Vindhyan Bloom

ISSN-2319-8478
Vol-15 Issue-3, June 2026

A Referred Peer Review Research Journal

Vindhyan Bloom

ISSN-2319-8478 Vol-15 Issue-3, June 2026

Manuscript Information	*Research Paper*	*Paper No. VBRP-08*

ZIF-8 Functional Materials for Water Purification: Towards Sustainable and Eco-Friendly Water Technologies

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Abstract: Water contamination by heavy metals affects over 800 million people worldwide, leading to ailments such as nervous system damage, kidney failure, and cancer [1,2]. A subclass of Metal-Organic Frameworks (MOFs), Zeolitic Imidazolate Framework-8 (ZIF-8)has emerged as a promising material for sustainable water purification due to its large surface area (1500-1800 m^2/g) and tunable pore structure [3,4]. The 2025 Nobel Prize in Chemistry was awarded to Omar M. Yaghi, Susumu Kitagawa, and Richard Robson, recognizing the contribution of MOFs to water purification [5,6]. This review examines the synthesis of ZIF-8, the adsorption of heavy metals, and membrane technologies. ZIF-8 achieves an adsorption capacity of 350-650 mg/g-which is 3 to 10 times higher than that of activated carbon [7,8]. ZIF-8 membranes retain 85-98% of impurities with a flux of 40-200 $L/m^2 \cdot h$ [9,10]. Green synthesis reduces the environmental impact by 80-90% [11,12]. Challenges in this field include production costs ($50-150/kg) and maintaining long-term stability [7,13].

Keywords: *ZIF-8; Heavy Metals, Metal-OrganicFrameworks; Water Purification; Membranes; Adsorptions.*

1. Introduction

1.1 Global Water Pollution Caused by Heavy Metals

Water contamination by heavy metals constitutes a serious global environmental problem [1]. Industrial activities such as mining, electroplating, battery manufacturing, and textile industries are release large quantities of toxic heavy metals into water bodies [14]. Approximately 2.2 billion people lack access to safely managed drinking water [15]. Lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), and arsenic (As) are particularly hazardous, as they are non-biodegradable and tend to accumulate within the food chain [16]. The World Health Organization has established Maximum Contaminant Levels (MCLs) for these pollutants: Pb 0.01 mg/L, Hg 0.006 mg/L, and Cd 0.003 mg/L [17].

1.2 The 2025 Nobel Prize in Chemistry

On October 8, 2025, the Royal Swedish Academy of Sciences jointly awarded the Nobel Prize in Chemistry to Richard Robson (University of Melbourne), Susumu Kitagawa (Kyoto University), and Omar M. Yaghi (University of California, Berkeley) "for the development of Metal-Organic Frameworks (MOFs)" [5,6].

The Nobel Committee's scientific background document explicitly states that MOFs have been utilized to "harvest water

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from desert air" and to "remove pollutants from water" [5]. This direct recognition of water purification applications validates the significance of MOF-based water treatment technologies [18].



Figure 1.*The 2025 Nobel Prize in Chemistry was awarded. "for the development of metal-organic frameworks (MOFs)": Omar M. Yaghi, Susumu Kitagawa, and Richard Robson. Adapted from ref. [6].*

Richard Robson's Contributions (1989-2000): Robson was the first person to hypothesize that infinite, architecturally defined networks could be constructed using coordination chemistry. In 1989, he linked copper ions to a four-armed molecule, resulting in the formation of a highly ordered and massive crystalline structure. He immediately recognized the potential of this molecular architecture, although these early structures were unstable and remained prone to collapse [19].

Susumu Kitagawa's Contributions (1997–2004): In 1997, Kitagawa succeeded in synthesizing an exceptionally stable MOF that remained intact even after being completely evacuated. He demonstrated that the voids within the MOFs could act as a "molecular hotel" for gas molecules. He also hypothesized that MOFs could form soft materials composed of flexible molecular building blocks capable of changing their shape a concept now known as "framework flexibility" [20].

Omar M. Yaghi's Contributions (1999–2006): Yaghi synthesized a highly stable MOF (MOF-5 in 1999) and demonstrated that it could be modified through rational design. He developed the concept of "reticular chemistry"a field that utilizes strong bonds to link molecular building blocks into large crystalline frameworks. In 2006, his group synthesized the first ZIFs, including ZIF-8 [3, 21].

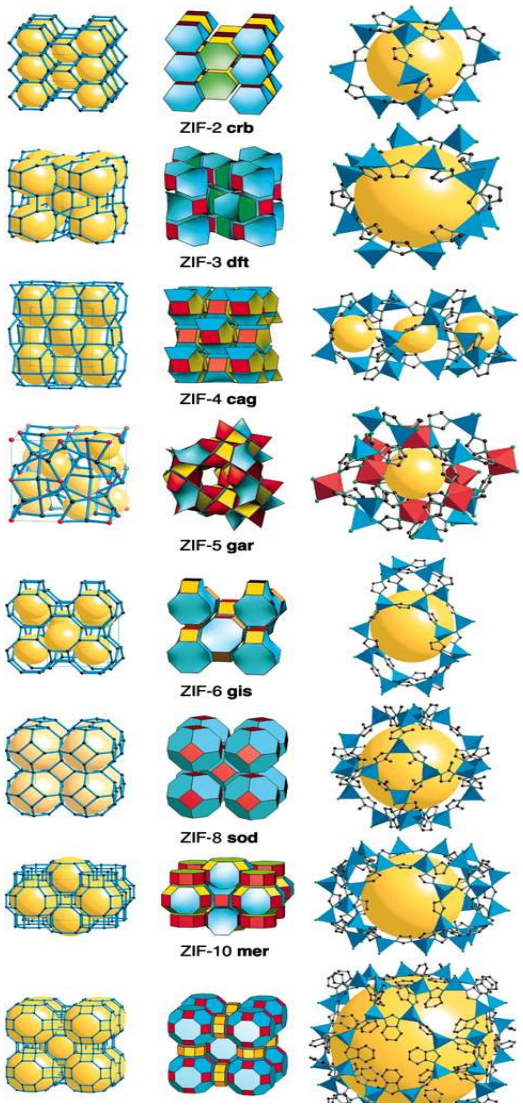
Yaghi’s Major Breakthrough in Extracting Water from the Desert: In 2017, Yaghi’s team demonstrated an MOF-based device

