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Sustainable MOFs for Pb^{2+} Removal: Adsorption, Regeneration, and Environmental Impact

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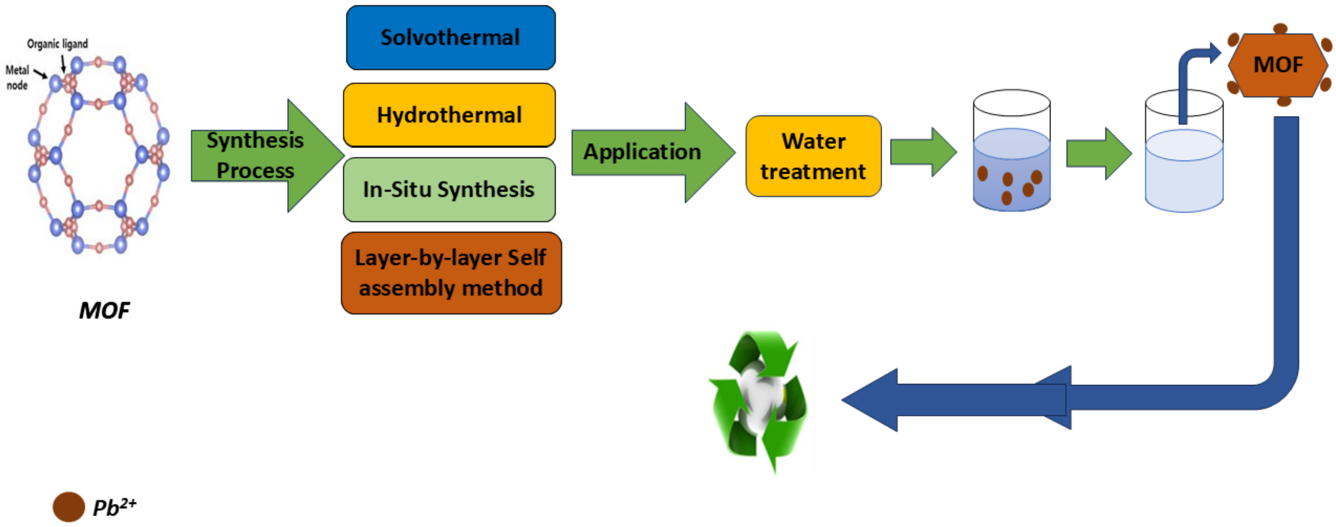
***Keywords*— Lead (Pb^{2+}) Removal, MOF Synthesis Methods, MOF-Based Adsorbents, Cost-Effectiveness, Environmental Remediation, Industrial Wastewater Treatment.**

***Abstract*—** *Heavy metal contamination, particularly with lead (Pb^{2+}), poses significant environmental and public health risks. In response to this, metal-organic frameworks (MOFs) have arisen as effective adsorbents due to their high surface areas, tunable structures, and reusability. This study reviews advancements in MOF-based adsorbents for lead removal from wastewater, with a focus on cost-effectiveness, adsorption efficiency, and environmental impact. Among various MOFs examined, ZIF-67 and ZIF-8 show superior performance, achieving high adsorption capacities (up to 1978.63 mg/g) and excellent regeneration potential, maintaining effectiveness over multiple cycles. Cost analyses reveal that while some MOFs, such as Cu-MOFs/CMFP, incur higher synthesis costs, others like UiO-66-(OPO_3)X and Cs-ZIF-8 offer a balance between cost and performance, rendering them economically viable for large-scale application. Further, the environmental sustainability of MOFs is enhanced through greener synthesis methods and biodegradable components. Although challenges remain in scaling production and ensuring durability in varied wastewater conditions, this study demonstrates the potential of MOFs as efficient, sustainable, and cost-effective adsorbents for heavy metal remediation, paving the way for safer water treatment solutions.*

GRAPHICAL ABSTRACT



HIGHLIGHTS

- MOFs like ZIF-67 and ZIF-8 have significant Pb^{2+} adsorption capabilities, reaching up to 1978.63 mg/g, making them effective for lead remediation.
- Diverse Synthesis processes: MOFs are produced using a variety of synthesis procedures, including solvothermal, hydrothermal, and microwave-assisted processes, which affect their structural characteristics and scalability.
- Relevant Characterization: Techniques such as SEM, BET, and XRD are used to assess the shape, surface area, and crystalline structure of MOFs, validating their validity for adsorption.
- Regeneration and Stability: Many MOFs have good regeneration capability, and ZIF-67 retains around 95% of its adsorption capacity after many cycles, assuring long-term usage and structural integrity.
- Cost-effectiveness and Sustainability: The economic feasibility of MOF-based adsorbents is highlighted, with competitive pricing and the utilization of nontoxic, biodegradable materials improving their environmental friendliness.

I. INTRODUCTION

Heavy metal pollution has become a worldwide environmental issue that is attracting more and more attention. The presence of heavy metal (HMIs) in wastewater produced by industries is diagnosed as the most injurious pollutants. It has been known that the chromium(VI), lead(II), Cd^{2+}, Cu^{2+}, Hg^{2+}, Fe^{3+}, Ni^{2+} and Zn^{2+} are the most familiar toxic pollutants, so an acceptable method is needed for the preconcentration and removal them [1] . [2]. Among the various heavy metals, lead (II) is one of the most popular and well-known water pollutant. Lead is a heavy metal contaminant with high biological toxicity, normally present in water as divalent lead ions. They may accumulate in the human body via the food chain and cause a variety of human ailments, including anemia, heart disease, neurological disorders, renal disease, cancer, and even death. As a result, there is an urgent need to find an effective technique for removing Pb^{2+} from aqueous solutions.

Researchers have devised several techniques to remove contaminants from wastewater, including filtration[3]., chemical precipitation [4] coagulation , [5] electrochemical treatment [6], membrane separation [7] chemical oxidation [8], photocatalysis [9], ozonation [10] and adsorption [11]. Among these methods, adsorption has received a particular attention because of its numerous advantages. Adsorption, unlike absorption, involves the accumulation of pollutants on the surface of a material. This method, mainly does not suffer from the limitations of the other methods, such as high startup and operation costs, long treatment times, process complexity, and space requirements [12] It has been widely embraced because to its great efficiency, simplicity, low energy demands, adaptability, and reusability [13].

However, some traditional adsorbents used for wastewater treatment including clays [14]., zeolites [15], ion exchange resins [16] , Carbon nanotubes [17], silica [18], and activated carbon [19], have limitations , such as : low adsorption capacity, limited reuse capability, and the generation of post-treatment sludge [20]. Metal oxide-based adsorbents are distinguished by low selectivity and delayed adsorption kinetics. At the same time, activated carbon is limited by its high procurement cost, low surface area and porosity, and the difficulty of maintaining high adsorption effectiveness during usage [21]. Resins, like activated carbon, have limited recovery and reuse possibilities.

Recent research efforts have focused on generating innovative and highly efficient adsorbents that can overcome the limits of existing adsorbents while being environmentally friendly and low-cost. MOFs are one type of very effective adsorbent. MOFs are a promising material for removing lead (Pb^{2+}) ions from wastewater due to their high adsorption capacity, reusability, and adjustable characteristics. MOFs are porous crystalline solids made up of metal ions or clusters that are coupled with organic ligands. Their distinguishing characteristics, such as large surface area, variable pore size, and various functions, make them ideal candidates for environmental remediation applications [22]. In recent years, numerous MOF-based materials have been studied for Pb^{+} adsorption, including zeolitic imidazolate frameworks.

