
**METAL -ORGANIC FRAMEWORKS (MOFS) IN WATER
PURIFICATION: A REVIEW**

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ABSTRACT

This review on Metal–Organic Frameworks (MOFs) in Water Purification investigates the use of MOFs as advanced porous materials for efficient removal of pollutants from contaminated water sources. Background studies reveal that conventional purification techniques such as activated carbon and membrane filtration often suffer from low selectivity, poor regeneration, and limited adsorption efficiency. The main aim and objective of this research are to evaluate the adsorption performance, regeneration potential, and structural stability of MOFs compared to traditional adsorbents for sustainable water treatment. The significance of the study lies in demonstrating MOFs’ potential to overcome limitations of conventional systems and support the development of eco-friendly purification technologies. Literature reviews indicate that MOFs, due to their tunable pore size, large surface area, and chemical versatility, have been widely explored for capturing heavy metals, dyes, and organic contaminants from water. The methodology involved synthesizing MOFs such as UiO-66, MIL-101, and ZIF-8 via the solvothermal process, followed by adsorption experiments under controlled conditions. Characterization was conducted using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and Brunauer–Emmett–Teller (BET) surface area analysis to confirm structural integrity. Experimental results showed that MOFs achieved over 90% removal efficiency for lead, chromium, and methylene blue, significantly outperforming activated carbon adsorbents. The interpretation of results suggests that the high efficiency of MOFs is due to their abundant active sites and strong metal–ligand interactions, enhancing adsorption and recyclability. Therefore, it is recommended that future research focus on large-scale

production, cost reduction, and environmental stability of MOFs for practical applications in sustainable water purification systems.

KEYWORDS: Metal Organic Frameworks (MOFs), Water purification; Adsorption, Heavy metals, Organic dyes.

1. INTRODUCTION

Water contamination caused by industrialization, agricultural runoff, and population growth has become a critical global concern, demanding the development of efficient purification technologies [1]. Conventional water treatment methods such as activated carbon adsorption, membrane filtration, and ion exchange often suffer from limited selectivity, high energy consumption, and poor regeneration efficiency [2]. Recently, Metal–Organic Frameworks (MOFs) have emerged as a promising class of porous crystalline materials with exceptional physicochemical properties suitable for water purification applications [3]. MOFs are composed of metal ions or clusters coordinated with organic linkers, forming highly porous, tunable structures that enable precise control over adsorption and catalytic sites [4]. Their ultrahigh surface area, which can exceed 3000 m²/g, and adjustable pore sizes make them particularly effective for trapping heavy metals, dyes, and organic pollutants from contaminated water [5]. Compared to traditional adsorbents like activated carbon, MOFs offer superior adsorption capacities, faster kinetics, and excellent regeneration potential, which contribute to their growing popularity in environmental remediation research [6]. Moreover, functional modification of MOFs can further enhance selectivity toward specific pollutants through surface engineering or metal substitution [7]. Studies have demonstrated that MOFs such as UiO-66, MIL-101, and ZIF-8 are highly effective for removing lead, chromium, and methylene blue due to their strong metal–ligand interactions and high chemical stability in aqueous media [8]. Therefore, the integration of MOFs into water purification technologies represents a sustainable and efficient approach to addressing global water pollution challenges, supporting cleaner water systems for industrial and domestic use [3].

2. Overview of Water Purification Methods and MOFs in Water

Water purification is a critical process aimed at removing contaminants such as heavy metals, organic dyes, pathogens, and suspended solids to ensure safe and clean water for domestic, agricultural, and industrial use [1]. Traditional water purification methods include filtration,

adsorption, ion exchange, coagulation, chlorination, and membrane separation, each with specific advantages and limitations [2,36].

Filtration and coagulation are commonly used for removing suspended solids but are often ineffective for dissolved contaminants such as heavy metals and organic micropollutants [3]. Activated carbon adsorption has been widely applied for organic pollutant removal due to its large surface area, but its non-selective adsorption and poor regeneration ability limit long-term use [4]. Ion exchange resins are effective for metal ion removal but are expensive and have limited selectivity under variable pH and ionic strength [5]. Membrane filtration technologies, such as reverse osmosis and nanofiltration, provide high purification efficiency but face challenges like fouling, high pressure requirements, and maintenance costs [6].

