on regenerative performance and sorbent stability. The development of MOFs represents an emerging field of study (Petit, 2018). Thus, the literature considered spans just over a decade of research, reflecting the period of rapid

advancement in MOF technologies development. Relevant literature published between 2015 and 2026 was retrieved from major scientific databases, including Google Scholar, Scopus, PubMed, Web of Science, and ScienceDirect. The search was conducted using combinations of keywords such as adsorption, heavy metal, metal-organic framework, stability, and regeneration. Only English-language original research articles reporting experimental studies on heavy metal adsorption by MOFs were included. Duplicate records were removed during screening, and review articles were excluded except where used for general background. Also, studies limited to only MOF synthesis or purely theoretical analyses without experimental validation were excluded.

From both an operational and economic perspective, MOF regeneration influences life-cycle costs, material replacement frequency, and overall process sustainability (Satyam & Patra, 2024). Although numerous studies report on the regeneration of conventional adsorbents following heavy metal sorption, MOFs, as an emerging class of adsorbents, have gathered very little attention. Further, work on MOFs for heavy metals focuses mainly on uptake capacity rather than regeneration efficiency. Accordingly, to support the development of this emerging adsorbent, the present study reviews the regeneration performance of MOFs following the adsorption of the most frequently reported heavy metals, which include Hg(II), Pb(II), Cd(II), Cu(II) and Cr(VI). Particular emphasis is placed on the regeneration strategies, key performance metrics and the structural stability of the MOFs following repeated adsorption-desorption cycles. Ultimately, the work aims to guide future research towards the rational design of robust, reusable, and economically viable MOF-based adsorbents for heavy metals remediation in water treatment applications.

2. Regenerative Performance and Stability

Tables 1-5 summarise representative studies that evaluated the adsorption of heavy metals by MOFs. These tables provide a comparative overview of the key parameters influencing desorption behaviour and include MOF type, initial absorbate concentration, first-cycle adsorption capacity, regeneration strategy, loss of adsorption capacity/loss of desorption efficiency, and recyclability. The compiled studies illustrated a diverse range of MOF frameworks and desorption strategies. Regeneration was mainly achieved through chemical extraction. A variety of eluents were employed, which included mineral acids, alkaline solutions, phosphate-based solutions and chelating agents. Most significantly, many MOF systems demonstrated favourable regeneration performance, whereby high adsorption capacity and structural stability were maintained after multiple cycles. Notable regeneration strategies, performances and structural stability are highlighted and examined in greater detail in the following section.

2.1 Regeneration following Hg(II) adsorption

An overview of studies evaluating the regeneration behaviour of various MOFs following Hg(II) adsorption is presented in Table 1. Ji et al. (2022) highlighted that using strong acids to regenerate MOFs can lead to structural degradation via protonation and disruption of metal-ligand bonds. To avoid this effect, the authors employed a chelating agent (0.1% thiourea) in combination with an acid (0.1 M HCl) (Figure 1) for the regeneration of a post-synthetically functionalised MOF, TMU-40. A very good regeneration performance was reported. After attaining an initial adsorption capacity of 720.0 mg/g, the adsorbent showed only a 1.4% reduction in capacity after the first adsorption-desorption cycle and a 1.1%

reduction after the 6th cycle. Incorporating the chelating agent led to complexation of the sorbed metal ion, while allowing the use of a lower acid concentration, a shorter contact time and reduced proton attack on the framework. Following elution, X-ray diffraction (XRD) revealed the retention of the characteristic diffraction peaks of the original sorbent, confirming the preservation of the crystalline structure.

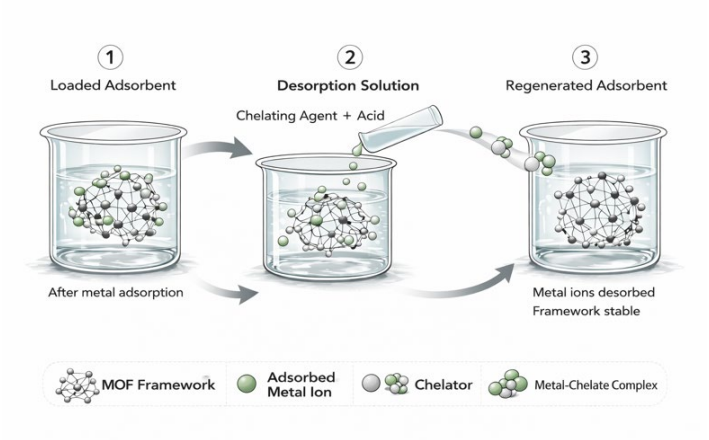

Figure 1. Schematic illustration of chelation-assisted chemical desorption of metal-loaded MOF