Such as ZIF-8 and ZIF-67 [23] copper-based MOFs like Cu-BTC, zinc-based MOFs such as Zn-BTC. [24] and zirconium-based MOFs like UiO-66 and its derivatives [25]. These materials demonstrate exceptional adsorption capacities, ranging from 215 mg/g to 1978 mg/g for Pb^{2+} ions. Among the studied MOFs, ZIF-67 and ZIF-8 exhibit particularly high capacities of 1978.63 mg/g and 1780.91 mg/g, respectively, making them highly efficient for lead remediation. [23]. The superior performance of these materials can be attributed to their high surface area, abundant active sites, and favorable interactions with Pb^{2+} ions. The adsorption mechanism of Pb^{2+} onto MOF-based materials typically involves a combination of processes, including surface complexation, ion exchange, and electrostatic interactions. The presence of functional groups such as -OH, -COOH, and -NH2 on the organic ligands of MOFs plays a crucial role in enhancing their affinity towards Pb^{2+} ions. [26]. [27]. Additionally, the metal nodes in MOFs can act as Lewis acid sites, further contributing to the adsorption process. The reusability of MOF-based adsorbents is a crucial factor in their cost-effectiveness and environmental impact. Many of the studied materials show excellent regeneration capabilities, maintaining high adsorption efficiencies over multiple cycles. For instance, ZIF-67 retains approximately 95% of its adsorption capacity after five cycles, demonstrating its potential for long-term use in water treatment applications. Similarly, the SUZ-4 zeolite, another promising material, maintains its performance over ten adsorption-desorption cycles without significant decline [28]. This high regeneration efficiency not only reduces the overall cost of the treatment process but also minimizes waste generation and environmental impact.

Cost-effectiveness is another important consideration in the development of MOF-based adsorbents. The synthesis of these materials often involves readily available and relatively inexpensive precursors, contributing to their economic viability. For example, the production cost of SUZ-4 zeolite is estimated at 11,855.5 CNY per ton, which is only 23.14% of the cost for a comparable material. [28]. This competitive pricing makes MOF-based adsorbents attractive for large-scale water treatment applications, particularly in regions where lead contamination is a significant concern.

Environmental friendliness is addressed through the use of non-toxic precursors and the ability to regenerate and reuse the adsorbents. Materials such as CS-ZIF-8 composite beads, which incorporate biodegradable chitosan, [29] offer a sustainable approach to Pb^{2+} remediation. The use of bio-based or naturally occurring materials in MOF synthesis not only reduces the environmental footprint but also enhances the biocompatibility of the adsorbents. Recent research has also focused on developing MOF-based composites to further improve their performance and stability. For example, magnetic MOF composites simplify adsorption by using an external magnetic field, enhancing treatment efficiency [30]. Adsorption on MOF-based materials follows pseudo-second-order kinetics, with chemisorption as rate-limiting step. Adsorption is spontaneous and endothermic, favoring Pb^{2+} removal with increasing temperature. This review examines recent advancements in MOF-based adsorbents for Pb^{2+} removal, focusing on their cost-effectiveness, environmental friendliness, and performance characteristics.

II. MOF MATERIALS AND THEIR APPLICATION IN PB^{2+} REMOVAL

MOFs are known for their exceptional ability to adsorb heavy metals due to their unique structural properties. The metal ions within MOFs serve as **coordination centers**, facilitating the adsorption of Pb^{2+} ions through interactions such as **electrostatic attraction, ion exchange, or surface complexation**, while their porous structures facilitate high adsorption capacities.

The adsorption process in MOFs relies on the interaction between metal centers (nodes) and lead ions (Pb^{2+}), as well as the pore structure that facilitates the diffusion of ions.

Factors such as the surface area, pore size, and functionality of organic linkers significantly affect their adsorption efficiency. The structural tunability of MOFs allows for the optimization of adsorption conditions, making them highly adaptable for wastewater treatment.

Common MOFs used in lead removal include UiO-66, MIL-53 and ZIF-8. These frameworks can be synthesized through methods such as solvothermal, hydrothermal, and microwave-assisted synthesis. Scalability, a critical factor in cost-effectiveness, remains a challenge. While these methods produce high-quality MOFs, the scalability of these processes for industrial applications requires further investigation.

Table 1: Performance of some typical metal-organic frameworks (or their composites) as adsorbents for the removal of Pb^{2+} from some aqueous solutions and wastewaters.

The table provides a detailed comparison of various adsorbents used for the removal of lead ions (Pb^{2+}) from aqueous solutions and wastewaters. It includes key parameters such as the type and amount of adsorbent, synthesis methods, conditions of the Pb^{2+} solution (volume, concentration, and pH), contact time, adsorption capacity, removal efficiency, and references to relevant studies. The table highlights the diversity in adsorbent materials, ranging from metal-organic frameworks (MOFs) to zeolites, synthesized using techniques such as hydrothermal and solvothermal methods. This comparison aids in evaluating the effectiveness and reusability of different adsorbents for lead removal.

Adsorbent/ amount	**Synthesis method**	**Pb2+ solution Volume(ml)/ Concentration(ppm) pH**	**Contact time (min)**	**Adsorption capacity (mg/g)**	**Removal Efficiency (%)**	**References**
Cs-Zif-8/20 mg 1:2	In Situ Synthesis	20 / 20 /5	120	131.4	98.2(Initial) 80.2 (After 5 cycles of Reuse)	[31]
Fe_3O_4@Cu_3(btc)$_2$ / 10 mg	Hydrothermal	20/100/5	120	215.05	57.3	[31]
PHCS-15@ZIF-8/ 15 mg	Stöber method/hydrothermal	100/15/5.5	120	462.9 /310.5	95	[32]
SCC-CuMOF/ 0.6 g 1:1:1:1	Solvothermal	1000/400 /6	60	531.38	79.707	[33]
-UiO-66-(OPO_3) X)/1.5g	Classical Solvothermal	400/400/6	30	445.88	85.76	[34]
Cu-BTC and Zn-BT / 10 mg	Solvothermal	50/50/5	<30	333/312 (Cu-BTC/ Zn-BT)	98.9 96.4	[24]

PEIUiO-66-NH_2/1.2g	Solvothermal /Chemical Grafting	20/136/5	40	692.80	84	[35]
Zif-8/Zif-67 1000 mg	Solvothermal	20 /20/ 6.5	120	1978.63	99.5	[23]
ZIF-67@Yeast/ 50 mg	Hydrothermal	50 /100/	480	62.5	31	[36]
ZIF-90@CS/SA 0.2 g	hydrothermal	N/A/300/5.5	150	300	92.11	[37]
HNTs@PDA/Zif-8 /0.01 g	Solvothermal	50 / N/A /7.0	150	515.46	N/A	[38]
MTV-MOFSWCNT-BP/0.05g	N/A	200/200/6.6	4320	180	98	[39]
Cu-MOFs/CMFP/0.03 g	Layer-by-Layer Self-Assembly method	10/10 /N/A	35	31.77 N/A	90	[40]
Cu-MOF HKUST-1-EDA	N/A	50 / 400 / 5.2	20	12.85	90	[41]
Fe-MOF	N/A	100/100/7	600	504	88.34	[42]
SUZ-4 zeolite/0.06 g	hydrothermal	50 /50/ 5	30	181.56	97.04	[28]
Ni-MOF-74	N/A	50 / 60/ 6	240	98.062	95-99	(Lou et al., 2022)
NH2-MIL-53	Hydrothermal	20/10 /6.0	60	223.4	99.98	[44]

2.3 MOFs adsorbent

Characterization and Application of ZIF-8-Based Composites for Wastewater Treatment

Generally, metal-organic frameworks (MOF), are specialized in their capacity to adsorb heavy metals from wastewater, through their large surface area, high porosity, and selectivity. Additionally, their some parameters as mentioned in the adsorption mechanism by MOF, like: p^H; concentration … Basically, after the synthesis process the adsorbent made, needs to go through a characterization process, referring at: SEM, XRD, XPS BET tests to determine the porosity, surface area, and christalline structure, which confirms the ability of a MOF . [45] . Hence, in the following paragraphs are notified the various parameters and adsorption mechanism of the precited adsorbent in Table1.

ZIF-8-based composites have attracted major notice in environmental applications, particularly in wastewater treatment, due to their exceptional structural properties. Derived from Zeolitic Imidazolate Framework-8 (ZIF-8), these composites boast high surface area, thermal stability, and tunable porosity, making them highly effective for adsorbing pollutants like heavy metals, organic dyes, and other contaminants.

Characterization of ZIF-8 composites focuses on their physical and chemical properties, crucial for wastewater treatment performance. Advanced techniques like X-ray diffraction (XRD) and scanning electron microscopy (SEM) confirm crystalline structure and morphology, while Brunauer-Emmett-Teller (BET) analysis determines surface area. Thermogravimetric analysis (TGA) and Fourier-transform infrared spectroscopy (FTIR) assess thermal stability and chemical composition. Functionalization through metal doping or hybridization enhances adsorption capacity and selectivity.