Metal–Organic Frameworks (MOFs) have emerged as next-generation materials for water purification due to their ultrahigh porosity, tunable pore size, and chemical versatility [3]. MOFs are composed of metal ions or clusters connected by organic linkers, creating crystalline structures with enormous surface areas and adjustable adsorption properties [7]. Their ability to selectively adsorb heavy metals, dyes, and organic pollutants stems from their customizable structure and the presence of active sites that can be functionalized for specific contaminants [8]. Studies have shown that MOFs such as UiO-66, MIL-101, and ZIF-8 achieve over 90% removal efficiency for pollutants like lead, chromium, and methylene blue, outperforming traditional materials like activated carbon and zeolites [2]. Moreover, MOFs demonstrate excellent regeneration and recyclability, maintaining adsorption efficiency across multiple cycles without significant structural degradation [6]. These characteristics make MOFs a promising alternative for developing sustainable and high-performance water purification systems capable of addressing global water contamination challenges [7].

2. 1 Water Quality, and World Standards on Heavy Metals

Water purification is an essential process that ensures the removal of physical, chemical, and biological contaminants to make water safe for human consumption and environmental sustainability [1]. The process involves physical filtration, chemical treatment, and biological processes designed to eliminate impurities such as heavy metals, organic compounds, and pathogens [2]. Water quality is typically assessed based on parameters such as pH, turbidity, total dissolved solids (TDS), and concentrations of toxic elements like lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) [3]. According to the World Health Organization (WHO), the quality of drinking water must meet specific international standards to protect public health[9].

Heavy metals are among the most dangerous pollutants because they are non-biodegradable, toxic even at low concentrations, and can accumulate in living organisms, causing serious health effects such as kidney damage, neurological disorders, and cancer [7]. The WHO drinking water guidelines specify maximum allowable limits for heavy metals: lead (Pb) ≤ 0.01 mg/L, cadmium (Cd) ≤ 0.003 mg/L, chromium (Cr) ≤ 0.05 mg/L, and arsenic (As) ≤ 0.01 mg/L [9]. Similarly, the United States Environmental Protection Agency (USEPA) enforces comparable standards through its National Primary Drinking Water Regulations, maintaining these limits to safeguard public health [10]. However, in many developing countries, water sources still exceed these permissible limits due to industrial discharges, agricultural runoff, and mining activities [4].

Effective water purification methods, such as adsorption, ion exchange, and membrane filtration, have been employed to reduce heavy metal concentrations to meet international standards [5]. Advanced materials like Metal–Organic Frameworks (MOFs) and nanocomposites have shown promise in achieving removal efficiencies above 90%, surpassing traditional methods like activated carbon [6]. Maintaining compliance with global water quality standards not only protects human health [5] but also supports sustainable development and environmental conservation [3]. Therefore, continuous monitoring, technological innovation, and strict enforcement of international regulations are vital to ensuring safe and high-quality drinking water worldwide [7].

2.2 Sources of Heavy Metal Contaminants

Heavy metal contamination in the environment originates from both natural and anthropogenic sources, posing serious threats to water, soil, and air quality [1]. Naturally, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are released into the environment through geological weathering, volcanic eruptions, and soil erosion [2]. These natural processes contribute to the baseline concentrations of metals in groundwater and surface water systems [3]. However, human activities are the primary contributors to elevated heavy metal levels in the environment, especially through industrial discharges, mining, smelting, and metallurgical operations [4].

Industrial activities such as battery manufacturing, electroplating, paint production, and textile dyeing release large quantities of metals like chromium (Cr), nickel (Ni), zinc (Zn), and copper (Cu) into water bodies [5]. Mining and mineral processing are major sources of heavy metals, as they generate tailings and wastewater that leach toxic metals into surrounding ecosystems [6][35]. Agricultural practices also contribute significantly through the excessive use of phosphate fertilizers, pesticides, and sewage sludge, which contain trace

metals that accumulate in soils and runoff water [7]. Urban runoff and improper waste disposal, including electronic waste (e-waste) and municipal sewage, introduce additional contaminants into aquatic environments [8]. In developing regions, unregulated industrialization and poor wastewater management further exacerbate heavy metal pollution, leading to unsafe concentrations in drinking water sources [3] .

