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REVIEW PAPER

Next-Generation Remediation Using MOFs: A Comprehensive Review on ZIF-8, UiO-66, and MIL-101 for Water and Soil Desalination

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HIGHLIGHTS

- Compares ZIF-8, UiO-66, and MIL-101 for integrated water and soil desalination.
- MOF-membrane and CDI systems achieve up to 99% salt rejection at low energy cost.
- MOF-biochar hybrids curb soil Na^+/Cl^- mobility, boosting yield in saline soils.
- Plasma-assisted synthesis offers a scalable, low-cost route for MOF production.

ABSTRACT

The necessity of this work stems from the urgent need to address intertwined challenges of water scarcity and soil salinization in arid regions, where conventional methods are energy-intensive and unsustainable. This review innovates by integrating nanotechnology with plasma physics for MOF functionalization and biochar hybrids, focusing on three water-stable MOFs: ZIF-8, UiO-66, and MIL-101. Methods include a systematic literature review of experimental data from 2014–2025 on synthesis, ion removal performance, and technology integration.

Water scarcity and salinization of soil are two interlinked environmental challenges having a calamitous impact on farming sustainability and human advancement in semi-arid and arid zones. Traditional desalination processes and soil remediation technologies are either energy-consuming, costly, or uneconomical for practical implementation. Metal–Organic Frameworks (MOFs) with their ultrahigh surface area, adjustable porosity, and framework flexibility have emerged in recent times as superior materials for brackish water desalination and salt-affected soil remediation. In this review, the multifunctional applications of three commonly studied water-stable MOFs, i.e., ZIF-8, UiO-66, and MIL-101, their structural advantages, ion removal performance, and their prospects for integration of environmental technologies are presented. These MOFs act as adsorbents or as membrane fillers in water treatment processes to achieve selective ion sieving and enhanced salt rejection through control of the nanochannels, electrostatic attraction, and metal site-ligand coordination. In soil remediation, MOF composites, especially MOF-biochar hybrids, have been very efficient in restricting the mobility and bioavailability of salt ions like Na^+ and Cl^-, thereby improving plant health and yield. We distill recent experimental data that demonstrate the potential of these MOFs for sequestering heavy metals and salts from both aqueous solutions and matrices of soil. This strategy addressing desalination and salinity remediation places MOFs in the position of being a next-generation solution to two of the most pressing environmental challenges of the present day. The physicochemical stability, surface chemistry tunability, and recyclability, combined together uniquely in ZIF-8, UiO-66, and MIL-101, render these materials strong contenders for future sustainable technology. Application of such materials can revolutionize integrated water-soil management systems, particularly in desertifying and agriculture-degrading regions.

KEYWORDS:

Metal–Organic Frameworks (MOFs); Desalination; Soil Salinity Remediation; Environmental Nanotechnology; Sustainable

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1. INTRODUCTION

The increasing global crises of freshwater deficits and extensive soil salinization bring unprecedented threats to agricultural sustainability, food security, and human progress, particularly in arid and semi-arid regions. While over 70% of the Earth's surface is water, no more than 0.5% is usable in the form of freshwater, compelling reliance on increasingly stressed resources due to climate change, inefficient irrigation, and population growth. Meanwhile, salinization of soil ruins over 1 billion hectares globally, while secondary salinization affects almost 50% of all irrigated soils, heavily impairing soil fertility and health [1,2]. This dual burden triggers a destructive process of feedback: freshwater scarcity forces the use of saline water for irrigation, elevating the salinization of the soil, which in turn demands freshwater for leaching, fueling further reserves depletion. Currently practiced conventional methods of water desalination, such as reverse osmosis (RO) and multistage flash distillation (MSF), are often energy-intensive (e.g., 3–4 kWh/m^3 for RO), economically costly, and yield unsettling brine waste [3,4]. Similarly, conventional soil remediation procedures, using gypsum amendments and excess leaching, are unsustainable and chemically stressful. These limitations highlight one of the most significant technology needs: the absence of robust, scalable, and environmentally friendly technologies that can address both saline water treatment and salt-affected soil rehabilitation [5].

1.1 Methodology of Review

This review is based on a systematic literature search conducted on databases including PubMed, Scopus, Web of Science, and Google Scholar, covering publications from 2014 to 2025. Keywords such as "MOFs desalination," "ZIF-8 soil remediation," "UiO-66 water treatment," and "MIL-101 adsorption" were used. Inclusion criteria focused on water-stable MOFs with experimental data on ion removal, stability, and environmental applications. Approximately 150 articles were fully reviewed, with 73 cited for direct relevance. State-of-the-art analysis identified gaps in integrated water-soil approaches and scalability, guiding our focus on plasma-enhanced synthesis and field trials.