In wastewater treatment, ZIF-8-based composites demonstrate outstanding efficiency in removing heavy metals, particularly lead (Pb^{2+}), and organic pollutants from contaminated water. Their high adsorption capacity, fast kinetics, and selectivity make them ideal for real-world systems. They operate effectively under varying pH conditions, retain performance across multiple cycles, and are reusable and environmentally friendly.

The excellent structural properties and versatile application potential of ZIF-8-based composites make them promising materials for addressing the growing demand for efficient and sustainable wastewater treatment solutions. Their ability to be tailored for specific environmental conditions enhances their practical utility in mitigating water pollution.

2.3.1 Zif-8/Cs-Zif-8

The CS-ZIF-8 composite beads were developed to effectively adsorb heavy metals, specifically Cu (II) and Pb (II), from wastewater. Characterization results revealed a significant increase in surface area due to the incorporation of ZIF-8, with values of 1808.4 m²/g for ZIF-8 and only 2.5 m²/g for pure chitosan. The composite beads exhibited varying surface areas depending on the ratios used: CS-ZIF-8-1:1 had 114.6 m²/g, CS-ZIF-8-2:3 had 284.9 m²/g, and CS-ZIF-8-1:2 reached 712.7 m²/g. [31]

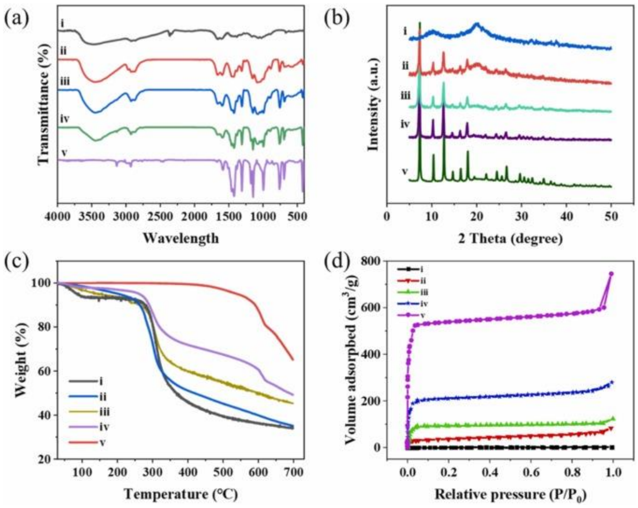


Fig. 1. (a) FT-IR spectra, (b) PXRD patterns, (c) TGA curves and (d) N2 adsorption/ desorption isotherms of CS (i), CS-ZIF-8-1:1 (ii), CS-ZIF-8-2:3 (iii), CS-ZIF-8-1:2 (iv) and ZIF-8 ***(v).*** *[31]*

In adsorption experiments, the initial removal efficiencies were impressive, with Pb(II) reaching 98.2%. However, after five reuse cycles, the efficiency decreased to 80.2% for Pb(II). Scanning Electron Microscopy (SEM) analysis, shown in Fig. 3, confirmed the porous structure of the composite, facilitating adsorption. Additionally, Fig. 2 shows that BET results indicated a decrease in pore volume after metal adsorption, further demonstrating the effectiveness of CS-ZIF-8 as a high-capacity adsorbent for heavy metal removal.

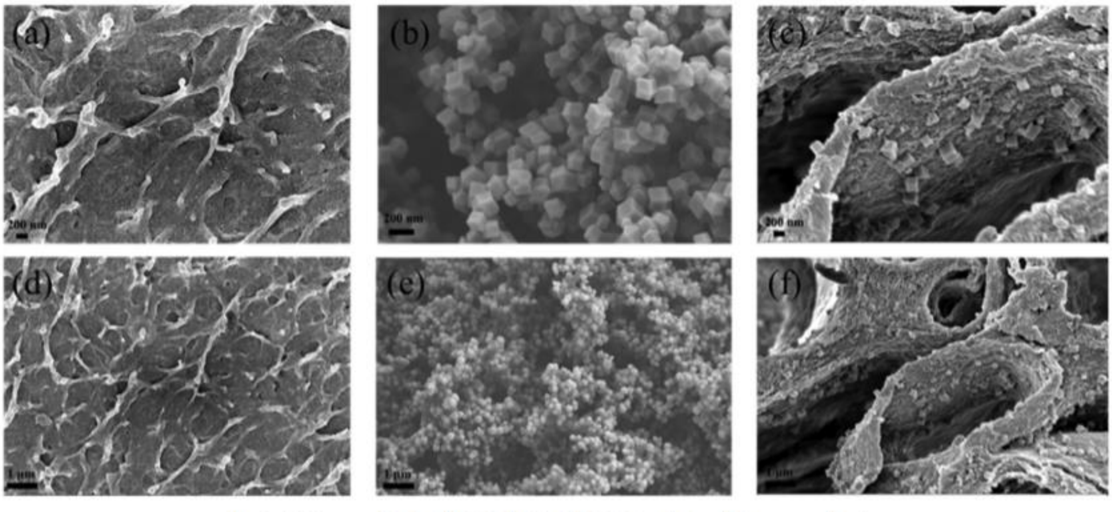


Fig. 2. SEM images of CS (a, d), ZIF-8 (b, e) and CS-ZIF-8-1:2 (c, f) at different magnification [31]

2.3.2 Fe_3O_4@$Cu_3(btc)_2$ magnetic core-shell microspheres)

The synthesis of thiol-functionalized Fe_3O_4@$Cu_3(btc)_2$ core-shell magnetic microspheres, referred to as SCC CUMOF, was reported by [31]. These microspheres were designed for the selective removal of heavy metals, specifically Hg^{2+} and Pb^{2+}, from aqueous solutions.

During the experiment the adsorption process of Pb^{2+} using thiol-functionalized $Fe_3O_4@Cu_3(btc)_2$ magnetic microspheres was examined in relation to the effects of a variety of parameters. The pH of the solution significantly influenced adsorption efficiency, with optimal removal occurring at pH levels between 6 and 7. This optimal removal was attributed to the strong interaction between thiol groups and metal ions. Additionally, the concentration of the adsorbent played a crucial role, as increasing the amount of thiol-functionalized microspheres enhanced the adsorption capacity for both heavy metals until reaching saturation.

Furthermore, contact time played a crucial role, with Pb^{2+} removal reaching near completion within 120 minutes. This highlights the importance of sufficient interaction time for effective adsorption. Collectively, these parameters are essential for optimizing the removal of heavy metals from wastewater using the developed adsorbent.

2.3.3 PHCS-15@ZIF-8/Zif-8

The synthesis of a novel core-shell composite, PHCS-15@ZIF-8, consisting of porous hollow carbon spheres (PHCS) coated with ZIF-8, was conducted using a combination of hydrothermal and Stöber methods. This composite exhibit significant potential for the adsorption of lead ions (Pb^{2+}) from aqueous solutions.

Characterization results reveal that PHCS-15@ZIF-8 has a BET specific surface area of 1140 m^2/g, indicating a substantial porous structure, and a microporous volume of 0.51 cm^3/g, enhancing its adsorption capabilities. Scanning Electron Microscopy (SEM) images (Fig. 4) demonstrate the uniform dispersion of ZIF-8 particles on the PHCS surface, contributing to improved adsorption performance.