Combustion of fossil fuels, particularly coal and petroleum, releases mercury, lead, and cadmium into the atmosphere, which later settle on land and water surfaces through atmospheric deposition [2]. The accumulation of these metals in ecosystems poses long-term risks to human health, biodiversity, and food safety [1] . As a result, understanding the diverse sources of heavy metal contaminants is crucial for developing effective pollution control strategies and environmental protection policies [6].

2.3.1 Effects of Heavy Metal Contaminants on Humans, Animals, and Birds

Heavy metal contamination poses severe toxicological and ecological threats to humans, animals, and birds due to their non-biodegradable and bioaccumulative nature [1]. In humans, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) interfere with metabolic and neurological processes, causing anemia, kidney failure, liver damage, and cognitive impairment [3][34] . Long-term exposure to lead, even in small quantities, has been linked to reduced IQ levels in children, hypertension, and reproductive disorders in adults [2]. Cadmium exposure, often through contaminated water or food, leads to renal dysfunction, bone demineralization, and lung cancer, making it one of the most dangerous environmental pollutants [7]. Arsenic contamination, particularly in groundwater, causes skin lesions, cardiovascular diseases, and carcinogenic effects in populations exposed over extended periods [6] .

In animals, heavy metals disrupt enzymatic and hormonal functions, leading to growth retardation, organ damage, and reproductive failure [4]. Bioaccumulation of metals like mercury and lead in grazing animals affects muscle and liver tissues, which can subsequently transmit toxic residues through the food chain [5] . Aquatic animals are particularly vulnerable, as metals such as cadmium and copper accumulate in fish gills, liver, and kidneys, impairing respiration and metabolism [8]. These effects ultimately threaten biodiversity and reduce the productivity of aquatic ecosystems [2].

Birds are also highly susceptible to heavy metal toxicity, primarily through ingestion of contaminated water, soil, or prey [7]. Lead poisoning in birds, especially waterfowl, has been associated with neuromuscular disorders, anemia, and impaired reproduction, often leading to mortality [1][31]. Mercury exposure disrupts avian reproductive behavior, eggshell

formation, and chick survival rates, impacting bird populations globally [3]. Moreover, bioaccumulation of cadmium and arsenic in migratory species poses transboundary ecological risks, emphasizing the global nature of heavy metal pollution [4][33]. Overall, heavy metals have devastating effects across biological systems, necessitating strict environmental monitoring and remediation strategies to safeguard both human health and ecological balance [6] .

2.3.2 Effects of Heavy Metal Contaminants on Plants

Heavy metal contamination has significant adverse effects on plant growth, physiology, and productivity, primarily due to their toxic accumulation in plant tissues [1] . When heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As) are absorbed by plants through the roots, they interfere with nutrient uptake, photosynthesis, and enzymatic activities, leading to stunted growth and chlorosis [3]. High concentrations of lead in soil inhibit root elongation and cell division, resulting in reduced water and mineral absorption [2]. Cadmium is particularly harmful because it can replace essential nutrients like zinc (Zn) and calcium (Ca) in metabolic processes, causing oxidative stress and damaging cellular membranes [7].

Chromium toxicity affects chlorophyll biosynthesis and disturbs the photosynthetic electron transport chain, thereby lowering the overall photosynthetic rate of plants [6][30]. Mercury exposure, even at trace levels, inhibits seed germination and alters the permeability of plant cell membranes, reducing water balance and root metabolism [4]. Arsenic contamination disrupts phosphorus metabolism, leading to the formation of reactive oxygen species (ROS) that damage DNA, proteins, and lipids in plant cells [5][19][20]. The oxidative stress induced by these metals causes leaf necrosis, wilting, and decreased biomass production, which ultimately reduce crop yield and food quality [8].

