Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 3, Issue 3, 2025

REMOVAL OF HEAVY METALS FROM AQUEOUS MEDIUM BY METAL ORGANIC FRAMEWORKS : A REVIEW

Asim Ali[1], Arslan Farooq[2], Uzma Yunus[*3], Farzana Yasmeen[4]

[1,2,*3,4]*Department of Chemistry Allama Iqbal Open University, Islamabad Pakistan*

DOI:https://doi.org/10.5281/zenodo.15001884

Keywords

Metal Organic Frame Works
Environmental Contaminants
Heavy Metals
Adsorption
Metal and MOF Interactions
Physical Adsorption
Chemical Adsorption
Adsorption Capacity

Article History
Received on 28 January 2025
Accepted on 28 February 2025
Published on 10 March 2025

Corresponding Author: *

Abstract

Due to the negative consequences that environmental contamination of heavy metals is having on people all over the world, it is becoming a bigger issue. Because of inappropriate waste management, pesticides, fertilizers, and fast expanding agriculture and metal industries, inorganic contaminants are ending up in our rivers, soils, and environment. Environmental and biological concerns have made the effective disposal of hazardous items from the environment crucial. One of the most appealing cleaning technology strategies is the adsorptive removal of harmful substances from fuel, wastewater, or air. Because of their special properties, porous metal organic framework (MOF) materials have shown great promise recently in the adsorption and separation of different liquids and gases. The most recent research on the adsorptive removal of several hazardous compounds, mostly from fuel, water, and air, using modified MOF materials is compiled in this article. In order to comprehend the adsorption mechanism, potential interactions between the adsorbate and the active adsorption sites of the MOFs will also be covered. The majority of the results that are seen can be described by the following mechanisms: adsorption onto a site that is coordinationally unsaturated, adsorption through acid-base interaction, adsorption through complex formation, and adsorption through hydrogen bonding, adsorption by electrostatic adsorption predicated on certain MOFs.

INTRODUCTION

The surroundings in which people, animals, plants, and microorganisms live or function are referred to as the environment. It is made up of the ocean, the land, and the atmosphere of Earth. The four spheres that comprise the Earth's system are the hydrosphere (water), lithosphere (land), atmosphere (air), and biosphere (living beings), all of which coexist peacefully. Pollutants and environmental contaminants are substances that are more prevalent than in any other area of the environment [1-3]. Because of their high density or large atomic weight, they are classified as heavy metals. These days, metallic chemical elements and metalloids that are hazardous to both humans and the environment are referred to as "heavy metals." Certain metalloids and lighter metals like aluminium, arsenic, and selenium are hazardous. They have been referred to as heavy metals, albeit some of them—like the element gold—are usually not hazardous [4-7].

Table 1. Chromium uses and properties [8-12].

Characteristics ▪ Density: 7.15 g/cm^3 ▪ It is twenty first abundant element ▪ Isolated as a chromite ore ▪ Hard ▪ Shiny, Steel-greyish ▪ This metal is quite active and reacts with most acids. ▪ Creates a coating of chromium (III) oxide, which lessens the metal's corrosiveness.
Applications ▪ Alloys ▪ Metal ceramics ▪ Electroplating ▪ Leather tanning ▪ Manufacturing of synthetic rubies, ▪ Dye paints ▪ Chromium salts are used to colour glass green
Effects Oral intake of chromium (VI) usually causes acute poisoning and various humans symptoms including: ▪ Gastro intestinal ulceration ▪ Nausea and vomiting ▪ Fever ▪ Diarrhea ▪ Vertigo ▪ Toxic nephritis ▪ Liver damage ▪ Coma ▪ death(usuallyat1–3g) ▪ Inhalation of chromium(VI)or having repeated skin contact will cause chronic poisoning. Chromium (VI) can cause: ▪ Allergic contact dermatitis and eczema, ▪ gingivitis ▪ irritation of mucous membranes ▪ bronchitis ▪ liver and kidney disease ▪ sinusitis ▪ pneumonia ▪ lung cancer

Table 2. Arsenic uses and properties [13-14].

Characteristics	▪ Density:5.75g/cm^3, ▪ 55th most common metal, ▪ It has three allotropic forms ▪ The minerals that were discovered are: ▪ arsenopyrite, which is composed of iron and arsenic sulphide;

	▪ realgar, which is composed of arsenic sulphide and is referred to as "ruby of arsenic" ▪ Dark silvery grey Appearance ▪ Brittle
Uses	▪ Protection of wood ▪ Preparation of glass ▪ Insecticides originations ▪ Doping material in semiconductors, ▪ Pyrotechnics, ▪ Bronze making
Effects on humans	▪ Poisonousness causes: ▪ Gastro-intestinal system irascibility, ▪ Lung irritation ▪ Skin fluctuations ▪ Reduced manufacture of both red blood cells and white blood cells, ▪ Enlarged probabilities of cancer have been proposed. ▪ Sterility and miscarriages, ▪ Heart difficulties ▪ Brain destruction ▪ Deoxyribonucleic acid (DNA) destruction ▪ Organic arsenic may cause: ▪ Stomach set backs ▪ Nerve destruction

Table 3. Lead uses and properties [15-18].

Characteristics	▪ Density:11.3g/cm^3 ▪ 37^{th} most common metal ▪ Found as ore known as galena ▪ Silver-grey metal ▪ Soft
Uses	▪ Hair dyes ▪ Insecticides ▪ Lead-acid batteries ▪ Lead crystal glass ▪ Cable cover ▪ Sports kit ▪ Canister for toxic fluids ▪ In buildings for roofing ▪ Lead pipes
Effects on Human	▪ Hypertension ▪ Miscarriages ▪ Premature and low births, ▪ Still births

	▪ Renal damage ▪ Brain harm ▪ Abdominal soreness ▪ Peripheral nerve destruction ▪ Sperm destruction ▪ Encephalopathic symbols ▪ Iron shortage due to trouble of haemoglobin production, ▪ Cognitive impairment, ▪ In children: ▪ Brain and central nervous system growth changed ▪ Compact cleverness, ▪ A decline in educational attainment, ▪ A decrease in the devotion span, ▪ Rise in anti-social behaviour

Table 4. Mercury uses and properties [19].

Characteristics	▪ Density: 13.5336 g/cm^3 ▪ 66^{th} the most abundant metal ▪ It is found in the ore cinnabar made from mercury sulphide ▪ At room temperature, it is a silvery liquid metal, ▪ Rare to find in a natural state
Uses	▪ Barometers ▪ Thermometers ▪ Manufacturing chlorine ▪ Gold recovery ▪ Tooth fillings ▪ Compact fluorescent light bulbs ▪ Photochemistry ▪ Calomel electrodes ▪ Insecticide ▪ Rat poison ▪ Mercuric Sulphide used as a pigment in paint, bright red ▪ Catalyst ▪ Rectifiers, ▪ Electrical switches
Effects on Human	▪ Inhalation caused: ▪ Lung irritation ▪ Eye irritation ▪ Rashes ▪ Vomiting and diarrhoea ▪ Genotoxic ▪ It damages the DNA and chromosomes, ▪ Mongolism, also known as Down's syndrome, ▪ Affects the reproductive system, which can lead to: ▪ Miscarriages, ▪ Congenital disabilities, ▪ Sperm damage in men, ▪ Neurological disorders,

	▪ Minamata disease or Chisso-Minamata disease: ▪ Learning disabilities, ▪ Speech defects, ▪ Memory loss, ▪ Tremors and muscle incoordination, ▪ Deafness, ▪ Vision complications, ▪ Personality changes, ▪ Insanity, ▪ Paralysis, ▪ Coma and death,

Table 5. Cadmium uses and properties [20-21].

Characteristics	▪ Density: 8.69 g/cm^3 ▪ 64th most common metal ▪ Found in combination with zinc ▪ Silvery bluish tint metal
Uses	▪ Phosphate fertilizer ▪ Pesticides ▪ Nickel–Cadmium batteries ▪ Glassware pigmentation, ▪ Corrosion-resistant plating, ▪ Stabilizer in plastic production, ▪ Nuclear reactors
Effects on Human	▪ It is produce nephrotoxicity ▪ Infertility produced by a reproductive system failure, ▪ Calcium metabolism changes ▪ Bone breakage ▪ DNA weakening, ▪ Cancer ▪ Reported to be genotoxic and ecotoxic in animals ▪ Psychological syndromes, ▪ Gastrointestinal illnesses, ▪ Central nervous system problems, ▪ Immune system deficiencies,

Table 6. Copper uses and properties [22-23].