In adsorption experiments, the PHCS-15@ZIF-8 composite achieved a remarkable Pb^{2+} removal percentage of approximately 95%, showcasing its effectiveness as an adsorbent. These results highlight the synergistic effect of the core-shell structure, facilitating the diffusion of Pb^{2+} ions into the mesoporous channels and enhancing the overall adsorption capacity of the material. [32]

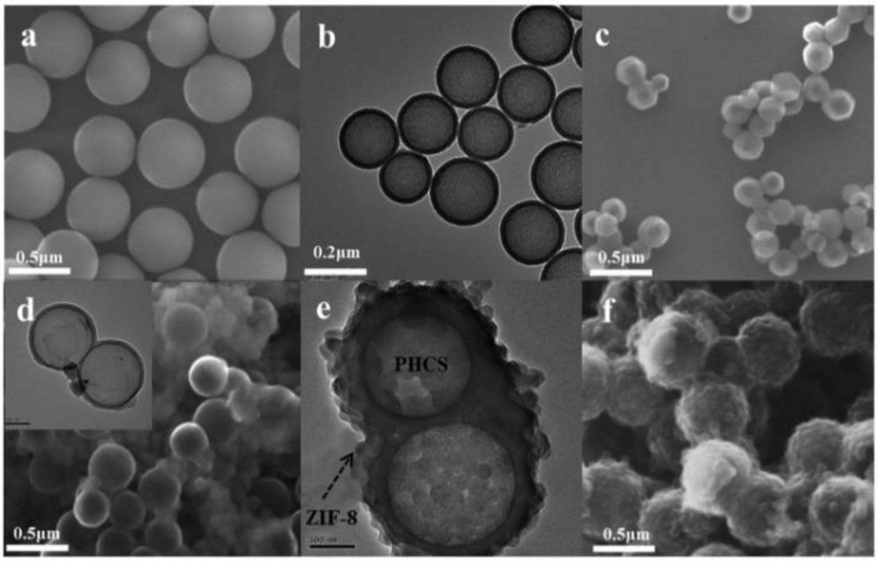


Fig 3. SEM and TEM images of SIO 2 (a), PHCS particles (b), ZIF-8 (c), PHCS@ZIF-8 core-shell nanocomposite without PSS (d) and with PSS treatment (e, f) (Chen et al., 2019)

2.3.4 SCC-CuMOF

the Sodium Carboxymethyl Cellulose-Copper Metal-Organic Framework (SCC-CuMOF) adsorbent, synthesized by ([33]for extracting Pb^{2+} ions from aqueous solutions, demonstrated exceptional efficacy. Its maximum adsorption capacity reached 531.38 mg/g at 308K.

Furthermore, the adsorption process of Pb^{2+} using SCC-CuMOF revealed significant influences from various parameters, including pH, adsorbent concentration, and contact time. Optimal adsorption occurred at pH 6.0, where the adsorbent's surface charge favored Pb^{2+} ion interaction. Increasing SCC-CuMOF concentration enhanced adsorption capacity by making more active sites available for metal ion binding. Contact time played a crucial role, with equilibrium reached within approximately 20 minutes, indicating rapid adsorption of Pb^{2+} ions.

These findings highlight the necessity of the optimization of pH, concentration, and contact time to maximize Pb^{2+} removal efficiency from wastewater.

2.3.5 UiO-66-(OPO_3) X

A comprehensive study on phosphorylated UiO-66, denoted as UiO-66-(OPO_3)X, evaluated its effectiveness in adsorbing lead ions (Pb^{2+}) from aqueous solutions, showcasing its potential for wastewater treatment. The introduction of phosphate ester groups significantly enhanced the adsorption capacity, with removal efficiencies reaching approximately 81.5% for UiO-66-(OH) X, 99.2% for UiO-66-o-$(OH)_2$, and an impressive 131.4% for UiO-66-p-$(OH)_2$.

[34] investigated key parameters affecting Pb^{2+} adsorption using UiO-66-(OPO_3)X, including pH, adsorbent concentration, and contact time. At pH levels below 3, H^+ ions compete with Pb^{2+}, inhibiting adsorption. However, as pH increases to 3 or above, phosphate group ionization enhances Pb^{2+} adsorption. The adsorbent concentration plays a crucial role, with higher concentrations generally leading to increased removal efficiency. Longer contact times also improve adsorption rates, allowing more Pb^{2+} ions to be captured.

Optimizing these parameters is essential for maximizing Pb^{2+} removal effectiveness from contaminated effluents [34].

2.3.6 Cu-BTC and Zn-BT

Cu- and Zn-based metal-organic frameworks (MOFs), specifically Cu-benzene-1,3,5-tricarboxylic acid (BTC) and Zn-BTC, were synthesized by [24]and demonstrated effectiveness in removing lead(II) ions from water. Adsorption experiments revealed that Cu-BTC achieved a maximum adsorption capacity of 333 mg/g, while Zn-BTC reached 312 mg/g for Pb (II) ions, showcasing their high efficiency in heavy metal ion removal.

Furthermore, the experiments revealed the effects of various parameters on Pb (II) ion adsorption using Cu-BTC and Zn-BTC MOFs. The solution pH significantly influenced adsorption efficiency, with optimal removal observed at pH 5. Adsorbent concentration also played a crucial role; however, higher dosages led to decreased adsorption capacity due to an unfavorable ratio of adsorbing concentration to available adsorbent sites. Contact time was critical, with rapid adsorption kinetics achieved in under 25 minutes, indicating chemical interactions between metal ions and framework adsorption sites predominantly controlled the adsorption process.

2.3.7 PEIUiO-66-NH_2

[35] conducted an adsorption experiment using the synthesized PEI@UiO-66-NH2 composite for Pb^{2+} removal, achieving an impressive adsorption capacity of 692.80 mg/g.

The adsorption process of Pb(II) using PEI@UiO-66-NH2 is significantly influenced by several parameters. The solution pH plays a crucial role, with optimal adsorption occurring within a specific pH range, affecting the ionization of functional groups on the adsorbent and the speciation of adsorbates. The initial Pb(II) concentration also impacts adsorption capacity, as increased concentration raises collision probability between adsorbate molecules and the adsorbent, enhancing adsorption until equilibrium is reached.

Furthermore, contact time is critical, with rapid initial adsorption reaching equilibrium within approximately 5 minutes. This indicates the adsorbent's high affinity for pollutants. Collectively, these parameters determine the efficiency and effectiveness of the adsorption process, highlighting the importance of optimizing conditions for maximum pollutant removal.

2.3.8 Zif-8/Zif-67

Ahmad et al. (2021) [23] assessed the performance of ZIF-8 and ZIF-67 as adsorbents for eliminating Pb^{2+} ions. The materials' surface areas and porosity were evaluated using the Brunauer-Emmett-Teller (BET) method, revealing their notable ability to promote adsorption due to their structural features. ZIF-67 outperformed ZIF-8 in lead and mercury adsorption, achieving capacities of 1436.11 mg/g for mercury and 1978.63 mg/g for lead. This versatility makes ZIF-67 suitable for heavy metal removal applications.

X-ray diffraction (XRD) analysis (Fig. 5) confirmed ZIF-8's crystalline structure, ensuring its integrity throughout the adsorption process. The findings indicated ZIF-8 achieved a Pb^{2+} adsorption capacity of 1780.91 mg/g, underscoring its potential as an effective adsorbent.

Scanning electron microscopy (SEM) analysis revealed ZIF-8's uniform polyhedral morphology, indicating consistent particle size and shape. This morphology enhances the material's surface area, facilitating interactions with Pb^{2+} ions during adsorption. The favorable surface area and optimal pore structure of ZIF-8 enable strong interactions between Pb^{2+} ions and the adsorbent, leading to efficient removal of lead from cosntaminated water sources.

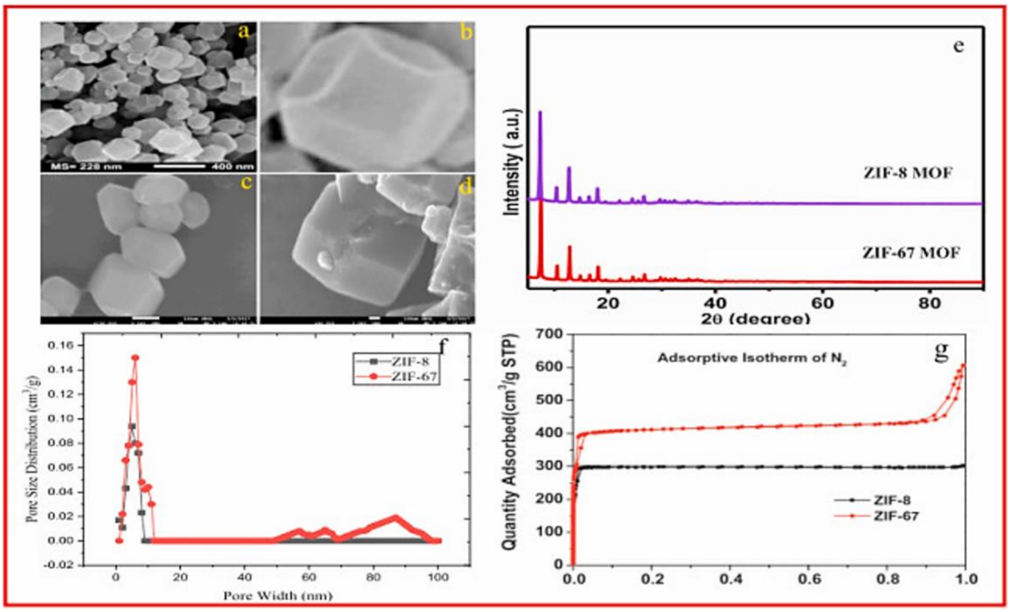


Fig 4. a and b) Morphology of ZIF-67 shown by SEM that the particles are well distributed having polyhedral shape, c and d) Morphology of ZIF-8 shown by SEM that the particles are well distributed having polyhedral shape, e) Diffraction peaks of ZIF-8 & ZIF-67 shown by Powder XRD, f) Pore size distribution of ZIF-8 and ZIF-67, from the figure it is clear that the pore size distribution and pore width of ZIF-67 is greater than ZIF-8, g) Nitrogen adsorption/desorption curve of ZIF-67 and ZIF-8 that represents that these MOFs have high surface area and are nanoparticles, further ZIF-67 have more nitrogen adsorption-desorption capacities as compared with ZIF-8. [23]

2.3.9 ZIF-67@Yeast

Wen et al. (2019) conducted an adsorption experiment to evaluate the effectiveness of ZIF-67@Yeast composite in removing Pb^{2+} ions from aqueous solutions. The results showed that several parameters significantly influenced Pb^{2+} adsorption efficiency.