1.2 Alternative Techniques for Water and Soil Desalination

Beyond MOFs, alternative water desalination techniques include thermal methods like multistage flash distillation (MSF) and multiple-effect distillation (MED), which evaporate saline water but consume high energy (10–16 kWh/m^3) and produce brine waste. Membrane-based methods such as electrodialysis (ED) use electric fields for ion separation (energy: 1–3 kWh/m^3), effective for brackish water but fouling-prone. Forward osmosis (FO) draws water through semi-permeable membranes using osmotic gradients, with lower energy (0.5–2 kWh/m^3) but requiring draw solute recovery. Capacitive deionization (CDI) adsorbs ions on electrodes (0.1–1 kWh/m^3), energy-efficient but with limited capacity. Solar distillation mimics natural evaporation, low-cost but low yield. For soil desalination, gypsum ($CaSO_4$) amendments displace Na^+ (cost-effective but slow), leaching with excess water flushes salts (water-intensive), and phytoremediation uses salt-tolerant plants (eco-friendly but time-consuming) [69]. Biochar amendments improve structure but lack selectivity. These methods are limited by energy/cost, environmental impact, or scalability compared to MOFs' tunability and efficiency [70].

Regions like the UAE and Armenia evidently show the paramount need for integral solutions. Armenia has a 1.23°C rise in temperature (1929-2016) and a 9% reduction in precipitation (1935-2016), with flows from rivers predicted to drop by more than 13% by 2040 and 27% by 2070 [6]. About 80% of Armenia's agriculture depends on irrigation, but 70% of reservoir water is lost because of outdated infrastructure. Soil salinization touches 30,000 hectares of Armenian territory, notably the agriculturally critical Ararat Plain (15.2% affected), where wheat yields are considerably lower when soil solution concentrations are above 4 mS/cm [7,8]. The UAE, the world's most water-stressed nation, has an average availability of water of just 1,200 cubic meters per capita, six times less than the world average [9]. It is heavily dependent on desalination, supplying 42% of the total water requirement and contributing 14% to global desalinated water output, at high economic and environmental costs through immense energy consumption and brine disposal.[10] Soil salinization affects about 34% of the UAE's total land area, with more than 80% of irrigated agricultural lands in Abu Dhabi Emirate adversely affected [10]. Cultivation of life-supporting crops like date palms is considerably impeded by combined water scarcity and high salinity [11]. Both countries have embarked on national plans to solve the problems, including Armenia's plan for soil degradation neutralization 5 and the UAE's Water Security Strategy 2036 [18], highlighting the urgent need for novel, energy-saving, and environmentally friendly technologies. Metal-Organic Frameworks (MOFs) offer a paradigm shift within desalination and remediation science. These metal-ion/clusters organic-linker crystalline porous solids possess ultra-high specific surface areas (often >1000 m^2/g, some >6000 m^2/g), tunable pore size (angstroms to nanometers), and high structural flexibility. Because of their unique properties, these materials can adsorb, catalyze, and selectively remove impurities from gaseous and aqueous phases efficiently. Recent studies highlight the application of functionalized MOFs for efficient monovalent and divalent ion elimination in wastewater and soil cleanup. This report is focused on the application of MOFs, namely ZIF-8, UiO-66, and MIL-101, as future materials for integrated water and soil desalination,