Characteristics	▪ Density: 8.96 g/cm^3 ▪ 26th most Common metal ▪ Golden Red appearance ▪ Found in minerals such as chalcopyrite, bornite (peacock ore) ▪ Good conductor of heat and electricity
Uses	▪ Copper alloys ▪ Copper wires

	▪ Electroplating ▪ Coins ▪ Piping ▪ Chemical tests for sugar detection in Fehling's solution ▪ Copper sulphate to cure mildew in agriculture ▪ Protection of wood ▪ Protection of fabric ▪ Fence cream
Effects on Human	▪ Metal fever giving it self with: ▪ flu-like indications ▪ diarrhoea ▪ vomiting ▪ irritation of the eyes ▪ dizziness ▪ irritation caused in the mouth cavity ▪ An acute dose of copper salts causes acute gastroenteritis due to necrosis ▪ In excess: ▪ Hepatocellular degeneration ▪ Necrosis ▪ Cytotoxic to erythrocytes leading to haemolysis ▪ Wilson's disease (copper accumulated in organs instead of being excreted by bile): ▪ Lack of appetite ▪ Fatigue ▪ Jaundice ▪ Kayser-Fleisher rings ▪ Speech impairment ▪ Difficulty in swallowing ▪ Uncontrolled poisoning ▪ Brain damage ▪ Demyelination ▪ Hepatic cirrhosis ▪ Oral intake will cause hepatic and kidney disease, ▪ Insomnia ▪ Anxiety ▪ Agitation ▪ Restlessness

Table 7. Nickel uses and properties [24-26].

Characteristics	▪ Density: 8.9 g/cm^3 ▪ 22nd most common metal ▪ Minerals found are pentlandite, sulphide; garnierite ▪ Silvery Appearance ▪ Repels corrosion at high temperatures ▪ Large quantity of Ni came from meteorites
Uses	▪ Jewelry ▪ Coins ▪ Oat propeller shafts, ▪ Rocket engines ▪ Nichrome alloy used in appliances that use heat while remaining non-corrosive ▪ Electroplating ▪ Alloy ▪ Welding ▪ Armour plating
Effects on Human	▪ Lung embolisms ▪ Asthma ▪ Allergic reactions (jewellery) ▪ Respiratory failure ▪ Heart disorders ▪ Dizziness (following gas exposure) ▪ Increased possibilities of cancer ▪ Nickel sulphide, nickel oxide and soluble nickel compounds are all carcinogenic. Workers in the nickel industry who are exposed to inhalation of the metal are at a greater risk of acquiring lung and nasal cancer

Anthropogenic sources

The primary source of drinking water and a vital resource for humanity, ground water reservoirs are mostly affected by anthropogenic organic and inorganic pollution. This pollution eventually poses a concern to human health and may cause poisoning in both aquatic and terrestrial animals. It is crucial to keep an eye on and manage any sources of pollution. This include sources such runoff from metropolitan areas, railroads, highways, mines, dredged sediments, landfills, sewage systems, and agricultural and industrial locations [27].Heavy metals can also be redistributed throughout the ecosystem as a result of ground water pollution, either by sorption/complexation (to particulate organic matter) or plant absorption. Figure 1, provides a broad summary of how heavy metals are transported via ground water systems. In general, a lot of human activities that cause heavy metal pollution may be linked to the processes involved in the manufacture, use, and disposal of goods in a variety of contexts, including industry, agriculture, and transportation. The elements released by these processes might originate from point sources or diffuse sources, and they are discharged into the environment as gases or particles in solid or watery forms. Pollutants from agriculture might come from fertilizers and other products used for crop management. For instance, phosphoric fertilizers have different amounts of zinc and cadmium depending on the kind of rock they are made of. Increased Cd concentration in sedimentary derivatives and decreased Cd content in derivatives of igneous rock [28]. Heavy metals are no longer included in pesticides; none the less, the use of metal-rich chemicals in the past caused arsenic, lead, and mercury to accumulate in soil and ground water. Because sewage effluents contain a lot of nutrients, they have been widely employed for soil enrichment over the past 100 years. Sewage effluents have benefits, but they can also include boron, cadmium, copper, lead, nickel, and zinc, which can be harmful to plants. Another significant cause of the environmental contamination caused by heavy metals is industrial activity. This is especially concerning for regions of the world that do not yet have contemporary legislation pertaining to this issue. The primary industrial causes of pollution are coal combustion, mining, waste water treatment, and product waste disposal. Large amounts of waste rock are produced by mining,

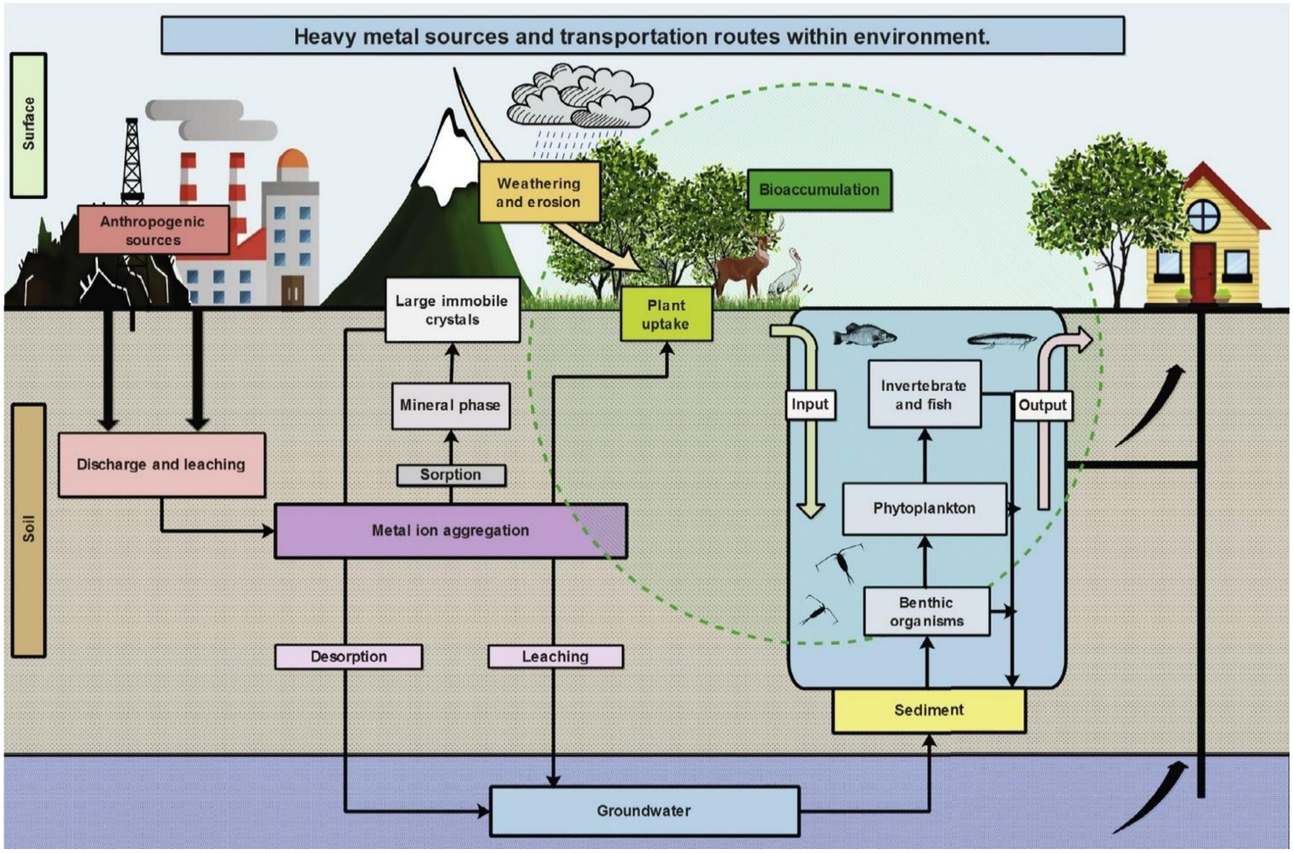

Fig 1. A flow chart showing how soil, fresh-and ground water systems redistribute heavy metal so anthropogenic origin

rock (As, Cu, Cd, Pb, and Hg) still contains small amounts of heavy metals. These trace metals are deposited in mine tailings and are subject to weathering and oxidizing conditions that cause acid drainage. The heavy metals are subsequently released, seeping into the nearby rock, soils, and even drinking water supplies. Fossil fuel combustion is another industrial form of pollution that mostly contributes to atmospheric heavy metal pollution (As, Cd, Mo, Zn, and Pb from petrol additives). Solid waste produced during industrial operations.