The solution pH played a crucial role, with optimal adsorption occurring at specific pH levels that favor Pb^{2+} ionization and align with the adsorbent's surface properties. The adsorbent concentration also impacted adsorption capacity, as higher concentrations increased the availability of active sites for Pb^{2+} binding.

Contact time was critical, with rapid initial adsorption reaching equilibrium within a few hours, depending on the initial Pb^{2+} concentration. These parameters collectively underscore the importance of optimizing conditions to enhance ZIF-67@Yeast's effectiveness in removing Pb^{2+} from aqueous solutions.

2.3.10 ZIF-90@CS/SA

[33] synthesized ZIF-90@CS/SA beads, which demonstrated remarkable efficiency in removing Pb(II) ions from industrial wastewater. The adsorption of Pb(II) onto ZIF-90@CS/SA beads was significantly influenced by pH, adsorbent concentration, and contact time.

Removal efficiency increased with pH, peaking at 84.87% at pH 5.0, and remained stable between pH 5.0 and 9.0. However, efficiency declined at higher pH levels due to electrostatic repulsion. As Pb(II) concentration increased, adsorption capacity improved, attributed to stronger interactions with adsorption sites.

Contact time played a vital role, with Pb (II) reaching equilibrium within 2.5 hours. Notably, rapid initial adsorption exceeded 75% within the first two hours. Optimizing these parameters is crucial for effective heavy metal removal from wastewater.

2.3.11 HNTs@PDA/ZIF-8

[38] investigated Pb(II) adsorption using Halloysite polydopamine/ZIF-8 (HNTs@PDA/ZIF-8) nanocomposites, achieving a remarkable adsorption capacity of 515.46 mg/g.

The adsorption process of Pb^{2+} ions onto HNTs@PDA/ZIF-8 is influenced by several parameters: pH, adsorbent concentration, and contact time. Adsorption efficiency increases with pH, rising from 3.0 to 7.0, due to reduced protonation of functional groups. Higher pH enhances

HNTs@PDA/ZIF-8 stability, facilitating improved adsorption.

The adsorption capacity increases with Pb^{2+} ion concentration, indicating greater interaction with available adsorption sites. Adsorption occurs rapidly initially, reaching equilibrium within 100-150 minutes. The pseudo-second-order kinetic model accurately describes the adsorption process, suggesting chemical adsorption dominance.

2.3.12 MTV-MOFSWCNT-BP

Adsorption experiments demonstrated the MTV-MOF/SWCNT-BP composite's effectiveness in removing lead ions from aqueous solutions. by [39]conducted an experiment revealing the composite's remarkable lead ion adsorption capacity, reducing lead concentration below EPA and WHO trigger levels, even in highly concentrated multicomponent solutions [46].

Notably, for initial lead concentrations between 200-1000 ppb, final concentrations were reduced to below 10 ppb, showcasing the material's efficacy. Scanning Electron Microscopy (SEM) images illustrated the composite's morphology, revealing MTV-MOF particles enmeshed within the SWCNT-BP structure. Micrometer-sized aggregates of smaller, nanosized primary particles contributed to the hybrid material's overall mechanical stability and enhanced adsorption properties.

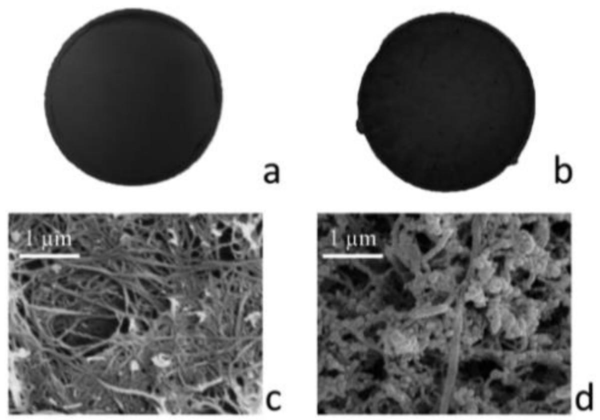


Fig 5. Final appearance of (a) neat SWCNT-BP and (b) MTV-MOF/SWCNT-BP. The average diameter of membranes was 38 ± 1mm. SEM images of (c) SWCNT-BP and (d) MTV-MOF/SWCNT-BP unveiling MTV-MOF micrometer particles as aggregates of smaller nanosized primary particles.

2.3.13 Cu-MOFs/CMFP

The adsorption experiment conducted by [40] utilized Cu-MOFs/CMFP to effectively remove organic dyes (methylene blue, rhodamine B, and malachite green) from aqueous solutions. A dosage of 30.00 mg of Cu-MOFs was added to dye solutions with an initial concentration of 10 mg/L, and after shaking for 35 minutes, residual dye concentrations were measured using UV-vis spectroscopy, achieving removal efficiencies exceeding 90%.

The adsorption of Pb^{2+} using SCC-CuMOF is significantly affected by pH, adsorbent concentration, and contact time. Optimal adsorption occurs at a pH of approximately 6.0, where the electrostatic interactions between the adsorbent and Pb^{2+} ions are maximized. Increasing the concentration of SCC-CuMOF enhances the adsorption capacity due to a greater availability of active sites for binding. Additionally, the contact time is crucial, with equilibrium typically reached within 20 minutes, indicating that the majority of Pb^{2+} ions are adsorbed rapidly. These results underscore the importance of optimizing these parameters to improve the efficiency of Pb^{2+} removal from aqueous solutions.

2.3.14 Cu MOF/HKUST -EDA

Ethylenediamine (EDA) modified copper-based MOF (HKUST-1-EDA) demonstrated excellent removal efficiency for Pb(II) ions from industrial wastewater, an experiment realized by [41] with maximum adsorption capacities of 12.85 mg/g for Pb(II) at pH 5.2.

The study investigated the effects of various parameters on the adsorption process of Pb(II) using the HKUST-1-EDA adsorbent. The pH of the solution as mentioned significantly influenced adsorption efficiency, with optimal removal observed at pH 5.2, where the adsorption capacities peaked before slightly decreasing at higher pH levels due to the presence of hydroxide ions. The concentration of the adsorbent also played a crucial role; an increase in dosage initially enhanced removal efficiency, reaching an optimum at 0.6 g/L, beyond which aggregation of particles reduced available adsorption sites and decreased efficiency. Additionally, contact time was critical, with maximum adsorption capacities achieved within 20 minutes, indicating rapid interaction between the adsorbent and metal ions. Overall, these parameters were essential in optimizing the adsorption process for effective heavy metal removal from aqueous solutions.

2.3.15 SUZ-4 zeolite

The purpose of the SUZ-4 zeolite adsorption experiment realized by [28] for Pb^{2+} removal, was to assess the zeolite's capacity and effectiveness. Na-T13, a sodium-exchanged form of SUZ-4 zeolite, plays a crucial role in the adsorption of Pb^{2+} ions from wastewater, and demonstrated a high adsorption capacity of 181.56 mg/g. The zeolite was synthesized through a hydrothermal method, and its structural characteristics were analyzed using various techniques.