The majority of reviewed studies investigating heavy metal removal by MOF-based adsorbents have been confined to batch laboratory scale, with limited assessment of continuous-flow systems. However, a notable study by Boix et al. (2020) reported on packed-bed column systems using a MOF composite microbead (CeO_2@UiO-66-$(SH)_2$). The adsorbent was regenerated following Hg(II) adsorption using a 0.25 M $H_2PO_4^-$ solution. The MOF evinced excellent short-term stability with only a 5% reduction in adsorption capacity after 10 adsorption-desorption cycles. The minimal loss in capacity highlighted the structural robustness of the composite and indicated its strong potential for practical water treatment applications. In contrast, Huang et al. (2015) developed a magnetic core-shell MOF composite (Bi-I-functionalised Fe_3O_4@SiO_2@HKUST-1) to enhance adsorption while enabling easy separation. To evaluate regeneration performance, several eluents were investigated, which included mineral acids (HNO_3, HCl), alkali solution (NaOH), thiourea solution, and mixtures of acid and thiourea. However, desorption efficiencies remained minimal across all tested eluents. Due to its poor regeneration capability, the adsorbent was deemed suitable only for single-use applications. This poor desorption behaviour was attributed to the strong coordination interaction between Hg(II) and the thiol (-SH) groups. This is consistent with the soft-soft acid-base affinity that stabilises Hg-S bonding. An overview of Table 1 indicates that composite MOFs generally exhibit superior long-term stability compared to pristine and functionalised frameworks. In contrast, post-synthetically functionalised MOFs demonstrated moderate regeneration performance, typically maintaining stable performance for up to 6 cycles. Functional groups such as EDTA and thiols enhanced Hg(II) binding; however, these strong interactions can make desorption more difficult. Given the limited number of studies, these trends should be regarded as indicative rather than definitive.

Table 1. Metal-organic framework regeneration following Hg(II) ion adsorption

Adsorbent	Adsorbent abbreviation	MOF Type	Adsorbate	Eluent	Initial concentration (mg/L)	First-cycle adsorption capacity (mg/g)	Loss in adsorption efficiency/*Loss in desorption efficiency after 1st cycle	Adsorption - desorption cycles	Loss in adsorption efficiency/*Loss in desorption efficiency	Reference
2D layer-based supramolecular MOF	TMU-40	Post-synthetically functionalised MOF	Hg(II)	0.5 M HNO_3	50.0	-	2.0%	3	5.0%	(Rouhani & Morsali, 2018)
EDTA modified UiO-66	UiO-66-EDTA	Post-synthetically functionalised UiO-66 framework via EDTA grafting	Hg(II)	0.1 M HNO_3	80.0	151.0	2.6%	6	9.3%	(Wu et al., 2019)
iNP@MOF composite microbeads	CeO_2@UiO-66-$(SH)_2$	MOF composite	Hg(II)	0.25 M $H_2PO_4^-$	0.1	-	-	10	5.0%	(Boix et al., 2020)
Zn(II)-Imidazole Framework	Zn-MOF	Pristine MOF	Hg(II)	10% thiourea	10.0	-	*2.2%	6	*8.0%	(Huang et al., 2020)
Integrated amine and sulfonic acid ligands MOF	NH_2-MIP-SO_3H	Pre-synthetically functionalised	Hg(II)	0.5 M NaOH	100.0	186.0	0.0%	10	15.5%	(Bi et al., 2024)
Magnetic MOF-808	Zr-MOF@Fe_3O_4	MOF composite (magnetic MOF composite)	Hg(II)	0.1 M NaOH	50.0	49.0	1.0%	5	3.0%	(Paz et al., 2022)
Thiol-functionalized MOF-808	MOF-808-SH	Post-synthetically functionalised MOF	Hg(II)	0.1 % thiourea + 0.01 M HCl	10.0	720.0	1.4%	6	1.1%	(Ji et al., 2022)
Bi-I-functionalized Fe_3O_4@SiO_2@HKUST-1	Bi-I-functionalized Fe_3O_4@SiO_2@HKUST-1	MOF composite (magnetic core–shell composite with post-synthetic functionalisation)	Hg(II)	HCl, HNO_3, NaOH and thiourea	20.0	-	-	-	-	(Huang et al., 2015)

Note: - Indicates information not reported in the original study; * desorption efficiency loss reported instead of adsorption capacity loss.