Adsorptive removal of Toxic Substances

Due to its relatively low cost, broad variety of applications, ease of design and operation, low production of toxic secondary products, and simple adsorbent renewal, adsorption has been deemed preferable to alternative decontamination techniques. The basis of adsorptive removal is a porous adsorbent's capacity to specifically adsorb certain molecules from the environment or refinery streams. Since the chemicals have easy access to the solid soil's pores, they can be removed via adsorption if they are of an appropriate size and form. An adsorbate and a porous sorbent can interact in different ways, leading to the classification of adsorption as either chemical or physical [29]. Adsorptive adsorption is the common term for physical adsorption, while reactive adsorption is the term used for chemical adsorption. Adsorbates are often confined inside the pores of solid adsorbents by weak (van der Waals) pressures in the case of adsorptive removal. As a result, simple solvent exchange or other physical processes like sonication and calcination can readily replenish the adsorbent. Conversely, genuine chemical bonds between the adsorbate and the adsorbent are formed during reactive adsorption. Chemical treatments are often used to regenerate the wasted adsorbent. The key factors influencing the effectiveness of adsorptive removal are the adsorbents' adsorption capacity, their durability, regenerability, and selectivity for certain chemicals. Hazardous chemical

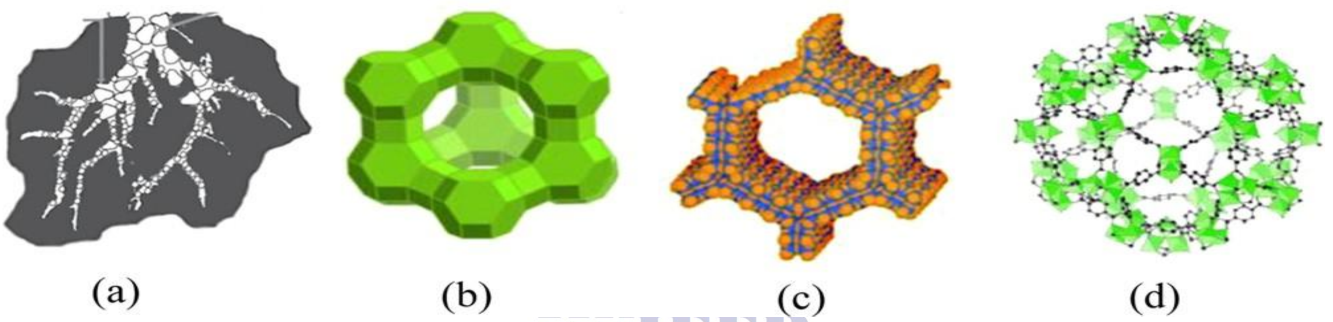

Fig 2. Widely used porous sorbents: (a) activated carbon, (b) HY (FAU) zeolite, (c) MCM-41 and (d) MIL-101 (Cr).

adsorptive removal has been explored for a variety of porous adsorbents Fig. 2, including zeolites [30-32], activated carbons [33-36], mesoporous materials [37-40], and MOFs [41-43]. Porosity, pore shape, and specific adsorption sites are necessary for effective adsorptive removal.

Fig 3. Techniques used for the removal of heavy metals from aqueous solutions

However, the metabolism of the human body only needs a little amount of metals as trace elements. They pose a serious risk to life if their amount rises. Figure 3 illustrates the many techniques now in use for removing heavy metal ions, including adsorption, chemical procedures, resin-mediated ion exchange, and fluctuation.

Metal Organic Frameworks

A metal ion or cluster of metal ions and an organic molecule known as a linker make up the two main parts of MOFs. Di-, tri-, or tetradendate ligands are the most common organic units [44- 45]. Fig. 4 displays a few common MOFs. Since the inorganic component of porous hybrid frameworks comprised either a solitary polyhedral or tiny clusters similar to those seen in coordination chemistry, they were previously referred to as coordination polymers. But it wasn't long before it was discovered that bigger dimensions inorganic components within porous hybrid solids might result in the formation of chains (1D), layers (2D), and even three-dimensional frameworks known as MOFs[46].

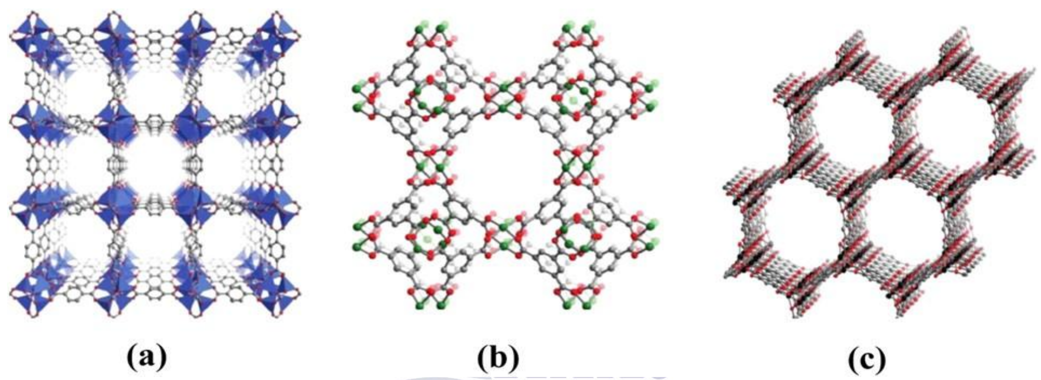

Fig 4. Structures of typical metal-organic frameworks. (a) MOF-5, (b) Cu-BTC and (c) CPO-27.

When compared to materials of the zeolite type, MOF materials provide several benefits. For zeolite-related inorganic hybrid materials to develop, an organic or inorganic template is required; however, the primary templating molecule in MOFs is a solvent. In contrast to inorganic materials, which rely on a few number of cations like Si, Al, and P, the majority of metal cations may take part in the production of MOFs, which is another significant characteristic. By only altering the ligand lengths of the same metal species, MOFs have made tremendous progress towards the construction of a series known as isoreticular MOFs, in which the pore size of the matching frameworks is dependent upon the ligand length. Additionally, a number of similar MOFs may be created using the same ligands and other metallic components [47-48]. The enormous porosity and ease with which the pore size and shape of MOF-type materials can be tuned from micro-porous to mesoporous scale by varying the nature of the organic linkers and the connectivity of the inorganic moiety, as well as the materials' capacity for hydrogen storage, vapour adsorption, chemical separation, drug delivery/biomedicine, polymerization, magnetism, catalysis, luminescence, and other processes. Because MOFs have potential applications in a wide range of industries, there has been a significant growth in both the number of publications (per year) and research on MOFs. Due to their simple pore surface modification, which allows for the selective adsorption of certain guest molecules with certain functional groups, MOFs are interesting materials for adsorption-related applications[49-59].

Fig 5. Application of MOFs in the environment cleanup

Because of their enormous porosity and pore geometry, MOF-type materials have recently been extensively studied for the adsorptive removal of numerous hazardous chemicals from the environment [60-62]. Furthermore, MOFs are superior to other porous adsorbents for the effective adsorptive removal of hazardous compounds because of the central metals [63-66], cooperatively unsaturated sites (CUS or open metal sites) [67-69], functionalized linkers [70-72], and loaded active species [73]. These interactions have been used successfully for a number of additional interactions between the adsorbates and MOF materials. Preferred adsorption is influenced by a variety of host-guest interactions, including acid-base [74], π-complexation [75], H-bonding [76], and coordination with open metal sites [77-79].

Table 8. Overview of pure MOFs as adsorbents for metals in aqueous systems. This table is organized for metals, concentration, the MOF adsorbents and their maximum uptake.