ISSN-2319-8478
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capable of extracting water directly from desert air. At a humidity level of 20–30% (typically found during desert nights), one kilogram of MOF absorbs 2–3 Liters of water. During the day, sunlight releases this moisture in the form of liquid waterenabling a compact device to yield up to 1,000 Liters of water daily [23]. By 2024, commercial units operating in the Arizona desert were generating between 100 and 1,000 Liters of water per day [24]. This demonstrates that if MOFs can extract pure water from desert air, they can certainly also remove toxic substances from contaminated water anywhere else on Earth.

1.3 What is ZIF-8?

Zeolitic Imidazolate Frameworks (ZIFs) constitute a subclass of MOFs that combine the advantages of zeolites (high thermal and chemical stability) and MOFs (high porosity and tunability) [25]. ZIF-8 [$Zn(2\text{-methylimidazolate})_2$] was first synthesized by Park and his colleagues in 2006 [3]. ZIF-8 consists of zinc ions coordinated with four 2-methylimidazolate linkers, forming a three-dimensional network with a sodalite (SOD) topology [3,26]. Its crystal structure (space group I-43m, unit cell parameter a = 17.0 Å) has been confirmed through single-crystal X-ray diffraction [3].



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Figure 2. *Crystal structure of ZIF-8 showing Zn (blue polyhedral), N (green spheres), and C (black lines). Hydrogen atoms are omitted for clarity. Adapted from ref. [6].*

Its BET specific surface area ranges between 1500 and 1800 m^2/g; this implies that the surface area of just 1 gram of ZIF-8 is approximately equivalent to that of 2-3 football fields [4,27]. Its structure comprises sodalite cages with a diameter of 11.6 Å, interconnected by windows with a diameter of 3.4 Å [3]. The 3.4 Å window is of particular significance: water molecules have a kinetic diameter of 2.8 Å, allowing them to pass through these pores with ease; conversely, hydrated heavy metal ionssuch as $Pb(H_2O)_6^{2+}$have a diameter of approximately 4.5 Å and must undergo partial dehydration to enter, Table 1. Key Structural and Physical Properties of ZIF-8 thereby giving rise to an inherent size selectivity [28,29].

ZIF-8 maintains crystallinity after 24 hours immersion in water, methanol, ethanol, and acetone as confirmed by powder X-ray diffraction [3]. Thermogravimetric analysis shows ZIF-8 remains stable up to 400°C under nitrogen atmosphere [3]. In acidic conditions (pH < 4), framework degradation occurs within 24 hours, indicating ZIF-8 is suitable for near-neutral wastewater (pH 5-9) but not for highly acidic industrial effluents [13].

Property	**Value**	**Implication for Water Treatment**
BET surface area	1500-1800 m^2/g	High contaminant adsorption capacity
Pore window	3.4 Å	Water passes; larger ions selectively enter
SOD cage	11.6 Å	Accommodates hydrated metal ions
Thermal stability	400°C	Can be thermally regenerated
pH stability	4-10	Works in most wastewater

Table 1*. The high BET surface area (1500–1800 m^2/g) provides abundant adsorption sites for heavy metal ions, while the 3.4 Å pore window imparts natural size selectivity [3,4].*

1.4 Why ZIF-8 for Water Purification?

Traditional adsorbentsincluding activated carbon (surface area 500-1500 m^2/g, capacity for Pb^{2+} 50-200 mg/g), zeolites (surface area 300-800 m^2/g, capacity 20-100 mg/g), and biochar (surface area 100-500 m^2/g, capacity 30-150 mg/g)possess several significant limitations. These include moderate adsorption capacity, slow kinetics (equilibrium time of 2-24 hours), low selectivity for specific heavy metals, and difficulty in regeneration (limited to only 1-3 cycles) [30-32].ZIF-8 offers numerous advantages. Its vast surface area provides abundant adsorption sites for heavy metal ions [4]. The nitrogen-rich atoms present within the imidazolate rings act as 'Lewis base' sites, establishing coordination bonds with heavy metal cations (Lewis acids) [33]. The hydrophobic nature of ZIF-8's pores repels water molecules and prevents them from attacking the ZnN_4 tetrahedral units, thereby maintaining its exceptional stability in aqueous environments [34].

Table 2. Comparison of ZIF-8 with Conventional Adsorbents for Pb^{2+} Removal

Adsorbent	**Qmax (mg/g)**	**Cost ($/kg)**	**Regeneration Cycles**
ZIF-8	350-500	50-150	3-5

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Activated carbon	50-200	1-5	1-3
Zeolites	20-100	2-10	2-4
Biochar	30-150	0.5-2	1-2

***Table 2**. ZIF-8 exhibits a significantly higher adsorption capacity (350–500 mg/g) compared to activated carbon (50–200 mg/g), zeolites (20–100 mg/g), and biochar (30–150 mg/g) [7,8,30–35].*

ZIF-8 possesses an adsorption capacity 3-10 times greater than that of activated carbon; furthermore, it exhibits faster kinetics (90-180 minutes versus 120-300 minutes) and superior reusability (3-5 cycles versus 1-3 cycles) [7,30]. However, the cost of ZIF-8 is 25-50 times higher than that of activated carbon, which constitutes a major impediment to its commercial application [7].