2.2 Regeneration following Pb(II) adsorption

Representative studies investigating the regeneration performance of different MOFs after Pb(II) adsorption are compiled in Table 2. Bi et al. (2024) presented a significant study highlighting the outstanding desorption performance of a pre-synthetically functionalised MOF following Pb(II) adsorption. The authors used 0.5 M NaOH as the eluent (Figure 2). The adsorbent (NH_2-MIP-SO_3H) exhibited good reusability, achieving only 0.5% reduction in adsorption capacity after the first and 8% after the 8th adsorption-desorption cycle. After 10 adsorption-desorption cycles, the adsorption capacity declined to 15.7% from an initial capacity of 184.0 mg/g. The observed loss in capacity was attributed to possible pore blockage and/or incomplete desorption of the Pb(II) species. Similar observations were reported by Wu et al. (2019) for an EDTA-grafted UiO-66 framework prepared via post-synthetic functionalisation. Using 0.1 M HNO_3 as the stripping solution, the authors achieved 6 cycles with the adsorbent suffering only 10.6% reduction in adsorption capacity (first-cycle adsorption capacity of 141.0 mg/g). The authors attributed the reduction in capacity to the incomplete removal of metal ions bound to active sites on UiO-66-EDTA. These results suggest that both acidic and alkaline eluents can support repeated adsorption-desorption cycles, depending on the chemical stability and functionalisation of the MOF framework.

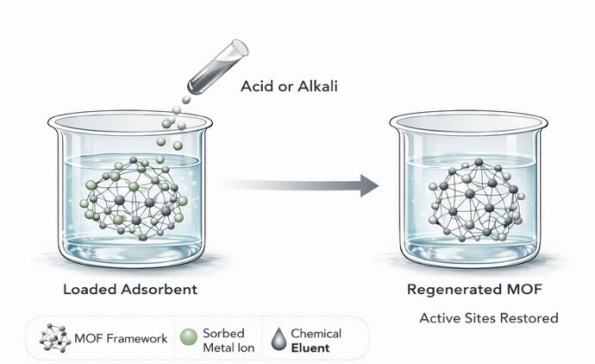

Figure 2. Schematic illustration of chemical elution of metal-loaded MOF using acidic or alkaline eluents

The structural stability of a pristine MOF (Tb-MOFs) was investigated by Zhu et al. (2019) following successive Pb(II) adsorption-desorption cycles. The study returned a moderate result, following an initial adsorption capacity of 330.0 mg/g, a 5.5% reduction after 1 cycle, and a 16% reduction in sorption capacity after 5 cycles of EDTA washes was recorded. XRD analysis confirmed that the crystalline structure was well preserved after each cycle. Transmission electron microscopy (TEM) images further demonstrated that the morphology remained intact after 5 cycles. Moreover, there was a release of terbium (Tb) into the elution solution of 2.6% in the first cycle, but it decreased to 1.9% by the 5^{th} cycle. The authors opined that this reduction in metal leaching suggests that during repeated use, structural collapse did not occur. Analysis of Table 2 reveals that MOF regeneration behaviour for Pb(II) varies with framework architecture and functionalisation strategy. Post-synthetically functionalised frameworks revealed sustained moderate recyclability of approximately 4-6 cycles. Further, both alkaline and acidic eluents can be effective in desorption when the framework is sufficiently robust.

Table 2. Metal-organic framework regeneration following Pb(II) ion adsorption

Adsorbent	Adsorbent abbreviation	MOF Type	Adsorbate	Eluent	Initial concentration (mg/L)	First-cycle adsorption capacity (mg/g)	Loss in adsorption efficiency/*Loss in desorption efficiency after 1st cycle	Adsorption-desorption cycles	Loss in adsorption efficiency/*Loss in desorption efficiency	Reference
EDTA modified UiO-66	UiO-66-EDTA	Post-synthetically functionalised UiO-66 framework via EDTA grafting	Pb(II)	0.1 M HNO_3		141.0	1.4%	6	10.6%	(Wu et al., 2019)
iNP@MOF composite microbeads	CeO_2@UiO-66-$(SH)_2$	MOF composite	Pb(II)	0.25 M $H_2PO_4^-$	0.1	-	-	3	2.0%	(Boix et al., 2020)
Zn(II)-Imidazole Framework	Zn-MOF	Pristine MOF	Pb(II)	10% thiourea	10.0	-	*0%	6	*9%	(Huang et al., 2020)
Zn-based MOF	UiO-66-EDA	Post-synthetically functionalised MOF	Pb(II)	0.1 M HCl	100.0		*3.2%	4	*12%	(Ahmadijokani et al., 2021)
Integrated amine and sulfonic acid ligands MOF	NH_2-MIP-SO_3H	Pre-synthetically functionalised MOF	Pb(II)	0.5 M NaOH	100.0	184.0	0.5%	10	15.7%	(Bi et al., 2024)
Zn(II)-based MOF decorated with O−groups	$[Zn_3L_3(BPE)_{1.5}]_n$ (1a, the activated 1)	Pristine MOF (Activated)	Pb(II)	0.1 mM HNO_3	10.0	-	0.0%	4	*6.0%	(Yu et al., 2017)
Tb-based MOF	Tb-MOFs	Pristine MOF	Pb(II)	0.2 mM EDTA	360.0	330.0	5.5%	5	16.0%	(Zhu et al., 2019)

Note: - Indicates information not reported in the original study; * desorption efficiency loss reported instead of adsorption capacity loss.