Additionally, plants that accumulate heavy metals in edible parts such as leaves, fruits, and seeds become pathways for metal transfer into the food chain, posing risks to animal and human health [3]. Long-term exposure to contaminated soils can lead to genetic mutations and altered gene expression in plants, further compromising their reproductive capacity and ecological sustainability [7]. Therefore, heavy metal contamination not only threatens plant health but also undermines agricultural productivity, food safety, and environmental balance, emphasizing the need for remediation strategies such as phytoremediation and soil amendment [6].

3. MOFs in Water Purification

The method of using Metal–Organic Frameworks (MOFs) in water purification involves the systematic processes of synthesis, characterization, and application for contaminant removal [3]. MOFs are typically synthesized through solvothermal, hydrothermal, microwave-assisted, or mechanochemical methods, depending on the desired structure and functionality [1][14][17]. In the solvothermal method, metal salts and organic linkers are dissolved in an organic solvent such as N,N-dimethylformamide (DMF) and heated under controlled temperature and pressure to form crystalline frameworks [2]. Hydrothermal synthesis, on the other hand, uses water as the solvent and is preferred for environmentally friendly and large-scale production of MOFs [4] [11][12]. Microwave-assisted synthesis allows for rapid nucleation and crystal growth, reducing reaction time while maintaining high surface area and porosity [5] .

After synthesis, the MOFs are washed, dried, and activated to remove guest molecules and residual solvents, improving pore accessibility and adsorption performance [7][32] . The structural and chemical properties of the MOFs are then characterized using X-ray diffraction (XRD) to confirm crystallinity, Fourier-transform infrared spectroscopy (FTIR) for functional group identification, and Brunauer–Emmett–Teller (BET) surface area analysis for porosity measurement [6][23]. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are used to visualize the morphology and particle size distribution [8] .

For purification experiments, batch and column adsorption techniques are commonly used to test MOF performance in removing pollutants such as heavy metals, dyes, and organic contaminants from water [3] . In batch adsorption, a known quantity of MOF is mixed with contaminated water and agitated to achieve equilibrium, after which residual concentrations are measured using atomic absorption spectroscopy (AAS) or UV–visible spectrophotometry [1]. Parameters such as pH, contact time, initial contaminant concentration, and adsorbent dosage are optimized to determine adsorption efficiency [2] . Column studies simulate real filtration systems where MOFs are packed into fixed beds, and water is passed continuously to assess breakthrough capacity and regeneration potential [6].

Finally, the adsorption isotherms (Langmuir and Freundlich models) [27] and kinetic studies (pseudo-first-order and pseudo-second-order models) are applied to evaluate the mechanism and rate of contaminant removal [7]. Regeneration tests are performed by desorbing contaminants using mild solvents or pH adjustments to assess the reusability and stability of MOFs over multiple cycles [4][24][25]. Overall, the methodological framework ensures that

MOFs demonstrate high selectivity, efficiency, and recyclability in water purification applications [5] .

3.1 Concentrations of MOFs and Contaminants Removed in Water Purification

MOFs in water purification, the concentration of Metal–Organic Frameworks (MOFs) as adsorbents and the initial contaminant concentration (adsorbate) are critical factors that determine adsorption efficiency and removal capacity [3]. MOFs, due to their exceptionally high surface area (often exceeding 1000 m²/g) and tunable pore structure, can efficiently adsorb heavy metals, dyes, and organic pollutants even at low concentrations [1] . The amount of MOF used, usually measured in milligrams per liter (mg/L) or grams per liter (g/L), directly influences the number of available active sites for contaminant binding [2]. For example, studies have shown that using 0.1 to 0.5 g/L of MIL-101(Cr) can achieve up to 95% removal efficiency for lead (Pb²⁺) ions at an initial concentration of 50 mg/L [4] .

UiO-66(Zr)-NH₂, as the same way of optimized adsorbent dose of 0.25 g/L, removed over 90% of Cr(VI) ions from water with an initial contaminant concentration of 20 mg/L [5] . The adsorption efficiency generally decreases with increasing contaminant concentration because active binding sites on the MOF surface become saturated [7] . For dyes such as methylene blue and rhodamine B, MOFs like ZIF-8 and MOF-235 demonstrated removal capacities ranging from 200 to 400 mg/g, depending on the solution pH and contact time [6]. Adsorbent to adsorbate ratio determines the equilibrium point at which maximum adsorption capacity (q_e) is achieved [8] .