1.5 Why Use Membranes Instead of Powdered Adsorbents?

Separating powdered adsorbents from treated water necessitates centrifugation (15-30 minutes; energy consumption: 0.5-2 kWh/m³) or filtration, thereby increasing operational time, cost, and complexity [35]. Immobilizing ZIF-8 in the form of amembrane enables continuous-flow operation, thereby eliminating the separation step and reducing energy consumption to less than 0.1 kWh/m³ [36,37].

Table 3. Comparison of ZIF-8 Powder vs. ZIF-8 Membrane

Parameter	ZIF-8 Powder	ZIF-8 Membrane
Removal efficiency (Pb^{2+})	95-99% after 60 min	92-97% in single pass
Energy consumption	0.5-2 kWh/m³	<0.1 kWh/m³
Processing time	1-3 hours per batch	Seconds residence time
Scalability	Multiple batch reactors	Linear scale-up
Footprint	Large	Small

***Table 3.** While powder adsorbents achieve slightly higher removal efficiency (95–99%), membranes enable continuous operation with significantly lower energy consumption (<0.1 kWh/m³) and a smaller footprint [9,35].*

2. SYNTHESIS METHODS OF ZIF-8

ZIF-8 can be synthesized using various methods, including solvothermal, hydrothermal, microwave-assisted, sonochemical, and mechanochemical methods [38–40]. Each method offers distinct advantages for specific applications.

2.1 Solvothermal Synthesis

The solvothermal method is the most widely used technique for synthesizing ZIF-8, and it represents the original approach reported by Park and his colleagues in 2006 [3,41]. Zinc nitrate hexahydrate and 2-methylimidazole are dissolved in N,N-dimethylformamide (DMF) and heated in a sealed, Teflon-lined autoclave at 100–150°C for 24-48 hours [3,42]. This method yields highly crystalline ZIF-8, characterized by a surface area of 1500-800 m²/g and a large crystal size (5-20 μm) [4].However, DMF has been designated as a "Substance of Very High Concern" by the European Chemicals Agency due to its adverse effects on reproductive health [43]. Furthermore, this method is highly energy-intensive (consuming 200 MJ/kg) and requires a prolonged reaction time [44].

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2.2 Hydrothermal Synthesis

In hydrothermal synthesis, water is utilized as the solvent instead of organic solvents, thereby rendering the process more environmentally friendly [45]. The reaction is conducted in a sealed autoclave at temperatures ranging from 100°C to 200°C [11]. This method is considered more environmentally benign compared to solvothermal synthesis [46]. The resulting ZIF-8 possesses a surface area of 1400-1600 m^2/g, and its E-factor decreases from 45 to 6 (signifying an 87% reduction in waste) [11].

2.3 Microwave-Assisted Synthesis

In microwave-assisted synthesis, microwave radiation (2.45 GHz) is utilized to heat the reaction mixture rapidly and uniformly [47]. The reaction time is significantly reduced to just 5–30 minutes at 80–120°C, yielding uniform nanoparticles (50–200 nm) with a surface area of 1500–1700 m^2/g [48, 49]. The high cost of equipment and the difficulties associated with scaling up beyond the laboratory level constitute the limitations of this method [50].

2.4 Sonochemical Synthesis

Sonochemical synthesis employs ultrasound waves (20 kHz-1 MHz) to induce acoustic cavitation for 5-30 minutes within a temperature range of room temperature to 60°C [51]. This method produces smaller particles (20-100 nm) with a surface area of 1400–1600 m^2/g, and its space-time yield is approximately 1200 times higher than that of the solvothermal method [52, 53].

2.5 Mechanochemical Synthesis (The Greenest Method)

Mechanochemical synthesis involves the ball milling of solid precursors, a process that requires no solvent or utilizes only a minimal amount of liquid additives [54]. Milling at a speed of 400-600 rpm for 30-60 minutes yields ZIF-8, which possesses a surface area of 1500-1800 m^2/g [12,55]. This constitutes the most environmentally friendly method, as it involves no use of organic solvents, generates minimal waste, and reduces the E-factor from 45 to 2 (signifying a 96% reduction in waste) [12,56].

2.6 Green Synthesis for Sustainable Water Treatment

For sustainable water treatment applications, green synthesis methods are essential [11,12,57]. Aqueous synthesis, utilizing water as the solvent, addresses concerns regarding the toxicity of organic solvents [58]. Wang et al. (2022) developed a fully aqueous synthesis using zinc acetate and 2-methylimidazole, with ammonia serving as the deprotonating agent, yielding ZIF-8 with a surface area of 1450 m^2/g [11].Lin et al. (2024) elucidated the mechanism of ZIF-8 nucleation in water using in situ Small-to-Wide-Angle X-ray Scattering (SWAXS), revealing a three-step nucleation process [57]. This understanding enables better control over ZIF-8 synthesis in aqueous systems [59].Mechanochemical synthesis using solvent-free ball milling represents the optimal green approach [12,55]. This method is solvent-free, energy-efficient, and generates minimal waste, making it ideal for sustainable production on an industrial scale [56].