2.3 Regeneration following Cd(II) adsorption

Studies evaluating the regeneration performance of various MOFs after Cd(II) adsorption are compiled in Table 3. Wu et al. (2023) investigated the regeneration performance of a polymer-supported bead immobilised MOF composite (CPZ-SH). Desorption was carried out using 0.1 M HCl as the eluent. The adsorbent evinced a 4.4% reduction in adsorption efficiency after 1 cycle and 14.4% after 10 cycles (first-cycle capacity of 9.0 mg/g), indicating acceptable long-term stability under acidic regeneration conditions. A comparable level of regeneration was reported by Bi et al. (2024) for Cd(II) desorption from a pre-synthetically functionalised MOF. The adsorbent (MOF NH_2-MIP-SO_3H) showed an initial sorption capacity of 197.0 mg/g, followed by a 14% reduction in capacity after 10 cycles when using a 0.5 M NaOH stripping solution. Moradi et al. (2016) reported effective regeneration of a magnetic MOF composite (Fe_3O_4@MOF-235(Fe)-OSO_3H) using EDTA as a chelating desorption agent. Although the authors reported minimal loss in adsorption efficiency after 10 cycles, the exact percentage decline was not explicitly reported. Kim et al. (2021) investigated electrochemically-assisted regeneration of a pristine MOF (Cu-MOF-74) following Cd(II) adsorption. Regeneration was conducted in 20 mM NaCl by applying an oxidative potential of +0.9 V (vs. Ag/AgCl). After 4 adsorption-desorption cycles, the adsorption capacity decreased by 26.4% (first-cycle capacity of 112.4 mg/g). The structural stability was evaluated by XRD, which showed that during electrosorption, the characteristic MOF reflections were preserved at -0.1 and -0.2 V (vs. Ag/AgCl). However, applying -0.3 V exceeded the electrochemical stability window of the Cu-MOF-74, which led to partial reduction of Cu(II) nodes and the formation of Cu_2O. These findings indicated that excessively negative potentials can induce metal-node reduction and secondary phase formation. More importantly, upon applying +0.9 V (vs. Ag/AgCl) during regeneration, the Cu_2O phase was re-oxidised and removed, and the original MOF diffraction pattern was restored. This demonstrated a reversible electrochemical behaviour within a defined potential window. Overall, Table 3 shows a clear pattern: composite MOF architectures consistently demonstrate high regeneration durability. This may be due to the ability of the composite architecture to reinforce the mechanical stability of the framework, reduce structural degradation and improve the accessibility of active sorption sites.

Table 3. Metal-organic framework regeneration following Cd(II) ion adsorption

Adsorbent	Adsorbent abbreviation	MOF Type	Adsorbate	Eluent	Initial concentration (mg/L)	First-cycle adsorption capacity (mg/g)	Loss in adsorption efficiency/*Loss in desorption efficiency after 1st cycle	Adsorption-desorption cycles	Loss in adsorption efficiency/*Loss in desorption efficiency	Reference
iNP@MOF composite microbeads	CeO_2@UiO-66-$(SH)_2$	MOF composite	Cd(II)	0.25 M $H_2PO_4^-$	0.1	-	-	3	2.0%	(Boix et al., 2020)
Zn-based MOF	UiO-66-EDA	Post-synthetically functionalised MOF	Cd(II)	0.1 M HCl	100.0	-	*5.6%	4	*14.6%	(Ahmadijokani et al., 2021)
MOF-based Ca-alginate/PAA granulate beads	CPZ-SH	MOF composite (polymer-supported bead-immobilised MOF composite)	Cd(II)	0.1 M HCl	10.0	9.0	4.4%	10	14.4%	(Wu et al., 2023)
Integrated amine and sulfonic acid ligands MOF	NH_2-MIP-SO_3H	Pre-synthetically functionalised MOF	Cd(II)	0.5 M NaOH	100.0	197.0	0.0%	10	14.0%	(Bi et al., 2024)
Copper-based MOF	Cu-MOF-74	Pristine MOF (solvent-exchanged and activated)	Cd(II)	20 mM NaCl at +0.9 V	112.4	86.0	17.0%	4	26.4%	(Kim et al., 2021)
Sulfonated MOF loaded onto iron oxide nanoparticles	(Fe_3O_4@MOF-235(Fe)-OSO_3H)	MOF composite (magnetic core-shell composite with post-synthetic sulfonation)	Cd(II)	0.5 M EDTA	-	-	-	10	-	(Moradi et al., 2016)
Amino-functionalized MIL-101(Cr)	ED-MIL-101(Cr)	Pre-synthetically functionalised MOF	Cd(II)	N,N-dimethylformamide (DMF)	100.0	-	*0.9%	3	*3.3%	(Elaiwi & Sirkecioglu, 2020)
MOF/zeolite nanocomposite	Co/Ni/Cu-NH_2BDC MOF/zeolite nanocomposite	MOF composite	Cd(II)	Dimethyl sulfoxide	-	-	*0.0%	3	*0.0%	(Abdelazeem et al., 2024)

Note: - Indicates information not reported in the original study; * desorption efficiency loss reported instead of adsorption capacity loss.