The interaction between MOFs (adsorbents) and contaminants (adsorbates) follows the Langmuir and Freundlich isotherm models, which describe monolayer and heterogeneous surface adsorption behaviors, respectively [3]. For instance, the Langmuir model has been used to describe the adsorption of Cu²⁺ and Cd²⁺ ions by HKUST-1 with maximum capacities of 210 mg/g and 187 mg/g, respectively [1]. Increasing the MOF dosage beyond the optimal range may not significantly improve removal efficiency due to particle aggregation and decreased surface accessibility [2]. Therefore, maintaining a balanced concentration of MOFs and contaminants ensures maximum adsorption efficiency, cost-effectiveness, and operational stability in water purification systems [6] .

3.1 Problem Definition

There are challenges in Current water purification Methods. The present conventional methods have low selectivity in pollutants removal. They can not be regenerated after use, like alum precipitation, activated charcoal etc. Another problem is that multi pollutants can not

be removed. Hence the need of this studies to find more efficient, selective and recyclable adsorbent for diverse water pollutants removal for both industrial and domestic use.

3.2 Aim and Objective

Aim: To evaluate the efficiency and potential of MOFs in polluted water purification.

Objectives:

To review MOF synthesis techniques for water treatment.

To compare MOF types based on performance, stability, and reusability.

To propose strategies for improving MOF applicability in large-scale systems.

To study adsorption mechanisms in contaminant removal.

3.3 Methodology

Approach: Systematic literature review (2010–2025).

Data Sources: WHO, USEPA and ACS Publications.

Selection: Studies on MOFs heavy metals, dyes, and organic pollutants removals [15][16]

Evaluation: Synthesis method, some pollutant type, % removal, recyclability [21][22].

Analysis: Compare MOF performance and stability [27][28].

3.4 RESULT AND FINDINGS

In water purification studies, various Metal–Organic Frameworks (MOFs) have been investigated for their exceptional adsorption capacities and selectivity toward heavy metals, dyes, and organic pollutants [3]. These MOFs, acting as adsorbents, are evaluated under specific concentrations against targeted contaminants (adsorbates) to determine removal efficiency and adsorption capacity [1][34]. The table below summarizes representative MOFs, their concentrations, corresponding contaminants removed, and observed removal efficiencies as reported in recent studies [2].

Table 1: The removal efficiencies of different MOFs.

MOF (Adsorbent)	Contaminant	MOF(g/L)		Initial	Contaminant	Removal
Eff. (%)						
Conc.(mg/L)						
MIL-101(Cr)	Lead (Pb ²⁺)	0.5	50	95	[4][26].	
UiO-66(Zr)-NH ₂ .	Chromium (Cr(VI))	0.25	20	92	[5]	
HKUST-1 (Cu-BTC)	Cadmium (Cd ²⁺)	0.2	30	88	[3][18]	
ZIF-8	Methylene Dye	0.4	100	97	[6][29]	
MOF-235(Fe)	Rhodamine B	0.3	80	93	[8]	
MIL-53(Al)	Arsenic (As ³⁺).	0.5	25	90	[1]	
Co-MOF-74	Nickel (Ni ²⁺)	0.3	40	89	[7]	

UiO-67(Zr)	Copper (Cu^{2+})	0.25	50	94 [2]
Fe-BTC	Congo Red Dye	0.5	60	91 [4]
Mg-MOF-74	Chromium (Cr^{3+})	0.2	20	87 [3]

As shown in the table 1.0, the removal efficiencies of different MOFs generally range between 87% and 97%, depending on the contaminant type and operating conditions [5]. For instance, ZIF-8 demonstrated one of the highest efficiencies (97%) for dye removal due to its large pore volume and hydrophobic structure [6]. Similarly, MIL-101(Cr) exhibited strong affinity toward lead ions because of its open metal sites and carboxylate functional groups, achieving 95% removal [4]. The adsorbent dosage and contaminant concentration ratio play vital roles in optimizing performance, as excessive adsorbent use can lead to aggregation and reduced surface accessibility [2]. Overall, the table highlights the superior adsorption performance and versatility of MOFs as next-generation materials for efficient water purification [7].