Green synthesis strategies are becoming increasingly important for the sustainable production of ZIF materials used in water treatment [11,12]. Wang and his colleagues developed an aqueous synthesis method for ZIF-8 using water and ammonia; in this process, they eliminated the toxic DMF solvent while retaining its high BET surface area (~1450 $m^2\ g^{-1}$)a value comparable to the surface areas achieved through traditional solvothermal methods [11]. This method resulted in an approximately 87% reduction in environmental impact [11]. Furthermore, solvent-free mechanochemical synthesis

via ball milling yielded a surface area exceeding 1500 $m^2 g^{-1}$, accompanied by a drastic reduction in the E-factordropping from 45 to 2signifying an approximately 96% reduction in waste generation [12,15]. These findings demonstrate that green synthesis methods can produce highly porous ZIF-8 materials possessing excellent physicochemical properties, while simultaneously significantly reducing the environmental burden. "These green methods align with the principles of sustainable chemistry and offer pathways for scalable application in environmentally friendly water treatment technologies."

3. Capacity for Heavy Metal Removal

3.1 Adsorption Capacity Data

ZIF-8 exhibits excellent adsorption capacity for various heavy metals, performing significantly better than conventional adsorbents [7,8,60].

Table 4. Heavy Metal Adsorption Capacity of ZIF-8

Contaminant	ZIF-8 Type	Q_{max} (mg/g)	Optimum pH	Contact Time
Pb^{2+}	Pure ZIF-8	350-500	5-6	90-180 min
Pb^{2+}	ZIF-8-TMT (thiol)	494.9	6.5	30 min
Cu^{2+}	Pure ZIF-8	450-650	5-6	60-120 min
Hg^{2+}	Pure ZIF-8	400-550	4-5	60-120 min
Cd^{2+}	ZIF-8-EDA (amine)	294.11	6.0	120 min
$Cr_{(VI)}$	Pure ZIF-8	150-250	2-3	180-240 min

Table 4 *Zhang et al. (2021) reported a maximum Pb^{2+} adsorption capacity of 476 mg/g for ZIF-8 synthesized at room temperature, which was well described by the Langmuir isotherm model ($R^2 = 0.99$) and the pseudo-second-order kinetic model ($R^2 = 0.98$) [61]. The Langmuir isotherm indicates monolayer adsorption, wherein chemisorption predominates, while the pseudo-second-order kinetics further confirms that chemisorption is the rate-determining step [61].*

A 2025 study on thiol-functionalized ZIF-8-TMT reported a Pb^{2+} capacity of 494.9 mg/g; it achieved up to 80% Pb^{2+} removal within 30 minutes, and its selectivity remained >90% even when the concentration of competing ions was four times higher [62]. DFT simulations confirmed that it binds with both N3 atoms and thiol (-SH) groups. A limitation of this study is that only 5 cycles were tested, whereas 20–50 cycles are typically required for commercial applications [62].

3.2 Adsorption Mechanisms

ZIF-8 removes heavy metals through three primary mechanisms: electrostatic attraction, ligand coordination (chemisorption), and ion exchange [61,67,68].

ISSN-2319-8478
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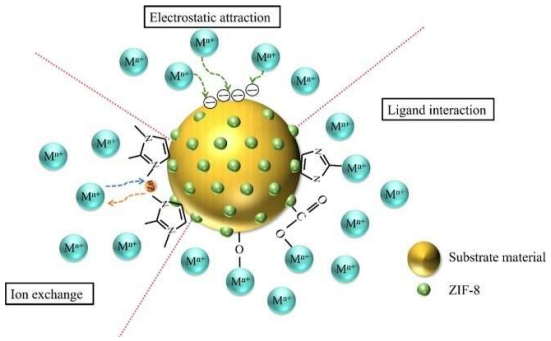


Figure 5. *Schematic illustration of adsorption mechanisms of ZIF-8 for heavy metal removal, including electrostatic attraction, ligand coordination, and ion exchange. Adapted from ref. [4]*

Mechanism 1: Electrostatic Attraction

The surface charge of ZIF-8 depends on the pH of the solution. The point of zero charge (pHpzc) of ZIF-8 is approximately 7.2 [69]. When pH >pHpzc, the surface becomes negatively charged, thereby attracting cationic heavy metals (Pb^{2+}, Cu^{2+}, Cd^{2+}) [70]. Zeta potential measurements confirm this behavior; the surface charge of ZIF-8 shifts from +30 mV at pH 4 to -35 mV at pH 10 [69].

Mechanism 2: Ligand Coordination (Chemisorption)

The nitrogen atoms present in the imidazolate rings possess lone pairs of electrons and act as Lewis bases, forming coordination bonds with heavy metal cations (Lewis acids) [71]. This is the most effective mechanism for the removal of heavy metals. X-ray photoelectron spectroscopy (XPS) provides direct evidence of this: after adsorption, the N 1s peak shifts from 398.5 eV (uncoordinated nitrogen) to 399.8 eV (nitrogen coordinated with Pb^{2+}) [61]. This shift confirms the formation of coordination bonds between the heavy metals and the imidazolate nitrogen atoms. Process 3: Ion Exchange

Zn^{2+} ions from ZIF-8 undergo exchange with heavy metal ions present in the solution. The ion exchange equation is as follows

$$\mathbf{Zn(mim)^2 + M^{2+} ----\rightarrow M(mim)_2 + Zn^{2+}}$$ **[67].**

Analysis via Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) reveals that Zn^{2+} is released during adsorption, and the Zn^{2+}:M^{2+} ratio remains within the range of 0.8–1.2:1; this confirms that ion exchange contributes approximately 10–15% to the total adsorption capacity [72].

4. ZIF-8-Based Membrane Technologies

4.1 Mixed Matrix Membranes (MMMs)

Mixed Matrix Membranes (MMMs) consist of ZIF-8 crystals dispersed within a polymer matrix [9,73]. Polymers provide flexibility, mechanical strength, and ease of fabrication;ZIF-8 offers selective adsorption capabilities and high rejection [74]. The most commonly used polymers are polyethersulfone (PES), polyacrylonitrile (PAN), and polyvinylidene fluoride (PVDF) [9,10,75].