Metal	The concentration of MCL causes health effects (mg /L)	MOF adsorbent	Maximum MOF Adsorption capacity (mg / g)	References
Antimony(V)	0.006	NU-1000	287.88	80
Antimony(III)		NU-1000	136.97	80
Arsenic(V)	0.01	Zn-MOF-74	325	81
		UiO-66	303	82
		ABUM-1	103	83
		MIL-100-Fe	110	84
		H-ZIF-8-14	90.9	85
		ZIF-8	76.5	85
		H-ZIF-8-12	74.0	85
		H-ZIF-8-11	72.6	85
		ZIF-8-MeOH	72.33	85
Arsenic(III)	0.01	Fe–Co-MOF-74	292	86
		Zn-MOF-74	211	87
		UiO-66	202	82
		UiO-66-(SH)2	40	87

Metal	The concentration of MCL causes health effects (mg /L)	MOF adsorbent	Maximum MOF Adsorption capacity (mg / g)	References
Barium(II)	0.02	Zr–bdc–NH_2–SO_4	181.8	88
		MOF-808-SO_4	131.1	89
		MIL-101-Cr–SO_3H	70.5	89
Cadmium(II)	0.005	MOF-808-EDTA	528	90
		FJI-H9	225	91
		NH_2–Zr-MOF	177.35	92
		$Cu_3(BTC)_2$–SO_3H	88.7	93
		UiO-66-NHC(S)NHMe	49	94
		TMU-4	48	95
		TMU-5	43	95
		TMU-6	41	95
Chromium(VI)	0.1	1DFe–gallic acid	179.2	96
		ZJU-101	245	96
		SCNU-Z1-Cl	241	97
		FIR-54	103	98-99
		Zn–Co–SLUG-35	68.5	100
		1-ClO_4	63	101
		SLUG-21	62.8	102
		FJI-H9	71.8	103

Metal	The concentration of MCL causes health effects (mg /L)	MOF adsorbent	Maximum MOF Adsorption capacity (mg / g)	References
		Cu–BTC	48	104
		$1\text{-}NO_3$	37	95
Chromium	(III)	TMU-4	127	95
		TMU-5	123	95
		TMU-6	118	95
Cobalt(II)	0.04	UiO-66-Schiff	256	95
		MOF-808-EDTA	150	90
		TMU-5	63	95
		TMU-6	59	95
		TMU-4	55	95
Copper(II)	0.13	ZIF-67	617.51	105
		ZIF-8	454.72	105
		MOF-808-EDTA	155	90
		TMU-4	62	95
		TMU-6	60	95
		TMU-5	57	95
Iron(III)	0.200	MOF-808-EDTA	150	90
Lead(II)	0.015	ZIF-67	134	105
		ZIF-8119	67	105
		MOF-808-EDTA	313	105

Metal	The concentration of MCL causes health effects (mg /L)	MOF adsorbent	Maximum MOF Adsorption capacity (mg / g)	References
		TMU-5	251	
		TMU-4	237	
		UiO-66-NHC(S)NHMe	232	
		TMU-6	224	
		NH_2–Zr-MOF	92.18	
		MIL-101(Cr)	15.78	
Lithium(I)	0.20	Zn-MOF5-12c4	12.3	106-107
		LMOF-321	12.18	
		MIL-121-a	3.89	109
		MOF-808-EDTA	63	90
Manganese(VII)	0.05	SCNU-21	292	99
Mercury(II)	0.002	$CaCu_6[(S,S)$-methox$]_3(OH)_2(H_2O)$	900	110
		JUC-62	836.7	67
		UiO-66-NHC(S)NHMe	769	52
		MOF-808-EDTA	592	48
		FJI-H12	439.8	68
		LMOF-263	380	69
		PCN-100	364.7	70

Metal	The concentration of MCL causes health effects (mg /L)	MOF adsorbent	Maximum MOF Adsorption capacity (mg / g)	References
		UiO-66-$(SH)_2$	236.4	71
		MIL-101-NH_2	30.67	72
		ZIF-90-SH	22.45	73
Nickel(II)	0.1	MOF-808-EDTA	155	90
Selenium(VI)	0.05	NU-1000	62	91
		UiO-66-$(NH)_2$	38.5	111-112
		UiO-66-HCl	86	113
		FJI-H9	187	114
Selenium(IV)	0.001	NU-1000	102	115
		UiO-66-$(NH)_2$	45	116
Silver(I)	0.000001	MIL-53(Al)	183	116
Thallium(IV)	0.002	UiO-66-$(COOH)_2$	350	117
		dMn-MOF	46.35	118
Uranium(VI)	0.000002	HKUST-1	787.4	119
		MIL-101-DETA	350	98
		MOF-76	298	116
		MOF-2	217	96
		MOF-3	109	119

Mechanism of Adsorption

Depending on the nature of the interaction between the heavy metals (adsorbates) and MOFs (adsorbents), MOFs can remove heavy metals from water by chemical or physical adsorption. Adsorptive adsorption is another name for physical adsorption; reactive adsorption is the general term for chemical adsorption. The adsorptive capacity of MOFs is influenced by the strength of chemical and physical adsorption.

Chemisorptions

The sorption of heavy metals on MOFs is mostly attributed to chemisorption processes. Coordination bonding, acid-base interaction, and chemical bonding are all included. Heavy metal sorption on MOFs typically results in the observation of a chemical bonding mechanism. The bond may be recognised by FTIR by exhibiting extra bands in the spectrum. An extra band for the Zr-O-As group is seen during the sorption of As(V) on UiO-66 from water as a result of the bonding of the adsorbate (As) with adsorbent (Ui-66). The sorption of heavy metals on three different ZIF morphologies—leaf-shaped ZIFs, dodecahedral ZIFs, and cubic ZIFs—has been reported. This is because the isotherms for these morphologies are better explained by the Langmuir model than by the Freundlich model, indicating that chemical bonding was a predominant mechanism [131].

Chemical Bonding

Heavy metal ions and adsorbate (modified MOFs) containing reactive groups like carboxyl, thiol (-SH), (-COOH), and amine ($-NH_2$) typically exhibit coordination bonding. Create an amine-functionalized version of MIL-101(Cr) by coordinating ethylenediamine with the unsaturated centres of Cr metal. A number of hydrogen ions in the water joined the $-NH_2$ of MIL-101(Cr) when the pH of the solution was acidic, forming $MOF(NH_2)_3^{3+}$, which was then coupled with heavy metal ions. This time, however, it was not true since the typical surface area predicted the adsorption capacity of the adsorbate. Modified UiO-66 and virgin have a bigger surface area than MIL-68 and MIL-53-NH_2, however the former have a lower sorption capacity than the latter [132].

Acid Base Interaction

According to some research, the hard-soft acid-base (HSAB) theory is necessary for the acid-base interactions in order for heavy metal ions to sorb onto metal oxide filaments (MOFs). This hypothesis states that although other features are comparable, hard acid responds firmly with hard base and soft acid reacts with soft base. Further more, absorbing or donating electron pairs provides the basis for the Lewis acid-base theory-explained process of heavy metal sorption on MOFs. The possessing donor atoms O or N plays a significant impact in the Cr(III) sorption process on TMU-5 [133-135].

Physisorption

Van Der Waals forces

The van der Waals sorption process often kicks in when the MOFs' surface area and porosity play a significant role. Because MOFs have a unique greater surface area, heavy metals are removed from the water in a selective manner. It is investigated how pore size, pore surface, and pore volume influenced MIL-100(Fe) sorption capacity, which increased as pore volume increased. Together, chemisorption and physisorption boost the sorption capacity, albeit neither process is very significant on its own [136-137].

Electrostatic Interaction

Electrostatic interaction is the term used to describe the sort of interaction that MOFs can have with heavy metal ions that have opposing charges. Electrostatic contact occurs during the sorption process, which determines whether the MOFs' surface had a negative charge. In addition to altering the pH of the solution, the charge on the MOFs' surface also introduces a unique group that is associated with protonation and deprotonation. The ability of the MOFs surface and the presence of heavy metal ions both influence the sorption process of heavy metals on MOFs. The pH of the solution affects the divalent heavy metals, such as Hg (II), Pb (II), and Cd (II). Common species are $M^{2+,}$ $M(OH)^{-1}$,

$(MOH)^{o}$, and $M(OH)_3^-$ .Greater amounts of hydrated ions H_3O^+ competed with heavy metal ion sorption on the MO Fs at lower pH values. Since the heavy metals and MOFs are both positively charged, there was no electrostatic contact between them. However, the solution has a negative charge at high pH levels, and heavy metals have a positive charge, therefore there is an electrostatic contact between them. the ability of MOF-5 to carry a negative charge between pH values of 2 and 7, and the capacity of HS-mSi@MOF-5 to carry a negative charge above pH value of 3. The greatest adsorption for Pb(II) and Cd(II) is attained at pH 7, and the capacities of raw MOF-5 and HS-mSi@MOF-5 increased as the pH of the solution increased. As a result, electrostatic interaction dominated the sorption process for both metals [140].