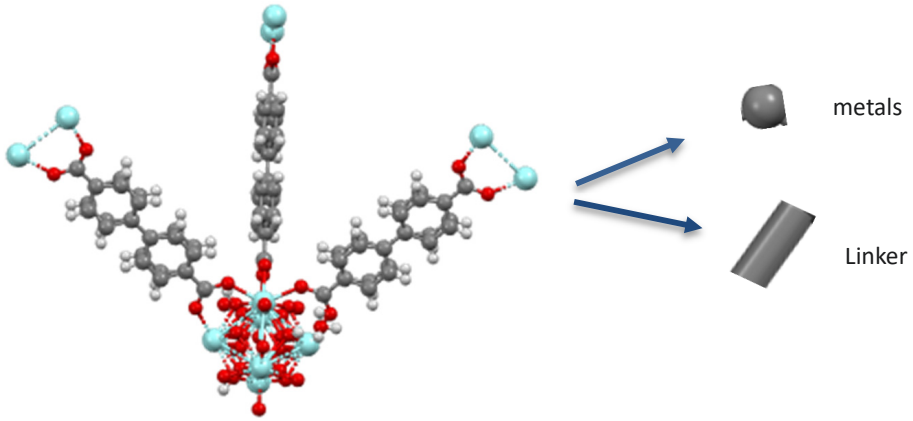

Fig. 1. MOF Structure, Schematic representation of a typical Metal-Organic Framework (MOF) structure, illustrating the coordination of metal ions/clusters with organic linkers to form a porous 3D network suitable for environmental applications in water and soil remediation.

discussing their structural advantages, ion removal processes, and potential for environmentally friendly technologies [12, 13]. Compared to existing reviews (e.g., Dutta et al. 2024 on MOF desalination, Rojas et al. 2022 on MOFs in agriculture [13]), this work uniquely integrates water and soil remediation, emphasizes plasma-functionalization and biochar hybrids for enhanced performance, and addresses regional challenges in Armenia/UAE with a focus on scalability and field trials. Advantages include lower energy use, recyclability, and holistic environmental impact reduction.

2. SYNTHESIS AND CHARACTERIZATION OF SELECTED MOFS

Before delving into applications, understanding synthesis and characterization is crucial for tailoring MOF properties.

2.1 Synthesis Strategies

ZIF-8 is typically synthesized via solvothermal methods (Zn^{2+} + 2-methylimidazole in methanol/DMF at 120–150°C for 24 h) or mechanochemical methods (ball milling for green, solvent-free production) [2, 4, 5]. UiO-66 uses hydrothermal/solvothermal routes ($ZrCl_4$ + terephthalic acid in DMF at 120°C) or electrochemical methods for scalable production [2, 8]. MIL-101 employs hydrothermal synthesis ($Cr(NO_3)_3$ + terephthalic acid in water/HF at 220°C) or plasma-assisted methods for defect introduction [1, 7]. Novel approaches include plasma-enhanced CVD for functionalization, enabling fast nucleation and improved stability.

2.2 Characterization Techniques

Common techniques include XRD for crystallinity (e.g., ZIF-8 peaks at 7.3°, 10.4°), BET for surface area (ZIF-8: 1970 m^2/g; MIL-101: 4100 m^2/g), FTIR for functional groups (-NH_2 at 3400 cm^{-1} in UiO-66-NH_2), SEM-EDS for morphology/elemental analysis, and TGA for thermal stability (UiO-66 stable to 500°C) [51,52]. These ensure quality for applications.

3. SCIENTIFIC INNOVATION: MOF-BASED NANOTECHNOLOGY FOR INTEGRATED REMEDIATION

3.1 Principles of MOFs: Structure, Properties, and Environmental Relevance

Metal-Organic Frameworks (MOFs) are a family of porous crystalline materials created by coordinating metal ions or metal clusters with organic ligands to produce highly ordered three-dimensional networks. Their typical features encompass exceptionally high specific surface areas (e.g., ZIF-8 as high as 1970 m^2/g, MIL-101 as high as 4100 m^2/g), very accurately tunable pore sizes (from sub-nanometer angstroms to nanometer ranges) [12], and exceedingly diverse and flexible structures [13]. This structural versatility provides for exceptional control over their physicochemical properties, making them suitable for custom design in targeted applications in adsorption, catalysis, and separation processes.

The ecologically beneficial nature of MOFs is diverse. Their large surface area and intrinsic porosity allow the efficient adsorption of a broad spectrum of aqueous solution impurities and gas-phase contaminants. Furthermore, their in-built catalytic sites allow active degradation of large organic molecules, and they possess photocatalytic and antibacterial activity, rendering them extremely versatile tools in future water treatment processes [14, 15]. In contrast to fixed-property materials historically used, MOFs may be precisely constructed and engineered at the molecular level, allowing precise design of targeted interventions rather than general treatments. This inherent tailoring ability, coupled with their potential for low-energy regeneration and insertion into renewable energy cycles, sets them apart as transformative agents in sustainable water and land resource management [16].

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3.2 Targeted questions for selection of MOF: ZIF-8, UiO-66, and MIL-101

For the removal of ions, this project aims to strategically target three thoroughly studied and water-stable MOFs—ZIF-8, UiO-66, and MIL-101—due to their proven superior performance in several desalination and remediation operations [17].