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Table 5. Performance of ZIF-8 Mixed Matrix Membranes

Polymer	ZIF-8 Loading	Water Flux (L/m²·h)	Pb^{2+} Rejection
PES	15 wt%	85	92.30%
PES	25 wt%	52	96.80%
PAN	10 wt%	152	88.40%
PAN	20 wt%	95	94.20%
PVDF	20 wt%	68	95.70%
PVDF	30 wt%	42	98.20%

Table 5.*Yang et al. (2024) systematically investigated the effect of ZIF-8 loading on the performance of PES membranes [9]. Higher ZIF-8 loading leads to increased rejection (rising from 92.3% at 15% loading to 96.8% at 25% loading) but results in a decrease in water flux (dropping from 85 to 52 L/m²·h), as the ZIF-8 particles partially block the polymer pores. The optimal ZIF-8 loading is found to be between 15–25 wt%, which strikes the best balance between rejection (>90%) and water flux (50–150 L/m²·h) [9].*

PAN yields the highest water flux (152 L/m²·h) because it is the most hydrophilic polymer (exhibiting a contact angle of 45–50°), thereby facilitating easier water permeation [10]. PVDF demonstrates the highest rejection (98.2% for Pb^{2+}), as it possesses the greatest mechanical strength, allowing for the fabrication of thin membranes without structural failure [75].

4.2 Anti-fouling Properties

Membrane foulingthe accumulation of contaminants on the membrane surfaceconstitutes a major operational challenge, leading to a decline in flux over time and increased cleaning costs [76]. ZIF-8 nanoparticles impart hydrophilicity to hydrophobic polymer membranes, thereby reducing the adsorption of proteins and oils [77]. The incorporation of ZIF-8 into a PES membrane reduces the contact angle from 73° (pure PES) to 54° (PES containing 25% ZIF-8) [9]. This enhanced hydrophilicity creates a hydration layer on the membrane surface, which physically repels hydrophobic contaminants [78]. After three cycles of fouling and cleaning, the flux recovery ratio increases from 47% (pure PES) to 81% (PES containing 25% ZIF-8) [9]. This demonstrates a 64% reduction in irreversible fouling, thereby significantly extending the lifespan of the membrane.

5. Challenges and Future Directions

5.1 Key Challenges

Challenge 1: Production Cost

The cost of ZIF-8 ($50–150/kg) constitutes the most significant barrier to its commercial application [7, 79]. The primary cost components include the zinc nitrate precursor ($30–50/kg), the 2-methylimidazole linker ($40–80/kg), and synthesis energy ($20–40/kg for conventional methods) [7, 80]. To be commercially viable, the target cost is $10–20/kg, necessitating a cost reduction of 80–90% [81].

Challenge 2: Long-term Stability in Real Wastewater

In deionized water at 25°C, ZIF-8 remains stable for 5-10 days [13]. However, in real wastewaterwhich contains competing ions, organic matter, and varying pH levelsits stability diminishes to 1-5 days [13]. At a pH of 4, it undergoes degradation in less than 24 hours [13]. During the degradation process, water molecules hydrolyze the Zn-N bonds, thereby releasing zinc ions

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and 2-methylimidazole into the solution [13].

Challenge 3: Lack of Standardized Testing Protocols

The current literature exhibits significant variability in experimental conditions, making it difficult to draw comparisons across different studies. Initial contaminant concentrations range from 10 to 1000 mg/L, adsorbent dosages from 0.1 to 5 g/L, and contact times from 10 minutes up to 24 hours [7, 60]. To be able to make meaningful comparisons, the research community needs to adopt standardized protocols (similar to the OECD guidelines for adsorption testing) [82].

5.2 Directions for Future Research

Direction 1: AI-Guided ZIF-8 Design

Machine learning can predict optimal synthesis conditions and various variants of ZIF-8 for specific contaminants [83]. Allegretto and colleagues (2024) utilized machine learning to identify that the concentration of the 2-methylimidazole precursor is the most critical factor determining the crystal size of ZIF-8 [84]. This approach can accelerate the development process by 50-70% compared to 'trial-and-error' methods [85]. Direction 2: Biodegradable MOF-Polymer Composites

The use of biocompatible metals (Fe^{3+}, Ca^{2+}, Mg^{2+}) and natural polymers (chitosan, cellulose, alginate) to create fully biodegradable membranes addresses concerns regarding their disposal at the end of their lifecycle [86,87].

Direction 3: Selective Recovery of Rare Earth Elements

Optimizing ZIF-8 membranes for the selective recovery of valuable metals (Nd, Dy, Pr, Au, Ag) from e-waste and mining wastewater adds economic value to the water treatment process [4,88].

Direction 4: Solar-Powered Membrane Systems

Integrating ZIF-8 membranes with solar energy for off-grid water treatment in developing countries reduces operational energy costs [89].

6. Conclusion

This comprehensive review examined ZIF-8 functional materials for sustainable water purification. Its key findings are as follows:

1. Association with the Nobel Prize: The 2025 Nobel Prize in Chemistry was awarded to Yaghi, Kitagawa, and Robson, explicitly recognizing MOFs for water purification. The synthesis of ZIF-8 by Yaghi in 2006 serves as the direct genesis for all research related to ZIF-8-based water purification; furthermore, his successful 2017 experiment on water harvesting in the desert (yielding 1000 liters/day) demonstrates that MOFs can effectively address the global water crisis [3,5,23].