2.4 Regeneration following Cu(II) adsorption

The regeneration behaviour of MOFs following Cu(II) adsorption has been examined in several studies, which are compiled in Table 4, highlighting the influence of framework structure, elution strategy and recyclability. Wu et al. (2023) developed a sulfur-functionalised MOF composite (CPZ-SH). The composite was produced by immobilising the MOF within a Ca-alginate/polyacrylic acid (PAA) granulated matrix. This strategy was aimed at improving the structural stability and sorbent separability. During Cu(II) adsorption-desorption testing, the composite exhibited excellent regeneration performance. Using a 0.1 M HCl as the eluent, the sorbent maintained its sorption capacity of 9.6 mg/g over 8 cycles, with only a 4.2% reduction after 10 cycles. These findings indicate that the MOF maintained both functional performance and structural stability under repeated acidic regeneration conditions. In contrast, Guo et al. (2021) fabricated an oxide-MOF composite (ZnO-NP@Zn-MOF-74) by integrating nano-ZnO particles with a Zn-MOF-74 framework. After 3 cycles, the desorption efficiency decreased by 18%, revealing a relatively poor regeneration performance. Most significantly, the authors reported that following adsorption, partial replacement of Zn(II) nodes by Cu(II) ions within the framework occurred. This ion-exchange process was likely due to the stronger coordination affinity of Cu(II) ions for the MOF ligand. As a result, the greater stability of the Cu-ligand coordination bond relative to the Zn-ligand likely hindered the Cu(II) desorption. This observation suggests that irreversible ion-exchange should be considered during MOF design. Potential mitigation strategies include steric shielding of metal nodes through appropriate ligand design and the use of more robust frameworks with less labile metal-linker bonds, particularly those based on high-valent metal nodes (Yuan et al., 2018b). Ahmadijokani et al. (2021) investigated the regeneration performance and stability of a post-synthetically functionalised MOF (UiO-66-EDA). Regeneration was performed using 0.1 M HCl as the eluent. A moderate performance was revealed with a 16.3% decline in desorption efficiency observed after 4 cycles. To assess the chemical stability of the MOF, the adsorbent was immersed in strong acidic (pH = 1.0) and alkaline (pH = 12) solutions for 24 h. X-ray diffraction patterns observed before and after treatment showed that the framework retained its crystallinity under acidic conditions, whereas partial collapse of the structure was observed when exposed to the basic solution. In general, MOF composites again demonstrated the highest operational durability. Functionalised frameworks exhibited moderate recyclability, typically sustaining 4-5 cycles. Copper removal systems can present a greater challenge, mainly due to the strong coordination affinity of Cu(II) for donor atoms within the framework and the potential for partial metal-node substitution. Furthermore, the high affinity of Cu(II) ions for donor atoms is corroborated by studies of biochemical processes, where biogenic hydrogen sulfide produced by sulfate- and sulfur-reducing bacteria is capable of almost completely binding copper ions (up to 1.5 mM) in the form of highly stable insoluble sulfides (Moroz et al., 2018).

Table 4. Metal-organic framework regeneration following Cu(II) ion adsorption

Adsorbent	Adsorbent abbreviation	MOF Type	Adsorbate	Eluent	Initial concentration (mg/L)	First-cycle adsorption capacity (mg/g)	Loss in adsorption efficiency/*Loss in desorption efficiency after 1st cycle	Adsorption-desorption cycles	Loss in adsorption efficiency/*Loss in desorption efficiency	Reference
MOF-based Ca-alginate/PAA granulate beads	CPZ-SH	MOF composite (polymer-supported bead-immobilized MOF composite)	Cu(II)	0.1 M HCl	10.0	9.6	1.0%	10	4.2%	(Wu et al., 2023)
Zn-based MOF	UiO-66-EDA	Post-synthetically functionalised MOF	Cu(II)	0.1 M HCl	100.0	-	*5.0%	4	*16.3%	(Ahmadijokani et al., 2021)
Integrated amine and sulfonic acid ligands MOF	NH_2-MIP-SO_3H	Pre-synthetically functionalised MOF	Cu(II)	0.5 M NaOH	100.0	191.0	0.0%	10	16.0%	(Bi et al., 2024)
Magnetic MOF composite (Fe_3O_4@Fe-BTC)	Fe_3O_4@Fe-BTC	MOF composite	Cu(II)	-	-	52.0	0.0%	3	21.2%	(Castañeda-Ramírez et al., 2022)
Schiff base-functionalized MOF	ligand@MIL-101 NPs	Post-synthetically functionalised MOF	Cu(II)	1.0 M HCl	-	-	*1.6%	5	*5.3%	(Nilash et al., 2019)
Amino-functionalized MIL-101(Cr)	ED-MIL-101(Cr)	Pre-synthetically functionalised MOF	Cu(II)	N,N-dimethylformamide (DMF)	100.0	-	*0.7%	3	*3.7%	(Elaiwi & Sirkecioglu, 2020)
ZnO-NP@Zn-MOF-74 composite	ZnO-NP@Zn-MOF-74	MOF composite (oxide-MOF composite)	Cu(II)	-	20.0	-	*0.0%	3	*18.0%	(Guo et al., 2021)