Furthermore, characterizations were performed on the Na-T13 zeolites before and after adsorption 10 times to determine the adsorption mechanism of Pb^{2+} on the zeolite. The XPS is very useful to recognize the functional groups and element compositions on the fresh and spent adsorbent [47] [48]. As displayed in Fig. 8a, before adsorption, the main characteristic peaks of zeolites were attributed to Al 2p, Si 2p, O 1 s, and Na 1 s. After adsorption in Pb^{2+} solution, the strong peaks belonged to Pb 4f and $Pb_{4d5/2}$ and $Pb_{4d3/2}$ appeared on zeolite, but the Na 1 s peak was almost disappeared, suggesting the ion-exchange of Na+ by Pb^{2+} in adsorption. X-ray diffraction (XRD) analysis confirmed the crystalline nature of the synthesized SUZ-4, showing distinct peaks corresponding to the zeolite structure, which indicated successful synthesis and purity of the material. Scanning Electron Microscopy (SEM) images illustrated the morphology of the SUZ-4 zeolite, revealing aggregates of tiny, spiny crystals that maintained their structure even after multiple adsorption cycles, demonstrating the stability of the material. The combination of these results underscores the effectiveness of SUZ-4 zeolite as an adsorbent for Pb^{2+} ions, highlighting its structural integrity and high surface area as key factors contributing to its adsorption performance.

2.3.16 Ni-MOF-74

The adsorption experiments conducted by (Lou et al., 2022) to evaluate the efficacy of Ni-MOF-74 for removing $Pb^{2+}$from wastewater, was investigated. Furthermore, the characterization of Ni-MOF-74 material, by Brunauer-Emmett-Teller (BET) analysis was performed, revealing a specific surface area of 466.001 m²/g before adsorption, which decreased to 61.587 m²/g after Pb^{2+} adsorption. This significant reduction in surface area suggests that Pb^{2+} ions occupy the active sites and micropores of the Ni-MOF-74, confirming its role as an effective adsorbent.

X-ray diffraction (XRD) analysis was conducted to investigate the crystallinity and structural integrity of Ni-MOF-74 before and after Pb^{2+} adsorption. The XRD patterns indicated that the material retained its crystalline structure post-adsorption, which is essential for maintaining its adsorption properties.

Additionally, in (fig 8) as it can be observe the morphological changes of Ni-MOF-74 before and after the adsorption process The SEM images revealed a distinct alteration in surface morphology, with the presence of Pb^{2+} ions leading to changes in the texture and particle size distribution of the adsorbent. These characterization techniques collectively affirm the successful adsorption of Pb^{2+} ions onto Ni-MOF-74 and highlight its potential as a promising material for environmental remediation applications.

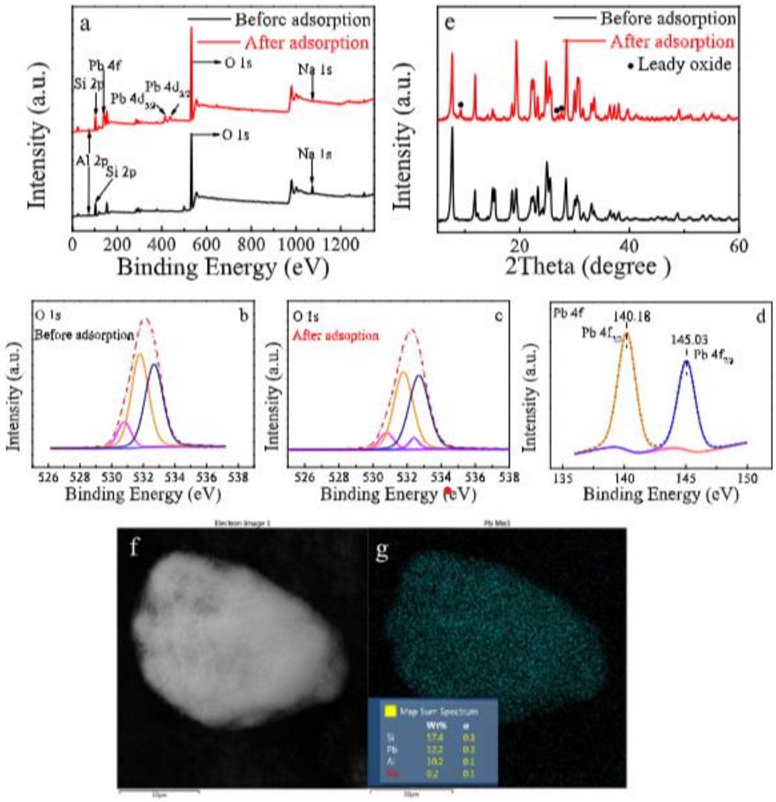


Fig 6. Characterizations of Na-T13 before and after adsorption: XPS spectra (a-d), XRD patterns (e), SEM-EDS (f, g).

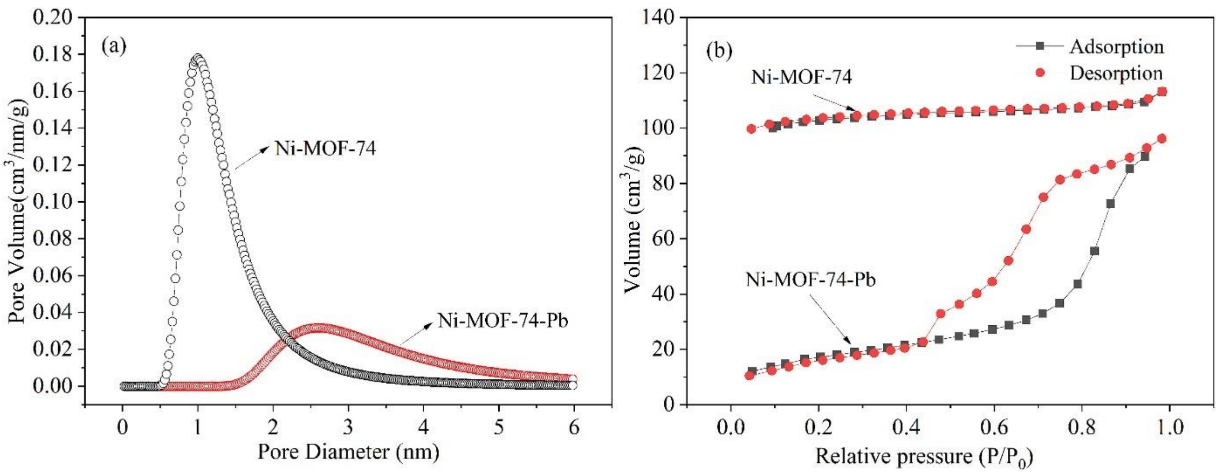


Fig7. (a) pore size distribution curves of Ni-MOF-74 and Ni-MOF-74-Pb, (b) N 2 adsorption/desorption isotherms. [43]

2.3.17 Fe-MOFs

The sulfate-functionalized Fe-based metal-organic framework (Fe-MOF) synthesized by [42] for the adsorption process of Pb(II) was significantly influenced by several parameters, including pH, concentration of the adsorbent, and contact time. The study revealed that under acidic conditions (pH 2-5), the surface charge of Fe-MOF was positive, leading to a decrease in removal efficiency due to competition with H^+ ions.

As the pH approached neutral (pH 6-7), the removal rate stabilized, indicating optimal conditions for adsorption. Additionally, the adsorption capacity increased with higher initial concentrations of Pb (II) ions, reaching a maximum capacity of 504 mg/g. The kinetics of adsorption showed a rapid increase in capacity within the first 2 hours, followed by a gradual slowdown, suggesting that internal diffusion may control the process. Overall, these parameters play a crucial role in optimizing the adsorption efficiency of Fe-MOF for Pb (II) ion removal from wastewater.

2.3.18 NH2 -MIL-53

The adsorption process of Pb^{2+} onto NH_2-MIL-53/WC hybrid membrane synthesized by [44] was significantly influenced by several parameters, including pH, initial concentration of the adsorbate, and contact time. The solution pH affects the surface charge of the adsorbent and the speciation of Pb^{2+}, optimizing the adsorption performance.

Higher initial concentrations of Pb^{2+} lead to increased adsorption capacities, as all potential active sites become occupied, with the NH_2-MIL-53/WC exhibiting superior performance compared to other materials. Additionally, the contact time is crucial, with equilibrium being reached after 12 hours, indicating that the adsorption kinetics are governed by chemisorption and multi-stage processes, including fast external surface adsorption followed by gradual intra-particle diffusion. These parameters collectively enhance the efficiency of the adsorption process, making the NH_2-MIL-53/WC membrane a promising candidate for lead ion removal in water treatment applications. Membrane as an effective adsorbent for the removal of heavy metal ions from contaminated water sources.