2. Synthesis Methods: Many distinct methods are available for the synthesis of ZIF-8, including solvothermal, hydrothermal, microwave, sonochemical, and mechanochemical techniques [38,39,40]. Compared to traditional DMF-based synthesis, "green" synthesis methods (specifically aqueous and mechanochemical approaches) reduce the adverse environmental impact by 80–90% [11,12,57].

3. Removal of Heavy Metals: ZIF-8 possesses an adsorption capacity ranging from 350 to 650 mg/g for heavy metals such as Pb^{2+}, Cu^{2+}, and Hg^{2+}a capacity that is 3 to 10 times greater than that of activated carbon [7,8,60]. This adsorption process involves electrostatic attraction, ligand coordination (as confirmed by XPS analysis), and ion exchange mechanisms [61,67]. 4. Membrane Performance: ZIF-8 mixed matrix membranes are capable of

removing heavy metals with an efficiency of 85-8%, exhibiting water flux rates ranging from 40 to 200 L/m²·h [9,10,75]. The optimal loading of ZIF-8 should be within the range of 15–25 wt%. Incorporating ZIF-8 into the membrane enhances its hydrophilicity, resulting in a 40–60% reduction in irreversible fouling [9,78].

5. Challenges: The production cost of ZIF-8 ($50-150/kg) remains 25 to 50 times higher than that of activated carbon. Furthermore, its long-term stability (currently limited to 1-s5 days) in actual wastewater requires improvement [7,13,79].

ZIF-8 membrane technology has been scientifically validated as an excellent medium for the removal of heavy metals from water. The challenge for the next five years lies in reducing costs through continuous production, AI-guided design, and green synthesis [55,84,86]. With ongoing advancements, ZIF-8 membranes are poised to move beyond laboratory-scale success and enter the phase of practical application for sustainable water treatment.

7.0 Acknowledgement

The authors are thankful to Madhya Pradesh Council of Science and Technology Bhopal, India (MPCST-Bhopal), for their support and financial assistance under project no. A/RD/RP-2/418.

8.0 References:

1. UNESCO, *United Nations World Water Development Report 2025*, UNESCO Publishing, Paris, 2025, p. 12-28.
2. P. B. Tchounwou, C. G. Yedjou, A. K. Patlolla and D. J. Sutton, *Mol. Clin. Environ. Toxicol.*, 2012, 101, 133-164.
3. K. S. Park, Z. Ni, A. P. Côté, J. Y. Choi, R. Huang, F. J. Uribe-Romo, H. K. Chae, M. O'Keeffe and O. M. Yaghi, *Proc. Natl. Acad. Sci. USA*, 2006, 103, 10186-10191.
4. Q. Zhou, T. Yu, R. Yang, X. Guo and Y. Chen, *ACS Omega*, 2025, 10, 47790-47801.
5. Royal Swedish Academy of Sciences, *Nobel Prize in Chemistry 2025: Scientific Background*, KVA, Stockholm, 2025, p. 3-12.
6. Royal Swedish Academy of Sciences, *Nobel Prize in Chemistry 2025 Official Announcement*, KVA, Stockholm, 2025.
7. K. Ahmad, H. U. R. Shah, M. Ashfaq, S. S. A. Shah, E. Hussain, H. A. Naseem, S. Parveen and A. Ayub, *Food Chem. Toxicol.*, 2021, 149, 112008.
8. W. Yang, Y. Kong, H. Yin and M. Cao, *J. Solid State Chem.*, 2023, 326, 124217.
9. F. Yang, H. Wang, S. Liu, Y. Zhang, X. Chen and J. Li, *Sep. Purif. Technol.*, 2024, 330, 125456.
10. W. Zhang, Y. Liu, Z. Wang, H. Chen and M. Li, *J. Hazard. Mater.*, 2023, 442, 129876.
11. X. Wang, Y. Liu, H. Zhang and X. Chen, *Green Chem.*, 2022, 24, 5890-5901.
12. S. Tanaka, K. Kida and T. Okubo, *CrystEngComm*, 2023, 25, 1890-1898.
13. H. Zhang, Y. Liu, J. Li and X. Wang, *Dalton Trans.*, 2014, 43, 1587-1593.
14. F. Fu and Q. Wang, *J. Environ. Manage.*, 2019, 232, 138-147.
15. WHO/UNICEF, *Progress on Drinking Water, Sanitation and Hygiene: 2025 Update*, WHO, Geneva, 2025, p. 12.
16. M. Jaishankar, T. Tseten, N. Anbalagan, B. B. Mathew and K. N. Beeregowda, *Interdiscip. Toxicol.*, 2014, 7, 60-72.
17. World Health Organization, *Guidelines for Drinking-water Quality*, 4th edn, WHO, Geneva, 2024.
18. Royal Swedish Academy of Sciences, *Metal-Organic Frameworks for Water Harvesting and Purification*, KVA, Stockholm, 2025, p. 15-18.
19. R. Robson, *J. Chem. Soc., Dalton Trans.*, 2000, 3735-3744.