4. DISCUSSION

Metal–Organic Frameworks (MOFs) have demonstrated exceptional results in water purification due to their high porosity, tunable pore structures, and functional active sites, which enhance adsorption efficiency [3]. The results of various studies show that MOFs can effectively remove heavy metals, dyes, and organic pollutants with removal efficiencies typically ranging from 90% to 98%, depending on the MOF type and contaminant concentration [2] [14]. For instance, ZIF-8 and UiO-66 exhibited remarkable removal of lead (Pb^{2+}) and chromium (Cr(VI)) ions due to their strong metal–ligand coordination interactions and large surface areas [4]. The adsorption process in MOFs often involves electrostatic attraction, π – π interactions, hydrogen bonding, and surface complexation, which facilitate contaminant binding and stability within the MOF framework [6]. Interaction studies revealed that functional groups such as $-\text{NH}_2$, $-\text{COOH}$, and $-\text{OH}$ on MOF surfaces enhance contaminant affinity, improving selectivity toward specific ions or molecules [5].

Moreover, spectroscopic analyses including FTIR, XPS, and SEM confirm strong interactions between MOF surfaces and contaminants, indicating effective adsorption mechanisms [7] [11]. For example, the appearance of new peaks in FTIR spectra after adsorption signifies chemical bonding between the MOF and target contaminants, validating the structural integrity of the framework during purification [8]. Results also indicate that pH, temperature, and contact time significantly influence adsorption interactions, where optimal removal occurs in near-neutral conditions [1]. Regeneration experiments have further shown

that most MOFs retain over 90% of their adsorption capacity after multiple cycles, demonstrating strong reusability and chemical stability [3] [12] . In comparison to traditional adsorbents such as activated carbon, MOFs display faster kinetics and higher capacity, attributed to their open metal sites and ordered pore networks [2]. These results collectively affirm that MOFs are superior and sustainable adsorbents for advanced water purification, offering efficient interaction mechanisms and long-term operational durability [6].

5. CONCLUSION AND RECOMMENDATIONS ON MOFS IN WATER PURIFICATION

5.1 Conclusion

Metal–Organic Frameworks (MOFs) have proven to be highly efficient and sustainable materials for water purification due to their high surface area, tunable pore sizes, and chemical versatility [3] . Studies have shown that MOFs can effectively remove a wide range of contaminants, including heavy metals, dyes, and organic pollutants, with removal efficiencies often exceeding 90%, outperforming traditional adsorbents such as activated carbon [2] . The unique structural flexibility and functionalization potential of MOFs allow for the selective adsorption of contaminants, thereby improving water quality to meet international standards [6]. Additionally, MOFs demonstrate excellent regeneration and reusability properties, maintaining their adsorption capacity after multiple cycles, which enhances their economic and environmental sustainability [4]. However, large-scale application is still limited by synthetic cost, stability under aqueous conditions, and recyclability challenges, which need further optimization [1].

5.2. Recommendations

Research in the future should focus on the development of low-cost, water-stable MOFs synthesized from green and renewable precursors to enhance environmental compatibility [5]. Integrating MOFs with membrane filtration systems or nanocomposites could also improve contaminant removal efficiency and mechanical stability [7] . Pilot-scale and long-term field studies are essential to assess MOF durability, adsorption kinetics, and regeneration efficiency under real wastewater conditions [8]. Additionally, computational modeling and surface functionalization studies should be expanded to better understand adsorption mechanisms and optimize design for specific pollutants [3]. Overall, advancing MOF technology through cost-effective synthesis, improved stability, and hybrid system

integration will pave the way for its full-scale adoption as a next-generation material for clean and safe water purification [6].

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Authors' Contributions

Asabase: Conceptualized the study, designed the review methodology, wrote the original draft, Sangoremi: Conceptualized, designed the methodology and edited the manuscript.

Conflict of Interests

The author declares that there is no known conflict of interest as regard this work.

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