- **ZIF-8:** A Zeolitic Imidazolate Framework composed of Zn^{2+} ions and 2-methylimidazole, ZIF-8 incorporates a sodalite-like framework with an accessible micropore diameter of 11.6 Å through smaller 3.4 Å pores. It possesses high surface area (up to 1970 m^2/g) and superior thermal and chemical stability, resisting boiling water for seven days or 8 M NaOH at 100°C for 24 hours [27]. ZIF-8 in cation-exchange membranes (CEMs) has shown over 99% rejection of Na^+ ions in mixed Na^+/Mg^{2+} and Na^+/Ca^{2+} solutions with good permselectivity for monovalent ions [57]. Its derivatives with two metals can attain high adsorption capabilities for heavy metals, e.g., 1196.82 mg/g for Cu^{2+} [18].
- **UiO-66:** This zirconium MOF is widely known for its exceptional hydrothermal and chemical stability, owing to stable Zr-O bonds and high metal cluster connectivity, up to 500°C and under prolonged wet conditions. Its 0.6 nm triangular pore openings are most ideally suited for water permeability while rejecting larger salt ions and impurities. UiO-66 membranes have achieved high rejection percentages for multivalent ions (e.g., 98% for Mg^{2+}, 99.3% for Al^{3+}) and high rejection of NaCl (96%). Functionalization (e.g., with NH_2 groups) significantly enhances its adsorption capacities for many pollutants, such as diclofenac sodium (668.7 mg/g) [19].
- **MIL-101 (Cr):** A Cr-based MOF featuring an unprecedentedly large cavity system and two kinds of distinct mesopores, providing a very high surface area (up to 4100 m^2/g) and pore volume, which boosts the adsorption capacity. MIL-101(Cr) possesses outstanding high-temperature (up to 350°C) and wide chemical

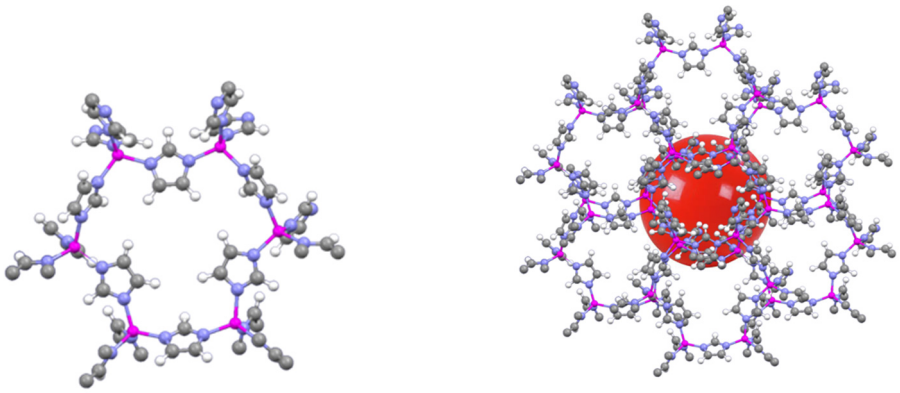

Fig. 2. ZIF-8 Structure, Crystal structure of ZIF-8, a zeolitic imidazolate framework composed of Zn^{2+} ions and 2-methylimidazole ligands, featuring sodalite-like topology with micropores of 11.6 Å and window apertures of 3.4 Å, highlighting its high surface area and stability for ion removal.

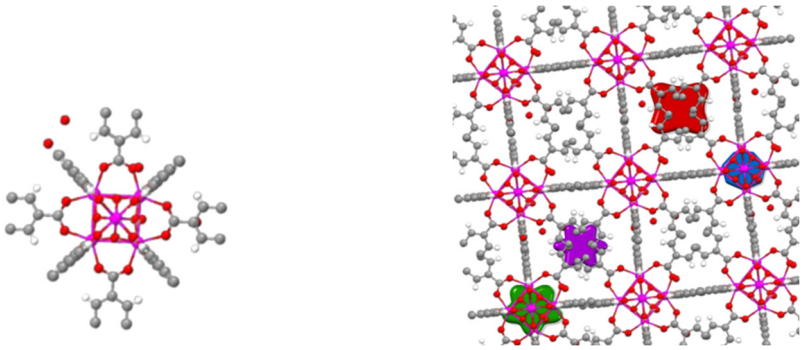

Fig. 3. UiO-66 Structure, Crystal structure of UiO-66, a zirconium-based MOF with octahedral $Zr_6O_4(OH)_4$ clusters linked by terephthalic acid, showing triangular pore openings of ~0.6 nm, emphasizing its exceptional hydrothermal stability and suitability for selective salt rejection in desalination membranes.

stability [20]. In TFN membranes, the introduction of MIL-101(Cr) nanoparticles significantly increases water permeance (by 44%) without compromising high NaCl rejection (>99%). Sulfonation of MIL-101 can also further improve its absorptivity, for instance, to be as high as 141 mg/g for Ba^{2+} [20].