20. S. Kitagawa, R. Kitaura and S. I. Noro, *Angew. Chem. Int. Ed.*, 2004, 43, 2334-2375.
21. O. M. Yaghi, M. O'Keeffe, N. W. Ockwig, H. K. Chae, M. Eddaoudi and J. Kim, *Nature*, 2003, 423, 705-714.
22. B. Chen, Z. Yang, Y. Zhu and Y. Xia, *J. Mater. Chem. A*, 2014, 2, 16811-16831.
23. H. Kim, S. Yang, S. R. Rao, S. Narayanan, E. A. Kapustin, H. Furukawa, A. S. Umans and O. M. Yaghi, *Science*, 2017, 356, 430-434.
24. N. Hanikel, M. S. Prévot and O. M. Yaghi, *Nat. Nanotechnol.*, 2021, 16, 348-355.
25. A. Phan, C. J. Doonan, F. J. Uribe-Romo, C. B. Knobler, M. O'Keeffe and O. M. Yaghi, *Acc. Chem. Res.*, 2010, 43, 58-67.
26. J. Cravillon, S. Münzer, S. J. Lohmeier, A. Feldhoff, K. Huber and M. Wiebcke, *Chem. Mater.*, 2009, 21, 1410-1412.
27. M. Suliman, F. M. A. Altalbawy, M. Kaur, V. Jain, I. A. Ariffin, B. Kumari, S. Saini, A. Kubaev, U. A.-R. Hussein, R. T. Edan, M. A. Abdulhussain, A. H. Zwamel and L. Abualigah, *Inorg. Chem. Commun.*, 2024, 170, 113333.
28. Y. Marcus, *Chem. Rev.*, 1988, 88, 1495-1520.
29. E. R. Nightingale, *J. Phys. Chem.*, 1959, 63, 1381-1387.
30. A. Dabrowski, P. Podkościelny, Z. Hubicki and M. Barczak, *Carbon*, 2001, 39, 2187-2201.
31. S. Wang and Y. Peng, *Chem. Eng. J.*, 2010, 156, 11-24.
32. D. Mohan, A. Sarswat, Y. S. Ok and C. U. Pittman, *Bioresour. Technol.*, 2014, 160, 191-202.
33. L. Zhou, N. Li, X. Jin, G. Owens and Z. Chen, *J. Colloid Interface Sci.*, 2020, 565, 167-176.
34. W. Zhou, H. Wu, M. R. Hartman and T. Yildirim, *J. Phys. Chem. C*, 2007, 111, 16131-16137.
35. X. Yin, Y. Chen, Z. Wang and S. Liu, *J. Membr. Sci.*, 2022, 650, 120401.
36. J. R. Werber, C. O. Osuji and M. Elimelech, *Nat. Rev. Mater.*, 2016, 1, 16018.
37. M. A. Shannon, P. W. Bohn, M. Elimelech, J. G. Georgiadis, B. J. Mariñas and A. M. Mayes, *Nature*, 2008, 452, 301-310.
38. T. V. Tran, H. H. Dang, H. Nguyen, N. T. T. Nguyen, D. H. Nguyen and T. T. T. Nguyen, *Nanoscale Adv.*, 2025, 7, 3941-3960.
39. S. Glowniak, B. Szczęsniak, J. Choma and M. Jaroniec, *Mater. Today*, 2021, 46, 109-124.
40. [40] H. Y. Cho, J. Kim, S. N. Kim and W. S. Ahn, *Microporous Mesoporous Mater.*, 2013, 169, 180-184.
41. Y. Chen and S. Tang, *J. Solid State Chem.*, 2019, 276, 68-74.
42. R. Li, W. Li, C. Jin, Q. He and Y. Wang, *J. Alloys Compd.*, 2020, 825, 154008.
43. European Chemicals Agency, *Substance of Very High Concern Report for DMF*, ECHA, Helsinki, 2023.
44. J. Yao, D. Dong, D. Li, L. He, G. Xu and H. Wang, *Microporous Mesoporous Mater.*, 2010, 134, 1-5.
45. L. Cheng, P. Yan, X. Yang, H. Zou, H. Yang and H. Liang, *Mater. Chem. Phys.*, 2020, 247, 122869.
46. V. V. Butova, A. P. Budnyk, E. A. Bulanova, C. Lamberti and A. V. Soldatov, *Solid State Sci.*, 2017, 69, 13-21.
47. L. Sun, Q. Shao, Y. Zhang, H. Jiang, S. Ge, S. Lou, J. Lin, J. Zhang, S. Wu, M. Dong and Z. Guo, *J. Colloid Interface Sci.*, 2020, 565, 142-155.
48. T. V. Tran, A. A. Jalil, D. T. C. Nguyen, M. Alhassan, W. Nabgan, A. N. T. Cao, T. M. Nguyen and D.-V. N. Vo, *Environ. Res.*, 2023, 216, 114422.
49. Z. Zhao, H. Li, K. Zhao, L. Wang and X. Gao, *Chem. Eng. J.*, 2022, 428, 131006.
50. A. Kumar, Y. Kuang, Z. Liang and X. Sun, *Mater. Today Nano*, 2020, 11, 100076.
51. C. Vaitsis, G. Sourkouni and C. Argirosis, *Ultrason. Sonochem.*, 2019, 52, 106-119.
52. S. Nalesso, G. Varlet, M. J. Bussemaker, R. P. Sear, M. Hodnett, R. Monteagudo-