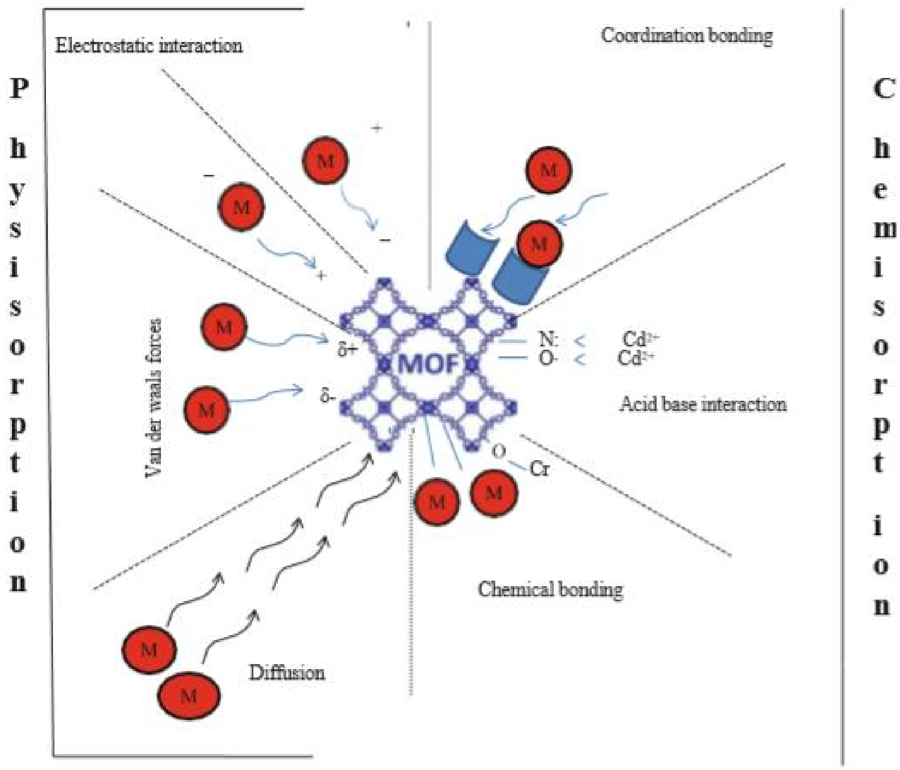

Fig. 6. Mechanistic representation of removal of heavy metals on MOFs

Conclusion

Because of its remarkable porosity, large surface area, and chemically adjustable characteristics, Metal-Organic Frameworks (MOFs) have become very successful materials for purifying water. They are better than conventional adsorbents because of their capacity to specifically collect and eliminate impurities such as organic pollutants, heavy metals, and radioactive materials. Their powerful attraction to metal ions, which enables them to efficiently remove harmful compounds from water, is one of the main reasons underlying their effectiveness. They are a viable option for large-scale water treatment because of their structural adaptability, which also allows for adjustments to improve selectivity and reusability. Even if there are still issues with increasing its stability and scalability, further development and research in MOFs technology has the potential to completely transform water purification, resulting in cleaner water sources and a more sustainable environment.

REFERENCES

V. Masindi, K.L. Muedi, Environmental contamination by heavy metals, in: HeavyMetals, InTech, 2018.

C.H.Walker,R.M.Sibly,S.P.Hopkin,D.B.P.,in:PrinciplesofEcotoxicology;Group,T.AndF., Ed.;4thEdition,CRCPress,2012.

Y.E. Martin, E.A. Johnson, Biogeosciences survey: studying interactions of thebiospherewiththelithosphere,hydrosphereandatmosphere,Prog.Phys.Geogr.36(2012) 833–852.

P.B. Tchounwou, C.G. Yedjou, A.K. Patlolla, D.J. Sutton, Heavy metal toxicity andthe environment, In EXS 101 (2012) 133–164.

Lenntech BV Heavy Metals, Available online: https://www.lenntech.com/processes/heavy/heavy-metals/heavy-metals.htm. (Accessed 29 June 2018).

J.H. Duffus, Heavy metals" a meaningless term? Pure Appl. Chem. 74 (2002)793–807.

L.K. Wang, Heavy Metals in the Environment, CRC Press, 2009.

WHO Air Quality Guidelines for Europe, second ed., 2000.

J. Occurrences Barnhart, Uses, and properties of chromium, Regul. Toxicol.Pharmacol. 26 (1997) S3–S7.

ATSDR Toxicological Profile for Chromium, 2012.

Sabine Martin, Griswold Wendy Human Health Effects of Heavy Metals, Environ.Sci. Technol. Briefs Citizens (2009).

A.D. Dayan, A.J. Paine, Mechanisms of chromium toxicity, carcinogenicity andallergenicity: review of the literature from 1985 to 2000, Hum. Exp. Toxicol. 20(2001) 439–451.

W.M. Haynes, in: W.M. Haynes (Ed.), CRC Handbook of Chemistry and Physics,92nd ed., CRC Press, Florida, 2011.

ATSDR Toxicological Profile for Arsenic, 2007.

WHO Lead Poisoning and Health, Available online: http://www.who.int/en/news-room/fact-sheets/detail/lead-poisoning-and-health. (Accessed 29 June 2018).

Mayo Clinic Lead Poisoning, Available online: https://www.mayoclinic.org/diseases-conditions/lead-poisoning/symptoms-causes/syc-20354717. (Accessed 29 June 2018).

ATSDR Toxicological Profile for Lead, 2019.

ATSDR Toxicological Profile for Lead, 2007.

R. Bernhoft, Mercury toxicity and treatment: a review of the literature, J. Environ.Public Health (2012) 1–10.

IARC, WHO Beryllium, Cadmium, Mercury, and Exposures in the GlassManufacturing Industry, IARC, 1993.

G.Q. Yang, S.Z. Wang, R.H. Zhou, S.Z. Sun, Endemic selenium intoxication ofhumans in China, Am. J. Clin. Nutr. 37 (1983) 872–881.

G.J. Fosmire, Zinc toxicity, Am. J. Clin. Nutr. 51 (1990) 225–227.

ATSDR Toxicological Profile for Zinc, 2005.

ATSDR Toxicological Profile for Nickel, 2017.

E. Denkhaus, K. Salnikow, Nickel essentiality, toxicity, and carcinogenicity, Crit.Rev. Oncol. Hematol. 42 (2002) 35–56.

A.D. Sharma, Low nickel diet in dermatology, Indian J. Dermatol. 58 (2013) 240.

H.B. Bradl, Heavy Metals in the Environment: Origin, Interaction andRemediation, 1st ed.,Elsevier Academic Press, London, 2005.

D.C. Adriano, Trace Elements in Terrestrial Environments,Springer SBM, NewYork, 2001.

I.V. Babich, J.A. Moulijn, Science and technology of novel processes for deep desulfurization of oil refinery streams: a review, Fuel 82 (2003) 607–631.

S. Velu, X. Ma, C. Song, Selective adsorption for removing sulfur from jet fuel over zeolite-based adsorbents, Ind. Eng. Chem. Res. 42 (2003) 5293–5304.

S. Choi, J.H. Drese, C.W. Jones, Adsorbent materials for carbon dioxide capture from large anthropogenic point sources, ChemSusChem 2 (2009) 796–854.

J. Helminen, J. Helenius, E. Paatero, Adsorption equilibria of ammonia gas on inorganic and organic sorbents at 298.15 K, J. Chem. Eng. Data 46 (2001) 391–399.

A. Da̧browski, P. Podkos´cielny, Z. Hubicki, M. Barczak, Adsorption of phenolic compounds by activated carbon – a critical review, Chemosphere 58 (2005) 1049–1070.

K. Kadirvelu, K. Thamaraiselvi, C. Namasivayam, Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste, Bioresour. Technol. 76 (2001) 63–65.