III. PERFORMANCES EVALUATION OF MOF FOR THE REMOVAL OF Pb^{2+}

3.1. Regeneration, Stability and Structural Integrity

Metal-Organic Frameworks (MOFs) regeneration is crucial for cost efficiency and sustainability in adsorption applications. Effective regeneration methods, including thermal treatment, solvent washing, and chemical desorption, depend on the MOF's structural stability and ability to retain adsorption efficiency after multiple cycles. MOF reusability hinges on maintaining structural integrity, influenced by factors such as linker nature, functional groups, and metal-ligand bond robustness. Post-synthetic modifications, like phosphate or thiol group functionalization, can enhance durability and adsorption capacity under real-world conditions. Several MOF adsorbents prioritize stability and structural integrity, demonstrating sustained performance across multiple adsorption-desorption cycles. This emphasis on reusability is vital for practical applications, ensuring MOFs remain effective and efficient over time.

Overall, CS-ZIF-8 composite beads offer a sustainable solution for Pb (II) remediation in contaminated water sources. Liu et al. (2019) [29] prepared CS-ZIF-8 for U(VI) removal and reported a high adsorption capacity of 629 mg/g at an optimal pH of 3.0. The chitosan component in this hybrid framework may provide additional functional groups that interact effectively with Pb^{2+} ions improving it stability.

Again, Thiol-functionalized magnetic core-shell microspheres are designed to overcome adsorption challenges. After adsorption, the Fe3O4@Cu3(btc)2 magnetic core-shell was washed with NaOH and water and reused for multiple rounds without losing efficiency. This hybrid structure enhances stability during the adsorption and desorption processes, making it robust against structural degradation. The presence of carboxylate groups in the BTC ligand further contributes to its adsorption capacity, allowing for effective removal of heavy metals from wastewater. This indicates long-term stability and reusability, making it an environmentally friendly option. Other MOF adsorbents, such as porous hollow carbon sphere@ZIF-8, have also demonstrated effective Pb2+ adsorption, desorption, and regeneration capabilities [49].

PHCS-15@ZIF-8 decreased slightly after each desorption. The Pb-loaded sorbents was centrifuged and washed with ethanol for three times. After that, the regenerated adsorbents were dried at 60 °C overnight and reused for another adsorption process and more than 90% of the removal efficiency still can be retained after 5 cycles During the experiment process. These indicated that ethanol washing was a useful method for regenerating the used adsorbent. PHCS-15@ZIF-8 also exemplifies the importance of linker nature and functional groups. The ZIF-8 component provides a robust framework that supports structural integrity, while the hybridization with PHCS introduces additional functional sites that enhance adsorption. [32]

The reusability and environmental friendliness of SCC-CuMOF and UiO-66-(OPO_3)X were investigated for practical applications. Continuous adsorption-desorption cycles revealed that SCC-CuMOF maintained a percentage removal of Pb2+ from 93.0% to 73.9% after five regeneration cycles. In comparison, UiO-66-(OPO_3)X exhibited remarkable regeneration performance, sustaining over 87% removal efficiency after five consecutive cycles.

This durability enables repeated use without significant effectiveness loss, minimizing replacement needs. Notably, UiO-66-(OPO_3)X combines low production costs, high efficiency, and excellent reusability, positioning it as a sustainable and economically viable solution for addressing heavy metal pollution in industrial applications. [34]

Metal-organic frameworks (MOFs) like Cu-BTC and Zn-BTC effectively reduce lead concentrations in water, promoting public health and environmental safety. They demonstrate high adsorption capacities of 333 mg/g and 312 mg/g, respectively. Their stability and multiple reuses make them environmentally friendly solutions for removing heavy metal pollutants.

PEI@UiO-66-NH2, a non-toxic adsorbent, effectively removes anionic dyes and heavy metals from wastewater, resulting in cleaner water and reduced pollution. Its rapid adsorption kinetics enhance treatment efficiency and reduce resource consumption, making it a promising sustainable solution.

ZIF-67/ZIF-8 maintains a high adsorption capacity (95%) over multiple cycles, indicating effective reusability. This reduces waste and the need for new materials, contributing to a more sustainable water treatment approach. It stands out with its stable framework that supports high adsorption capacities due presence of functional groups enhances its interaction with heavy metals, contributing to its effectiveness. ZIF-67@Yeast composite material, stable after carbonization, is reusable and environmentally benign. ZIF-90@CS/SA beads exhibit excellent adsorption capacity, favorable recyclability, and environmental friendliness, showing potential for heavy metal removal from industrial wastewater.

HNTs@PDA/ZIF-8's reusability was tested through recycling experiments. Despite a capacity loss after four cycles, its adsorption capacity remained above 50 mg/g, indicating good regeneration properties.

The NH2-MIL-53/WC hybrid membrane selectively sequesters Pb^{2+} from wastewater, offering an environmentally friendly solution. Its exceptional reusability allows for multiple reuses without capacity loss, generating low waste and making it a sustainable alternative.

MTV-MOF/SWCNT-BP was preserved owing of its structural stability upon lead adsorption/desorption cycles, and complete regeneration was achieved for up to five cycles. MTV-MOF/SWCNT-BP has great potential in the field of water treatment and can be effectively used as a reliable adsorbent for Pb (II) removal for household drinking water, as well as in industrial treatment plants for water and wastewater decontamination. The Cu-MOFs/CMFP can be regenerated through a simple washing process, allowing for multiple cycles of use without significant loss of efficiency. This reusability contributes to sustainability by minimizing waste and reducing the need for new materials.

The study emphasizes the Fe-MOF's selectivity and recyclability, which are crucial for its practical application in treating industrial wastewater, further supporting its role as an environmentally friendly solution. SUZ-4 zeolite has also been investigated and one of the components reusability of Na-T13 for Pb^{2+} adsorption, the adsorption-desorption cycles were conducted 10 times as described in Section 2.5, and the adsorbent amount was kept constant during the investigation. That the stability and recyclability of Na-T13 are excellent and that the adsorption process is good.

To investigate stability and reusability of Ni-MOF-74, the desorption experiment was carried out at 0.2 M_{HCl}. Four (4) consecutive adsorption regeneration cycles were performed. After four cycles, the adsorption capacity of Pb^{2+} decreased, but still maintained a high adsorption capacity (153.21mg/g). Ni-MOF-74 showcases the significance of robust metal-ligand bonds, which contribute to its high stability. The presence of amine functional groups enhances its interaction.

And finally, NH2-MIL-53/WC membrane is reutilized for Pb^{2+} adsorption, effectively removing Pb2+ below WHO standards. After four regeneration cycles, the membrane maintains 97.7% of its original equilibrium sorption capacity, indicating successful recovery of adsorption sites by acidified EDTA solution. This reusability performance ensures the sustainable application of the proposed NH2-MIL53/WC hybrid membrane in water treatment.

3.2 Cost-Effectiveness of MOF-Based Adsorbents

3.2.1 Comparative Analysis of MOF-Based Adsorbents

The economic viability of MOFs for industrial wastewater treatment depends on their production costs, ease of regeneration, and longevity. While the initial costs of MOF synthesis can be high, their long-term cost efficiency lies in their reusability and high adsorption capacity.

A comprehensive comparison of various MOF-based adsorbents reveals significant variations in cost, adsorption capacity, regeneration cycles, and cost-effectiveness, have been notified in the following table 2. The cost analysis shows that Cu-MOFs/CMFP and NH2-MIL-53/WC are the most expensive options, ranging from \$1.50 to \$3.50 per gram. In contrast, UiO-66-(OPO_3)X, Cs-ZIF-8, and Fe-MOF are the least expensive, costing between \$0.30 and \$0.80 per gram.

ZIF-67/ZIF-8 demonstrates the highest adsorption capacity at 1978.63 mg/g, surpassing other adsorbents. UiO-66-NH2 and SCC-CuMOF exhibit medium adsorption capacities, with 692.80 mg/g and 531.38 mg/g, respectively. SUZ-4 (Na-13) stands out with a maximum of 10 regeneration cycles, indicating high reusability. UiO-66-(OPO_3)X and Cs-ZIF-8 offer around 5 regeneration cycles, balancing cost and reusability.