Note: - Indicates information not reported in the original study; * desorption efficiency loss reported instead of adsorption capacity loss.

2.5 Regeneration following Cr(VI) adsorption

Table 5 summarises representative studies examining the regeneration performance of MOFs following Cr(VI) adsorption. Boix et al. (2020) conducted dynamic column studies using an MOF composite. The spherical microbead adsorbent (CeO_2@UiO-66-$(SH)_2$) was subjected to washes with 0.25 M $H_2PO_4^-$ following Cr(VI) adsorption. The sorbent demonstrated good reusability, exhibiting only 2% reduction in sorption capacity after 3 cycles. Valizadeh et al. (2020) investigated the regeneration of an MOF@polymer composite bead (Zr-BDC-$(NH_2)_2$@PB), using an integrated photoregeneration and ion-exchange strategy (Figure 3). The regeneration was achieved by exposing the Cr(VI)-loaded beads to a 4 M HCl solution under visible light irradiation from a 300 W Xe lamp. The lamp was equipped with a UV cut-off filter (λ= 420nm). Under these conditions, the acidic solution promoted ion exchange, while the visible light irradiation induced photocatalytic reduction of Cr(VI) to Cr(III). During regeneration, the system was purged with N_2 in order to remove dissolved oxygen. After 5 cycles, no appreciable loss in sorption capacity was reported. X-ray Photoelectron Spectroscopy (XPS) analysis indicated that following irradiation, the Cr(VI) peaks disappeared. This confirmed the photoreduction of Cr(VI) to Cr(III).

Gao et al. (2018) developed a porous magnetic MOF ($Fe_{0.72}^{(0)}Fe_{2.28}^{(II)}C$) for the adsorption of Cr(VI) from aqueous solution. The regeneration performance was evaluated over 4 consecutive cycles. After each adsorption step, the sorbent was regenerated using 1 M NaOH. After the second cycle, an 80% decline in adsorption capacity was observed. An additional regeneration step was introduced to restore the adsorbent performance. The NaOH-treated MOF was subsequently calcined at 750°C for 4 h under vacuum. The thermal treatment successfully restored the active $Fe^{(0)}$ phase, which had partially decreased during Cr(VI) removal. Consequently, after the third cycle, the loss in adsorption capacity had recovered from 80% to 48%. After the fourth cycle, the loss in adsorption capacity was 75%. Structural analyses using Field Emission Scanning Electron Microscopy (FESEM), TEM and XRD showed no significant morphological damage, although decreased crystallinity and reduced $Fe^{(0)}$ were reported. The loss of $Fe^{(0)}$, which played a crucial role in Cr(VI) adsorption, was identified as the main cause for the decline in adsorption capacity. Overall, composite systems exhibited the most stable regeneration behaviour. Pristine MOFs demonstrated moderate recyclability, whereas MOF-derived materials experienced substantial capacity decline.

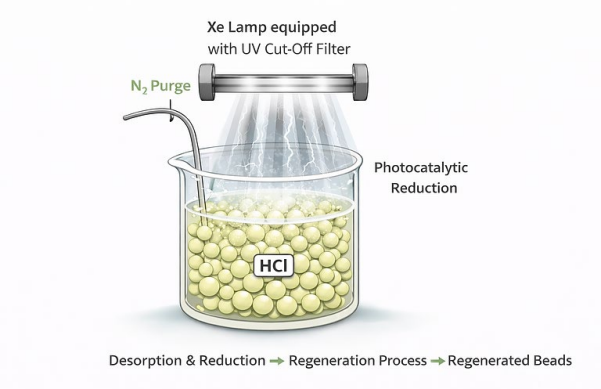

Figure 3. Schematic illustration of combined chemical elution and visible-light-assisted photocatalytic reduction of Cr(VI) to Cr(III)