C.Y. Yin, M.K. Aroua, W.M. Ashri, W. Daud, Review of modifications of acti- vated carbon for enhancing contaminant uptakes from aqueous solutions, Sep. Purif. Technol. 52 (2007) 403–415.

A. Zhou, X. Ma, C.S. Song, Liquid-phase adsorption of multi-ring thiophenic sulfur compounds on carbon materials with different surface properties, J. Phys. Chem. B 110 (2006) 4699–4707.

E. Deliyanni, M. Seredych, T.J. Bandosz, Interactions of 4,6- dimethyldibenzothiophene with the surface of activated carbons, Langmuir 25 (2009) 9302–9312.

E. Haque, J.W. Jun, S.N. Talapaneni, A. Vinu, S.H. Jhung, Superior adsorption capacity of mesoporous carbon nitride with basic CN framework for phenol, J. Mater. Chem. 20 (2010) 10801–10803.

Y. Wang, R.T. Yang, J.M. Heinzel, Desulfurization of jet fuel by π-complexation adsorption with metal halides supported on MCM-41 and SBA-15 meso- porous materials, Chem. Eng. Sci. 63 (2008) 356–365.

L. Zhang, W. Zhang, J. Shi, Z. Hua, Y. Li, J. Yan, A new thioether functionalized organic-inorganic mesoporous composite as a highly selective and capacious Hg2+ adsorbent, Chem. Commun. (2003) 210–221.

X. Wang, T. Sun, J. Yang, L. Zhao, J. Jia, Low-temperature H2 S removal from gas streams with SBA-15 supported ZnO nanoparticles, Chem. Eng. J. 142 (2008) 48–55.

J.-R. Li, Y. Ma, M.C. McCarthy, J. Sculley, J. Yub, H.-K. Jeong, P.B. Balbuena, H.-C. Zhou, Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks, Coord. Chem. Rev. 255 (2011) 1791–1823.

A. Samokhvalov, B.J. Tatarchuk, Review of experimental characterization of active sites and determination of molecular mechanisms of adsorption, desorption and regeneration of the deep and ultradeep desulfurization sor- bents for liquid fuels, Catal. Rev. Sci. Eng. 52 (2010) 381–410.

A.U. Czaja, N. Trukhan, U. Müller, Enantioselective catalysis with homochiral metal-organic frameworks, Chem. Soc. Rev. 38 (2009), 1284-1256.

G. Férey, Hybrid porous solids: past, present, future, Chem. Soc. Rev. 37 (2008) 191–214.

H. Li, M. Eddaoudi, M. O'Keeffe, O.M. Yaghi, Design and synthesis of an exceptionally stable and highly porous metal-organic framework, Nature 402 (1999) 276–279.

M. Eddaoudi, J. Kim, N. Rosi, D. Vodak, J. Wachter, M. O'Keeffe, O.M. Yaghi, Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage, Science 295 (2002) 469–472.

S.H. Jhung, N.A. Khan, Z. Hasan, Analogous porous metal-organic frameworks: synthesis, stability and application in adsorption, CrysEngComm 14 (2012) 7099–7109.

O.M. Yaghi, M. O'Keeffe, N.W. Ockwig, H.K. Chae, M. Eddaoudi, J. Kim, Reticular synthesis and the design of new materials, Nature 423 (2003) 705–714.

S. Kitagawa, R. Kitaura, S.-I. Noro, Functional porous coordination polymers, Angew. Chem. Int. Ed. 43 (2004) 2334–2375.

K. Sumida, D.L. Rogow, J.A. Mason, T.M. McDonald, E.D. Bloch, Z.R. Herm, T.-H. Bae, J.R. Long, Carbon dioxide capture in metal-organic frameworks, Chem. Rev. 112 (2012) 724–781.

M.P. Suh, H.J. Park, T.K. Prasad, D.-W. Lim, Hydrogen storage in metal-organic frameworks, Chem. Rev. 112 (2012) 782–835.

H. Wu, Q. Gong, D.H. Olson, J. Li, Commensurate adsorption of hydrocar- bons and alcohols in microporous metal organic frameworks, Chem. Rev. 112 (2012) 836–868.

J.-R. Li, J. Sculley, H.-C. Zhou, Metal-organic frameworks for separations, Chem. Rev. 112 (2012) 869–932.

P. Horcajada, R. Gref, T. Baati, P.K. Allan, G. Maurin, P. Couvreur, G. Férey, R.E. Morris, C. Serre, Metal-organic frameworks in biomedicine, Chem. Rev. 112 (2012) 1232–1268.
T. Uemura, N. Yanai, S. Kitagawa, Polymerization reactions in porous coordi- nation polymers, Chem. Soc. Rev. 38 (2009) 1228–1236.
M. Kurmoo, Magnetic metal-organic frameworks, Chem. Soc. Rev. 38 (2009) 1353–1379.
J.Y. Lee, O.K. Farha, J. Roberts, K.A. Scheidt, S.T. Nguyen, J.T. Hupp, Metal- organic framework materials as catalysts, Chem. Soc. Rev. 38 (2009) 1450–1459.
J. Rocha, L.D. Carlos, F.A.A. Paz, D. Ananias, Luminescent multifunctional lanthanides-based metal-organic frameworks, Chem. Soc. Rev 40 (2011) 926–940.
H. Furukawa, N. Ko, Y.B. Go, N. Aratani, S.B. Choi, Eunwoo Choi, A.Ö. Yazaydin,R.Q. Snurr, M. O'Keeffe, J. Kim, O.M. Yaghi, Ultrahigh porosity in metal-organic frameworks, Science 329 (2010) 424–428.
A.R. Millward, O.M. Yaghi, Metal organic frameworks with exceptionally high capacity for storage of carbon dioxide at room temperature, J. Am. Chem. Soc. 127 (2005) 17998–17999.
Z. Zhao, X. Li, S. Huang, Q. Xia, Z. Li, Adsorption and diffusion of ben- zene on chromium-based metal organic framework MIL-101 synthesized by microwave irradiation, Ind. Eng. Chem. Res. 50 (2011) 2254–2261.
N.A. Khan, J.W. Jun, J.H. Jeong, S.H. Jhung, Remarkable adsorptive performance of a metal-organic framework, vanadium-benzenedicarboxylate (MIL-47), for benzothiophene, Chem. Commun. 47 (2011) 1306–1308.
S.R. Caskey, A.G. Wong-Foy, A.J. Matzger, Dramatic tuning of carbon diox- ide uptake via metal substitution in a coordination polymer with cylindrical pores, J. Am. Chem. Soc. 130 (2008) 10870–10871.
T.G. Glover, G.W. Peterson, B.J. Schindler, D. Britt, O.M. Yaghi, MOF-74 building unit has a direct impact on toxic gas adsorption, Chem. Eng. Sci. 66 (2011) 163–170.
L. Hamon, C. Serre, T. Devic, T. Loiseau, F. Millange, G. Feˇırey, G.D. Weireld, Comparative study of hydrogen sulfide adsorption in the MIL-53(Al, Cr, Fe), MIL-47(V), MIL-100(Cr), and MIL-101(Cr) metal organic frameworks at room temperature, J. Am. Chem. Soc. 131 (2009) 8775–8777.
J.R. Karra, K.S. Walton, Effect of open metal sites on adsorption of polar and nonpolar molecules in metal organic framework Cu-BTC, Langmuir 24 (2008) 8620–8626.
S.-H. Huo, X.-P. Yan, Metal-organic framework MIL-100(Fe) for the adsorp- tion of malachite green from aqueous solution, J. Mater. Chem. 22 (2012) 7449–7455.
G. Blanco-Brieva, J.M. Campos-Martin, S.M. Al-Zahrani, J.L.G. Fierro, Effective- ness of metal-organic frameworks for removal of refractory organo-sulfur compound present in liquid fuels, Fuel 90 (2011) 190–197.
B. Arstad, H. Fjellvåg, K.O. Kongshaug, O. Swang, R. Blom, Amine function- alised metal organic frameworks (MOFs) as adsorbents for carbon dioxide, Adsorption 14 (2008) 755–762.
E. Haque, J.E. Lee, I.T. Jang, Y.K. Hwang, J.-S. Chang, J. Jegal, S.H. Jhung, Adsorp- tive removal of methyl orange from aqueous solution with metal-organic frameworks, porous chromium-benzenedicarboxylates, J. Hazard. Mater. 181 (2010) 535–542.
N.A. Khan, S.H. Jhung, Remarkable adsorption capacity of CuCl2 -loaded porous vanadium benzenedicarboxylate for benzothiophene, Angew. Chem. Int. Ed. 51 (2012) 1198–1201.
N.A. Khan, S.H. Jhung, Adsorptive removal of benzothiophene using porous copper-benzenetricarboxylate loaded with phosphotungstic acid, Fuel Pro- cess. Technol. 100 (2012) 49–54.
I. Ahmed, Z. Hasan, N.A. Khan, S.H. Jhung, Adsorptive denitrogenation of fuels with porous metal-organic frameworks (MOFs): effect of acidity and basicity of MOFs, Appl. Catal. B: Environ. 129 (2013) 123–129.
N.A. Khan, S.H. Jhung, Low-temperature loading of Cu+ species over porous

metal-organic frameworks (MOFs) and adsorptive desulfurization with Cu+- loaded MOFs, J. Hazard. Mater. 237–238 (2012) 180–185.