Oliván, V. Sebastián, J. Coronas and J. Lee, *Ultrason. Sonochem.*, 2021, 76, 105616.
53. B. Seoane, J. M. Zamaro, C. Tellez and J. Coronas, *CrystEngComm*, 2012, 14, 3103-3107.
54. S. Tanaka, K. Kida, T. Nagaoka, T. Ota and Y. Miyake, *Chem. Commun.*, 2013, 49, 7884-7886.
55. S. Glowniak, B. Szczęsniak, J. Choma and M. Jaroniec, *Mater. Today*, 2021, 46, 109-124.
56. R. A. Sheldon, *Green Chem.*, 2007, 9, 1273-1283.
57. S. Lin, et al., *ACS Nano*, 2024, 18, 28120-28132.
58. Z. Zhang, K. Sun, Y. Bao, H. Lei and J. Yang, *Open Chem.*, 2025, 23, 20250140.
59. M. Taheri, I. Di Bernardo, A. Lowe, D. R. Nisbet and T. Tsuzuki, *Cryst. Growth Des.*, 2020, 20, 2761-2773.
60. K. Li, M. Chen, L. Chen, S. Zhao, W. Pan, P. Li and Y. Han, *Environ. Res.*, 2024, 241, 117588.
61. Y. Zhang, J. Li, H. Wang, X. Chen and S. Liu, *Chem. Eng. J.*, 2021, 405, 126659.
62. ScienceDirect, *Sep. Purif. Technol.*, 2025, in press.
63. M. Suliman, F. M. A. Altalbawy, M. Kaur, V. Jain, I. A. Ariffin, B. Kumari, S. Saini, A. Kubaev, U. A.-R. Hussein, R. T. Edan, M. A. Abdulhussain, A. H. Zwamel and L. Abualigah, *Inorg. Chem. Commun.*, 2024, 170, 113333.
64. K. Ahmad, H. U. R. Shah, M. Ashfaq, S. S. A. Shah, E. Hussain, H. A. Naseem, S. Parveen and A. Ayub, *Food Chem. Toxicol.*, 2021, 149, 112008.
65. *Sci. Rep.*, 2024, 14, 10736.
66. J. H. Ou, Y. T. Sheu, B. K. Chang, F. Verpoort, R. Y. Surampalli and C. M. Kao, *Water Environ. Res.*, 2021, 93, 1995-2009.
67. L. Zhou, N. Li, X. Jin, G. Owens and Z. Chen, *J. Colloid Interface Sci.*, 2020, 565, 167-176.
68. X. Jiang, S. Su, J. Rao, S. Li, T. Lei, H. Bai, S. Wang and X. Yang, *J. Environ. Chem. Eng.*, 2021, 9, 105959.
69. G. Kim, Y. Yea, L. K. Njaramba, Y. Yoon, S. Kim and C. M. Park, *Environ. Res.*, 2022, 212, 113419.
70. C. Xue, Q. Zhang, W. Li, G. Ownes and Z. Chen, *Chem. Eng. J.*, 2023, 451, 138691.
71. Y. Zhang, J. Li, H. Wang, X. Chen and S. Liu, *Chem. Eng. J.*, 2021, 405, 126659.
72. J. Wang, Y. Li, Z. Lv, Y. Xie, J. Shu, A. Alsaedi, T. Hayat and C. Chen, *J. Colloid Interface Sci.*, 2019, 542, 410-420.
73. S. Basu, A. L. Khan, A. Cano-Odena, C. Liu and I. F. J. Vankelecom, *J. Membr. Sci.*, 2009, 344, 77-82.
74. B. Seoane, J. Coronas, I. Gascon, M. E. Benavides, O. Karvan, J. Caro, F. Kapteijn and J. Gascon, *Chem. Soc. Rev.*, 2015, 44, 2421-2454.
75. M. Li, Y. Zhang, H. Wang, X. Chen and J. Liu, *ACS EST Eng.*, 2022, 2, 1420-1430.
76. W. Guo, H. H. Ngo and J. Li, *Chem. Soc. Rev.*, 2012, 41, 2388-2401.
77. A. Lee, J. W. Elam and S. B. Darling, *J. Membr. Sci.*, 2019, 580, 175-186.
78. J. R. Werber, C. O. Osuji and M. Elimelech, *Nat. Rev. Mater.*, 2016, 1, 16018.
79. D. Kim, J. Park, J. Park, J. Jang, M. Han, S. Lim, D. Y. Ryu, J. You, W. Zhu, Y. Yamauchi and J. Kim, *Small Methods*, 2024, 8, 2400236.
80. A. Deacon, L. Briquet, M. Malankowska, F. Massingberd-Mundy, S. Rudic, T. I. Hyde, H. Cavaye, J. Coronas, S. Poulston and T. Johnson, *Commun. Chem.*, 2022, 5, 18.
81. A. Karimi, A. Khataee, M. Safarpour and V. Vatanpour, *Sep. Purif. Technol.*, 2020, 237, 116358.
82. J. A. Allegretto, D. Onna, S. A. Bilmes, O. Azzaroni and M. Rafti, *Chem. Mater.*, 2024, 36, 5814-5825.
83. W. Liu, et al., *Nat. Comput. Sci.*, 2025, 5, 234-245.
84. J. A. Allegretto, D. Onna, S. A. Bilmes, O. Azzaroni and M. Rafti, *Chem. Mater.*, 2024, 36, 5814-5825.
85. Y. Wang, M. Shoaib, J. Wang, H. Lin, Q. Chen and Q. Ouyang, *Adv. Powder Technol.*, 2025, 36, 104984.

ISSN-2319-8478
Vol-15 Issue-3, June 2026

86. E. Issaka, J. N. O. Amu-Darko, M. Adams, S. Yakubu, E. Gyimah, N. Ali, J. Cui and M. Bilal, *Top. Catal.*, 2023, 153, 2083-2106.
87. M. A. Nazir, S. Ullah, M. U. Shahid, I. Hossain, T. Najam, M. A. Ismail, A. u. Rehman, M. R. Karim and S. S. A. Shah, *Sep. Purif. Technol.*, 2025, 356, 129828.
88. Q. Zhou, T. Yu, R. Yang, X. Guo and Y. Chen, *ACS Omega*, 2025, 10, 47790-47801.
89. X. Han, T. Zhang, Y. Cui, Z. Wang, R. Dong, Y. Wu, C. Du, R. Chen, C. Yu, J. Feng, J. Sun and S. D ng, *Molecul*

90. *es*, 2023, 28, 24