Table 5. Metal-organic framework regeneration following Cr(VI) ion adsorption

Adsorbent	Adsorbent abbreviation	MOF Type	Adsorbate	Eluent	Initial concentration (mg/L)	First-cycle adsorption capacity (mg/g)	Loss in adsorption efficiency/*Loss in desorption efficiency after 1st cycle	Adsorption - desorption cycles	Loss in adsorption efficiency/*Loss in desorption efficiency	Reference
iNP@MOF composite microbeads	CeO_2@UiO-66-$(SH)_2$	MOF composite	Cr(VI)	0.25 M $H_2PO_4^-$	0.1 mg/L	-	-	3	2.0%	(Boix et al., 2020)
FIR-53	$[Zn_2(Tipa)_2(OH)]\cdot 3NO_3\cdot 12H_2O$	Pristine MOF (activated)	Cr(VI)	0.4 M HNO_3	-	-	1.0%	5	4.0%	(Fu et al., 2015)
Porous magnetic MOF	$Fe_{0.72}^{(0)}Fe_{2.28}^{(II)}C$	MOF-derived	Cr(VI)	1.0 M NaOH + calcination at 750 °C, 4 h	100.0	-	61.6%	4	80.0% (2nd cycle) after elution; 48.0% (3rd cycle) after elution + calcination; 75.0% (4th cycle)	(Gao et al., 2018)
CTAB-surface-functionalized magnetic MOF	Fe_3O_4@UiO-66@UiO-67/CTAB	Magnetic MOF composite (core-shell hierarchical MOF composite)	Cr(VI)	NaOH	50.0	-	*1.5%	5	*10.0%	(Li et al., 2020)
Porous Ni/Co-layered double hydroxide MOF	NiCo-LDH	MOF-derived	Cr(VI)	15% Ammonia	20.0	-	*14.3	5	*26.3%	(Hu et al., 2019)
MOF@Polymer Composite Beads	Zr-BDC-$(NH_2)_2$@PB	MOF composite	Cr(VI)	4 M HCl + 300 W Xe lamp visible light irradiation	5.0	-	-	5	0.0%	(Valizadeh et al., 2020)

Note: - Indicates information not reported in the original study; * desorption efficiency loss reported instead of adsorption capacity loss.

2.6 Cross-table analysis of MOF regeneration performance

A cross-analysis of Tables 1-5 indicates that composite MOF systems consistently demonstrated the highest stability, sustaining between 5-10 adsorption-desorption cycles with minimal loss in adsorption capacity. This stability is likely due to the reinforcing effect of composite matrices, which can reduce framework collapse, improve mechanical durability, and maintain accessibility of active sites during repeated cycling. Furthermore, improved separability of some composite systems can minimise material loss during regeneration. It should also be noted that the regeneration behaviour of MOFs may be influenced by the physical form of the adsorbent. While fine MOF powders generally provide short diffusion pathways, immobilisation into beads, pellets, membranes, or composite materials may introduce additional mass-transfer resistance that hinders the transport of adsorbed species during desorption (Li et al., 2011). Furthermore, incorporation of MOFs into polymeric or inorganic matrices may partially reduce pore accessibility and alter diffusion pathways within the adsorbent structure, thereby affecting regeneration performance (Choi et al., 2008; Yang et al., 2024). Although immobilisation can improve adsorbent handling, recovery, and process integration, the resulting increase in diffusional path length may reduce both adsorption and desorption efficiencies. Consequently, researchers should carefully consider the trade-off between improved separability and operational convenience on the one hand, and potential losses in mass-transfer performance and regeneration efficiency on the other. Several studies reported comparable regeneration performance for selected functionalised and pristine MOFs. For instance, pre-synthetically functionalised frameworks also achieved extended cycles; however, a gradual decline in capacity was often reported due to pore blockage and incomplete desorption. Post-synthetically functionalised MOFs generally exhibited moderate recyclability of approximately 4-6 cycles, possibly due to strong coordination interactions between the functional groups and the metal ion. Overall, these observations highlight that composite design and controlled functionalisation are key strategies for improving the long-term stability of MOF-based adsorbents for heavy metal remediation.

Grafting density, defined as the abundance of functional groups attached to a MOF, is an important but often overlooked design parameter. While increased functionalisation generally enhances the availability of metal-binding sites, excessive grafting may reduce pore accessibility, surface area, and structural integrity. For example, Ji et al. (2022) reported improved Hg(II) removal with increasing thiol loading on MOF-808 up to an optimum level, whereas Huang et al. (2015) observed that excessive Bi-I loading on HKUST-1 reduced crystallinity and porosity. These findings suggest that an optimal grafting density may exist; however, systematic investigations remain scarce. Consequently, identifying optimal functionalisation levels for specific heavy metals represents an important research gap for the rational design of reusable MOF adsorbents.