L. Hamon, H. Leclerc, A. Ghoufi, L. Oliviero, A. Travert, J.-C. Lavalley, T. Devic,

C. Serre, G. Ferey, G.D. Weireld, A. Vimont, G. Maurin, Molecular insight into the adsorption of H2 S in the flexible MIL-53(Cr) and rigid MIL-47(V) MOFs: infrared spectroscopy combined to molecular simulations, J. Phys. Chem. C 115 (2011) 2047–2056.

J.Li,X.Li,T.Hayat,A.AlsaediandC.Chen,Screening of zirconium-based metal–organic frameworks for efficient simultaneous removal of antimonite (Sb(III)) and antimonate(Sb(V))fromaqueoussolution,*ACSSustainable Chem.Eng.*,2017,5,11496–11503.

W. Yu, M. Luo, Y. Yang, H. Wu, W. Huang, K. Zeng and F. Luo,Metal-organicframework(MOF)showingboth ultrahighAs(V)andAs(III)removalfromaqueoussolution,

J.SolidStateChem.,2019,269,264–270.

C. Wang, X. Liu, J. P. Chen and K. Li, Superior removal of arsenicfromwaterwithzirconiummetal-organicframework UiO-66, *Sci. Rep.*, 2015, 5, 16613.

H.Atallah,M.ElcheikhMahmoud,A.Jelle,A.Loughand

M. Hmadeh, A highly stable indium based metal organic framework for efficient arsenic removal from water, *Dalton Trans.*, 2018, 47, 799–806.

J. Cai, X. Wang, Y. Zhou, L. Jiang and C. Wang, Selective adsorption of arsenate and the reversible structure transformation of the mesoporous metal–organicframework MIL-100(Fe), *Phys. Chem. Chem. Phys.*, 2016, 18, 10864–10867.

Y.-n. Wu, M. Zhou, B. Zhang, B. Wu, J. Li, J. Qiao, X. Guan and F. Li, Amino acid assisted templating synthesis of hierarchical zeolitic imidazolate framework-8 for efficient arsenate removal, *Nanoscale*, 2014, 6, 1105–1112.

J. Sun, X. Zhang, A. Zhang and C. Liao, Preparation of Fe–CobasedMOF-74anditseffectiveadsorptionofarsenic from aqueous solution, *J. Environ. Sci.*, 2019, 80, 197–207.

C. O. Audu, H. G. T. Nguyen, C.-Y. Chang, M. J. Katz, L. Mao, O. K. Farha, J. T. Hupp and S. T. Nguyen, The dual capture of As(V) and As(III) by UiO-66 and analogues, *Chem. Sci.*, 2016, 7, 6492–6498.

C. Kang, Y. Peng, Y. Tang, H. Huang and C. Zhong, Sulfate- richmetal–organicframeworkforhighefficiencyandselective removal of barium from nuclear wastewater, *Ind.Eng. Chem. Res.*, 2017, 56, 13866–13873.

Y. Peng, H. Huang, D. Liu and C. Zhong, Radioactive barium ion trap based on metal–organic framework for efficient and irreversible removal of barium from nuclear wastewater, ACS *Appl.Mater.Interfaces*,2016,8,8527–8535.

Y. Peng, H. Huang, Y. Zhang, C. Kang, S. Chen, L. Song, D. LiuandC.Zhong,AversatileMOF-basedtrapforheavymetal ion capture and dispersion, *Nat. Commun.*, 2018, 9, 187.

H. Xue, Q. Chen, F. Jiang, D. Yuan, G. Lv, L. Liang, L. Liu and M. Hong, A regenerative metal-organic framework for reversible uptake of Cd(II): From effective adsorption to insitu detection, *Chem. Sci.*, 2016, 7, 5983–5988.

K. Wang, J. Gu and N. Yin, Efficient removal of Pb(II) and Cd(II) Using NH_2-functionalized Zr-MOFs via rapid microwave-promoted synthesis, *Ind. Eng. Chem. Res.*,2017, 56, 1880–1887.

Y. Wang, G. Ye, H. Chen, X. Hu, Z. Niu and S. Ma, Functionalized metal–organic framework as a new platformfor efficient and selective removal of cadmium(II) from aqueous solution, *J. Mater. Chem. A*, 2015, 3, 15292–15298.

H. Saleem, U. Rafique and R. P. Davies, Investigations onpost-synthetically modified UiO-66-NH_2 for the adsorptive removal of heavy metal ions from aqueous solution, *Microporous Mesoporous Mater.*, 2016, 221, 238–244.

E. Tahmasebi, M. Y. Masoomi, Y. Yamini and A. Morsali, Application of mechanosynthesized azine-decorated zinc(II) metal–organic frameworks for highly efficient removal and extractionofsomeheavy-metalionsfromaqueoussamples: A comparative study, *Inorg. Chem.*, 2015, 54, 425–433.

H. Niu, Y. Zheng, S. Wang, S. He and Y. Cai, Stable hierarchicalmicrospheresof1DFe–gallicacidMOFsfor fast and efficient Cr(VI) elimination by a combination of reduction, metal substitution and coprecipitation, *J. Mater. Chem. A*, 2017, 5, 16600–16604.

Q. Zhang, J. Yu, J. Cai, L. Zhang, Y. Cui, Y. Yang, B. Chen and G. Qian, A porous Zr-cluster-based cationic metal–organicframeworkforhighlyefficient$Cr_2O_7^{2-}$removalfromwater,*Chem.Commun.*,2015,51,14732–14734.

S.-Q.Deng,X.-J.Mo,S.-R.Zheng,X.Jin,Y.Gao,S.-L.Cai, J.Fan and W.-G. Zhang, Hydrolytically stable nanotubular cationic metal–organic framework for rapid and efficient removal of toxic oxo-anions and dyes from water, *Inorg. Chem.*, 2019, 58, 2899–2909.

H.-R. Fu, Z.-X. Xu and J. Zhang, Water-stable metal–organic frameworksforfastandhighdichromatetrappingvia single-crystal-to-Single-crystal ion exchange, *Chem. Mater.*, 2015, 27, 205–210.

H. Fei, C. S. Han, J. C. Robins and S. R. J. Oliver, A Cationic metal–organic solid solution based on Co(II) and Zn(II) for chromate trapping, *Chem. Mater.*, 2013, 25, 647–652.

P.-F. Shi, B. Zhao, G. Xiong, Y.-L. Hou and P. Cheng, Fast capture and separation of, and luminescent probe for, pollutant chromate using a multi-functional cationic heterometal-organicframework,*Chem.Commun.*,2012, 48,8231–8233.

H. Fei, M. R. Bresler and S. R. J. Oliver, A new Paradigm for Anion trapping in high capacity and selectivity: Crystal-to- crystal transformation of cationic materials, *J. Am. Chem.Soc.*, 2011, 133, 11110–11113.

A. Maleki, B. Hayati, M. Naghizadeh and S. W. Joo, Adsorption of hexavalent chromium by metal organic frameworksfromaqueoussolution,*J.Ind.Eng.Chem.*, 2015, 28, 211–216.

L.-L. Li, X.-Q. Feng, R.-P. Han, S.-Q. Zang and G. Yang, Cr(VI) removal via anion exchange on a silver-triazolateMOF, *J. Hazard. Mater.*, 2017, 321, 622–628.

Y. Huang, X. Zeng, L. Guo, J. Lan, L. Zhang and D. Cao, Heavy metal ion removal of wastewater by zeolite-imidazolate frameworks, *Sep. Purif. Technol.*, 2018, 194, 462–469.