The cost-effectiveness rating reveals that UiO-66-NH2, ZIF-67/ZIF-8, and SUZ-4 (Na-13) are highly cost-effective due to their reasonable costs, high adsorption capacities, and strong regeneration potential. MTV-MOF/SWCNT-BP and SCC-CuMOF fall into the medium category, while Ni-MOF-74 and Cu-MOFs/CMFP are rated as low in cost-effectiveness due to their low adsorption capacities and higher costs per gram.

ZIF-67/ZIF-8 and UiO-66-NH2 emerge as optimal choices in terms of cost-effectiveness, adsorption capacity, and reusability. Conversely, Cu-MOFs/CMFP is less favorable due to its high cost and low adsorption efficiency. These findings provide valuable insights for selecting efficient and economical MOF-based adsorbents for various applications.

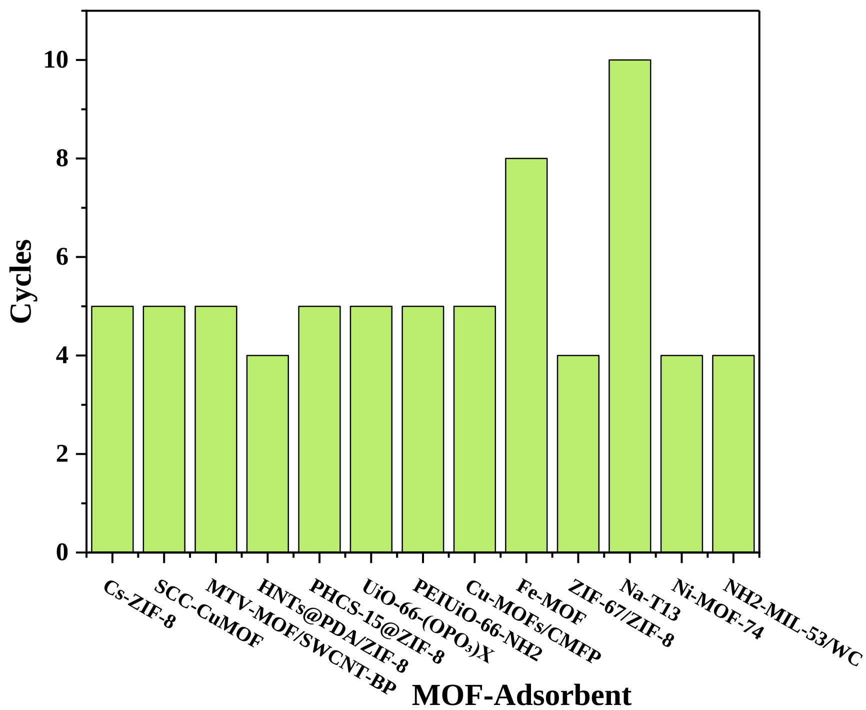


Fig 8. Regeneration cycles of MOF adsorbents

Table 2: Comparative Analysis of MOF-Based Adsorbents

MOF Type	Cost (USD/g)	Adsorption Capacity (mg/g)	Regeneration Cycles (n)	Cost-Effectiveness Rating
UiO-66-(OPO_3) X	• UiO-66-OH (1.0 g): \$100 to \$200 • Phosphorus Pentoxide (0.5 g): \$0.25 to \$0.50 • DMF (40 mL): \$2 to \$4 • Deionized Water (100 mL): \$0.10 • Methanol (100 mL): \$2 to \$3	512.8	5	Medium
Cs-ZIF-8	• Chitosan (0.48 g): \$0.48 to \$0.72 • Acetic Acid (2%, 16 mL): <\$0.10 • Zinc Nitrate Hexahydrate: \$0.50 to \$2 • Sodium Hydroxide (96 mL, 1 mol/L): <\$0.05 • 2-Methylimidazole: \$1 to \$3 • Methanol (40 mL): \$0.80 to \$1.20	131.4	5	Medium
Fe3O4@Cu3(btc)2	(\$0.40–\$1.00/g)	215.05	4	Medium
PHCS-15@ZIF-8	(\$0.40–\$0.70/g)	462.9 /310.5	5	High
SCC-CuMOF	\$0.40–\$0.80/g	531.38	5	Medium
UiO-66-(OPO_3) X)	\$0.80–\$1.50	445.88	5	High
Cu-BTC and Zn-BT	39\$ and \$0.30–\$0.70 (/g)	333(Cu-BTC) 312 (Zn-BT)	6	High
Fe-MOF	\$0.30–\$0.80/g	504	4	medium
UiO-66-NH2	0.36\$	692.80	5	High
ZIF-67/ZIF-8	1g (49.99\$/36.00\$)	1978.63	5	High
ZIF-90@CS/SA	\$0.40–\$1.00 /g	445.88	N/A	medium
HNTs@PDA/ZIF-8	\$0.70–\$1.50 / g	515.46	4	Medium
MTV-MOF/SWCNT-BP	\$0.40–\$1.00/g	180	5	Medium
Cu-MOFs/CMFP	\$1.50–\$3.00/g	31.77 N/A	5	Low
SUZ-4 (Na-13)	1.86 g	181.56	10	High
Ni-MOF-74	\$0.40–\$1.00 /g	98.062	4	Low
NH2-MIL-53/WC	\$1.50–\$3.50/g	223.4	4	Medium

3.3 Environmental Impact of MOFs

MOFs, being highly tunable, can be designed to minimize environmental impact. However, their synthesis often involves the use of toxic solvents and metal salts, raising concerns about their environmental footprint. To mitigate this, green synthesis methods, such as the use of water or ethanol as solvents, have been proposed.

To address these concerns, researchers have started exploring green synthesis methods that utilize more environmentally friendly solvents, such as water or ethanol. For example, the synthesis of **CS-ZIF-8 composite beads** incorporates biodegradable chitosan, which not only enhances the sustainability of the adsorbent but also reduces the environmental impact associated with its production 3. Similarly, **NH2-MIL-53/WC** has been noted for its environmentally friendly properties due to its selective sequestration of lead ions from wastewater, demonstrating the potential for MOFs to be both effective and sustainable 23.

By adopting these greener approaches, the environmental impact of MOFs can be significantly reduced, making them a more viable option for addressing heavy metal pollution and other environmental challenges.

IV. CHALLENGES AND FUTURE DIRECTIONS

Despite demonstrating great potential for Pb^{2+} removal, Metal-Organic Frameworks (MOFs) face scalability, stability, and environmental challenges. Current synthesis methods are difficult to scale for industrial applications, emphasizing the need for research into scalable, low-cost production techniques. Moreover, MOFs often degrade under harsh wastewater conditions, such as high salinity and pH extremes, necessitating the development of more robust materials with enhanced durability. To overcome these limitations, future research should focus on developing multifunctional MOFs that can target multiple contaminants, maintain removal efficiency over repeated use, and exhibit stability under variable conditions. This can be achieved through greener synthesis methods, non-toxic material design, and integration into hybrid systems, such as membranes or bio composites, to enhance practical application in wastewater treatment.

V. CONCLUSION

This study underscores the effectiveness of metal-organic frameworks (MOFs) as promising adsorbents for removing lead (Pb^{2+}) ions from wastewater. MOFs, such as ZIF-8, ZIF-67, and UiO-66 variants, demonstrate impressive adsorption capacities, high reusability, and significant structural versatility, making them ideal candidates for environmental remediation applications. Their high surface areas, tunable pore structures, and diverse functionalities enable efficient Pb^{2+} removal, even at varying pH levels and in the presence of co-existing ions.

Our findings suggest that several MOFs maintain their adsorption efficiency over multiple cycles, with minimal loss in performance, contributing to their cost-effectiveness and sustainability. The materials' tunability allows them to meet the demands of different wastewater conditions while promoting environmental safety by reducing the need for single-use adsorbents. Despite their promise, challenges such as scalability, stability under extreme conditions, and environmental impact during synthesis need further exploration to advance MOFs from research to practical applications.

Future work should focus on optimizing green synthesis methods and enhancing MOF stability, targeting multifunctionality for simultaneous removal of various contaminants. Addressing these areas will pave the way for MOFs to become a leading technology in sustainable wastewater treatment, contributing to cleaner water resources and improved public health.

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