An important observation from the reviewed studies is that little attention is given to life-cycle assessment (LCA) considerations when evaluating MOF regeneration performance. The primary focus has been placed on adsorption capacity retention, regeneration efficiency, and structural stability, with little focus given to the broader environmental and economic implications of repeated adsorbent use. Although LCA has increasingly been applied to evaluate MOF sustainability, important knowledge gaps remain. Most studies employ cradle-to-gate boundaries and laboratory-scale data, limiting assessment of use-phase performance, regeneration, degradation, and end-of-life management (Singh et al., 2026). In particular, environmental impacts associated with the disposal or treatment of spent MOFs remain poorly understood (Ungureanu et al., 2026).

Consequently, the environmental and economic competitiveness of MOFs relative to conventional adsorbents such as activated carbon has yet to be fully established. Future studies should therefore combine techno-economic analysis with cradle-to-grave assessments that incorporate synthesis and regeneration costs, adsorbent lifespan, degradation mechanisms, material recovery, and end-of-life treatment pathways.

The reviewed studies employed a wide range of initial concentrations. Despite this variability, satisfactory regeneration performance was reported across both low- and high-concentration systems, suggesting that regeneration behaviour is not governed solely by initial metal concentration. Rather, the findings indicate that MOF structure, functionalisation strategy, adsorption mechanism, and regeneration conditions may play equally important roles in determining long-term reusability. Nevertheless, the available data are insufficient to establish whether an optimal concentration range exists for specific MOF systems, highlighting an area requiring further investigation.

3. Conclusions and Future Work

This review evaluated the regeneration performance and structural stability of metal-organic frameworks (MOFs) following the adsorption of Hg(II), Pb(II), Cd(II), Cu(II) and Cr(VI). Collectively, the studies reviewed indicate that MOFs have significant potential as reusable adsorbents for heavy metal remediation. In many instances, loss in adsorption capacity remained below 10-15% after repeated cycles. This indicates that under laboratory conditions, well-designed MOFs can maintain acceptable operational durability. A consistent trend that emerged from the study was that composite architectures (such as polymer-supported MOFs, magnetic core-shell and MOF-oxide hybrid systems) afforded enhanced regeneration and operational stability. Consequently, such composite strategies are expected to remain a key design area for advancing MOFs towards full-scale implementation.

An important emerging direction in MOF regeneration involves hybrid and multi-step regeneration strategies that combine multiple mechanisms to improve desorption efficiency while preserving the integrity of the frameworks. For example, chelation-assisted regeneration with mild acidic eluents, electrochemically-assisted regeneration using controlled potentials, photodegradation involving light-induced transformation of metals and hybrid chemical-thermal treatments to restore active redox phases. Together, these advanced approaches enable multiple cycles while maintaining structural stability and adsorption performance. Functionalisation strategies also remain an important area of investigation. Both pre-synthetic and post-synthetic approaches have demonstrated success in improving metal selectivity and uptake capacity. However, excessively strong coordination interactions between functional groups and target metal ions were demonstrated to hinder desorption. Thus, future research should investigate the effect of grafting density on adsorption and regeneration performance, as current evidence suggests that an optimal level of functionalisation may exist, yet this aspect remains largely unexplored in MOF-based heavy metal adsorbents.

Despite these advances, several challenges remain before MOF-based solutions can be implemented at full scale. Most studies have remained at the batch laboratory scale, with few researchers exploring column systems. In addition, long-term regeneration studies up to and exceeding 10 cycles will allow better assessment of performance and stability. Evaluation of metal-node leaching, chemical stability, framework crystallinity and structural degradation after multiple cycles is insufficiently reported. Future research should extend beyond conventional evaluations of chemical stability and framework crystallinity to

investigate metal-node leaching, post-adsorption ion exchange, and structural degradation during repeated regeneration cycles. Comparative studies of powdered and immobilised MOFs are also needed to quantify the trade-off between improved separability and potential reductions in adsorption–desorption performance arising from increased diffusional resistance. Finally, life-cycle assessments are required to determine whether these MOF-based solutions can provide cost-effective alternatives to conventional treatment technologies. With continued advancement in framework stability, regeneration strategies, and scalable synthesis methods, MOF-based adsorbents are expected to play an increasingly important role in the development of next-generation water treatment technologies.

4. Authors' Contributions

Both authors contributed equally to the conceptualisation and writing of the article.

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5. Conflicts of Interest

The authors have declared that no competing interests exist.

6. AI Declaration

During the preparation of this manuscript, the authors used Grammarly to assist with grammar and punctuation corrections. The authors also used OpenAI's ChatGPT image-generation tools solely to create conceptual schematic illustrations based on the authors' ideas and instructions. All AI-generated content was critically reviewed, edited, and verified by the authors, who assume full responsibility for the accuracy, interpretation, and presentation of the figures. No artificial intelligence tools were used in the generation, analysis, interpretation, or reporting of the scientific data presented in this review.

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