X.Luo,L.DingandJ.Luo,AdsorptiveremovalofPb(II) ions from aqueous samples with amino-functionalization of metal–organic frameworks MIL-101(Cr), *J. Chem. Eng. Data*, 2015, 60, 1732–1743.

L.Bai,B.Tu,Y.Qi,Q.Gao,D.Liu,Z.Liu,L.Zhao,Q.Li and Y. Zhao, Enhanced performance in gas adsorption and Li ion batteries by docking Li^+ in a crown ether-based metal–organicframework,*Chem.Commun.*,2016,52, 3003–3006.

N.D.Rudd,Y.Liu,K.Tan,F.Chen,Y.J.ChabalandJ.Li, Luminescent metal–organic framework for lithium harvesting applications, *ACS Sustainable Chem. Eng.*,2019, 7, 6561–6568.

R. Ou, H. Zhang, J.Wei,S.Kim, L.Wan, N. S.Nguyen, Y. Hu,X.Zhang,G.P.SimonandH.Wang,Thermoresponsive amphoteric metal–organic frameworks for efficient and reversible adsorption of multiple salts from water, *Adv. Mater.*, 2018, 30, 1802767.

M. Mon, F. Lloret, J. Ferrando-Soria, C. Martí-Gastaldo, D. ArmentanoandE.Pardo,Selectiveandefficientremovalofmercuryfromaqueousmediawiththehighlyflexible arms of a BioMOF, *Angew. Chem., Int. Ed.*, 2016, 55, 11167–11172.

K.-K.Yee,N.Reimer,J.Liu,S.-Y.Cheng,S.-M.Yiu,J.Weber, N. Stock and Z. Xu, Effective mercury sorption by thiol- laced metal–organic frameworks: In strong acid and the vaporphase,*J.Am.Chem.Soc.*,2013,135,7795–7798.

X. Luo, T. Shen, L. Ding, W. Zhong, J. Luo and S. Luo,Novel thymine-functionalized MIL-101 prepared by post-synthesisandenhancedremovalofHg^{2+}fromwater,*J.Hazard.Mater.*,2016,306,313–322.

S. Bhattacharjee, Y.-R. Lee and W.-S. Ahn, Post-synthesis functionalizationofazeoliticimidazolatestructureZIF-90: A study on removal of Hg(II) from water and epoxidation of alkenes, *CrystEngComm*, 2015, 17, 2575–2582.

A.J.Howarth,M.J.Katz,T.C.Wang,A.E.Platero-Prats,K.W.Chapman,J.T.HuppandO.K.Farha,High efficiency adsorption and removal of selenate and selenitefrom water using metal–organic frameworks, *J. Am. Chem. Soc.*, 2015, 137, 7488–7494.

J. Wei, W. Zhang, W. Pan, C. Li and W. Sun, ExperimentalandtheoreticalinvestigationsonSe(IV)andSe(VI) adsorption to UiO-66-based metal–organic frameworks, *Environ. Sci.: Nano*, 2018, 5, 1441–1453.

J. Li, Y. Liu, X. Wang, G. Zhao, Y. Ai, B. Han, T. Wen, T. Hayat,A.AlsaediandX.Wang,Experimentaland theoretical study on selenate uptake to zirconium metal– organic frameworks: Effect of defects and ligands, *Chem.Eng. J.*, 2017, 330, 1012–1021.

N. Zhang, L.-Y. Yuan, W.-L. Guo, S.-Z. Luo, Z.-F. Chai and W.-Q. Shi, Extending the use of highly porous and functionalized MOFs to Th(IV) capture, *ACS Appl. Mater. Interfaces*, 2017, 9, 25216–25224.

X.-G. Guo, S. Qiu, X. Chen, Y. Gong and X. Sun, Postsynthesis modification of a metallosalen-containing metal–organic framework for selective Th(IV)/Ln(III) separation, *Inorg. Chem.*, 2017, 56, 12357–12361.

Y. Feng, H. Jiang, S. Li, J. Wang, X. Jing, Y. Wang and M. Chen,Metal–organicframeworksHKUST-1forliquid- phase adsorption of uranium, *Colloids Surf.*, A, 2013, 431, 87–92.

Z.-Q.Bai,L.-Y.Yuan,L.Zhu,Z.-R.Liu,S.-Q.Chu,L.-R.

Zheng, J. Zhang, Z.-F. Chai and W.-Q. Shi, Introduction of amino groups into acid-resistant MOFs for enhanced U(VI) sorption, *J. Mater. Chem. A*, 2015, 3, 525–534.

W.Yang,Z.-Q.Bai,W.-Q.Shi,L.-Y.Yuan,T.Tian,Z.-F.Chai,

H.WangandZ.-M.Sun,MOF-76:Fromaluminescent probe to highly efficient U(VI) sorption material, *Chem. Commun.*, 2013, 49, 10415–10417.

M. Carboni, C. W. Abney, S. Liu and W. Lin, Highly porous andstablemetal–organicframeworksforuranium extraction, *Chem. Sci.*, 2013, 4, 2396–2402.

W. Lu, Z. Wei, Z.-Y. Gu, T.-F. Liu, J. Park, J. Park, J. Tian, M. Zhang, Q. Zhang, T. Gentle III, Chem. Soc. Rev. 43 (2014) 5561–5593.

N.A. Khan, Z. Hasan, S.H. Jhung, J. Hazard. Mater. 244 (2013) 444–456.

E.M. Dias, C. Petit, J. Mater. Chem. A 3 (2015) 22484–22506.

Z. Hasan, S.H. Jhung, J. Hazard. Mater. 283 (2015) 329–339.

Z. Hasan, J. Jeon, S.H. Jhung, J. Hazard. Mater. 209 (2012) 151–157.N.A. Khan, B.K. Jung, Z. Hasan, S.H. Jhung, J. Hazard. Mater. 282 (2015) 194– 200.

J.W. Jun, M. Tong, B.K. Jung, Z. Hasan, C. Zhong, S.H. Jhung, Chem. Eur. J. 21 (2015) 347–354.

K.-Y.A. Lin, H. Yang, C. Petit, F.-K. Hsu, Chem. Eng. J. 249 (2014) 293–301.

Liu, L., Oza, S., Hogan, D., Perin, J., Rudan, I., Lawn, J. E., ... & Black, R. E. (2015). Global, regional, and national causes of child mortality in 2000–13, with projections to inform post-2015 priorities: an updated systematic analysis. *The lancet*, *385*(9966), 430-440.

Wen, J., Fang, Y., & Zeng, G. (2018). Progress and prospect of adsorptive removal of heavy metal ions from aqueous solution using metal–organic frameworks: a review of studies from the last decade. *Chemosphere*, *201*, 627-643.

Moradi, A., & Rahmani, K. (2014). Trend of traffic accidents and fatalities in Iran over 20 years (1993-2013). *Journal of Mazandaran University of Medical Sciences*, *24*(119), 223-234.

Tahmasebi, P., Javadpour, F., & Sahimi, M. (2015). Three-dimensional stochastic characterization of shale SEM images. *Transport in Porous Media*, *110*, 521-531.

Ahmed, I., & Jhung, S. H. (2016). Adsorptive desulfurization and denitrogenation using metal-organic frameworks. *Journal of Hazardous materials*, *301*, 259-276.

Liu, E. K., He, W. Q., & Yan, C. R. (2014). 'White revolution'to 'white pollution'—agricultural plastic film mulch in China. *Environmental Research Letters*, *9*(9), 091001.

Hasan, Z., & Jhung, S. H. (2015). Removal of hazardous organics from water using metal-organic frameworks (MOFs): Plausible mechanisms for selective adsorptions. *Journal of hazardous materials*, *283*, 329-339.

Shiha, G., Ibrahim, A., Helmy, A., Sarin, S. K., Omata, M., Kumar, A., ... & Kumar, M. (2017). Asian-Pacific Association for the Study of the Liver (APASL) consensus guidelines on invasive and non-invasive assessment of hepatic fibrosis: a 2016 update. *Hepatology international*, *11*, 1-30.

Zhang, J., Terrones, M., Park, C. R., Mukherjee, R., Monthioux, M., Koratkar, N., ... & Bianco, A. (2016). Carbon science in 2016: Status, challenges and perspectives. *Carbon*, *98*, 708-732.