These MOFs have superior and selective ion sieving and enhanced salt rejection due to a sophisticated interplay of exact nanochannel regulation, beneficial electrostatic attraction, as well as particular coordination of metal sites and ligands. Strategic functionalization through sulfonic ($-SO_3H$) or amino ($-NH_2$) functional groups can also increase their absorptivity in addition to selectivity. As summarized in Table 1, ZIF-8 offers high surface area for monovalent ion selectivity (e.g., 99% Na^+ rejection), UiO-66 excels in hydrothermal stability for multivalent rejection (98% Mg^{2+}), and MIL-101 provides large pores for high-capacity adsorption (141 mg/g Ba^{2+}) [17-20].

3.3 Enhancing MOF Performance through Plasma Physics and Nanotechnology

The unique scientific added value of the project lies in the merging of advanced nanotechnology and plasma physics for enhanced MOF synthesis and functionalization. While MOFs possess outstanding inherent properties, their optimum performance, particularly in complex real-life applications and on a large scale, can be significantly enhanced by carefully

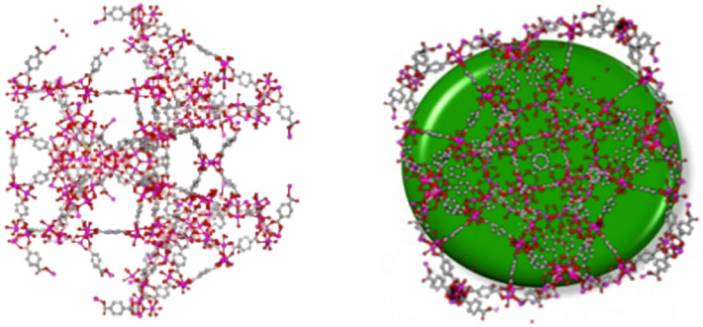

Fig. 4. MIL-101 Structure, Crystal structure of MIL-101(Cr), a chromium-based MOF with supertetrahedral building units forming large mesopores (up to 3.4 nm) and high surface area (~4100 m²/g), illustrating its cavity system for enhanced adsorption in water treatment and soil remediation.

Table 1. Comparative Summary of ZIF-8, UiO-66, and MIL-101(Cr) for Water and Soil Remediation

Feature	ZIF-8	UiO-66	MIL-101(Cr)
Metal Center	Zn^{2+} [15]	Zr^{4+} [18]	Cr^{3+} [22]
Main Ligand	2-methylimidazole [15]	Terephthalic acid [18]	Terephthalic acid [22]
Framework Type	Sodalite-type structure [15]	Face-centered cubic (fcu) [18]	3D mesoporous framework [22]
BET Surface Area	Up to 1970 m^2/g [15]	Up to 1200 m^2/g [18]	Up to 4100 m^2/g [22]
Pore Size	~3.4 Å (window), ~11.6 Å (cavity) [15]	~6 Å [18]	29–34 Å [22]
Thermal Stability	High (up to 550°C) [15]	Excellent (up to 500°C) [18]	High (up to 350°C) [22]
Chemical Stability	Resistant to alkaline and boiling water [15]	Highly stable across a wide pH range [18]	Good stability under acidic and aqueous media [22]
Application in Water	Effective for monovalent ions (Na^+), selective removal in membrane systems [36], [41]	Removal of multivalent ions (Mg^{2+}, Al^{3+}) and organic pollutants [18], [46]	High adsorption capacity, suitable for composite membranes [22], [43]
Application in Soil	Stabilizes Na^+ and Cl^-, promotes plant growth [36]	Reduces EC and ESP, improves soil structure [46]	Enhances soil quality when combined with biochar [43]
Performance in Membranes	High performance in cation exchange membranes (CEM) and thin-film nanocomposites (TFN) [41]	Strong compatibility with MMM and nanocomposites [18], [46]	Excellent performance in TFN membranes with 44% permeability boost [43]
Plasma Modification	Suitable for introducing hydrophobic functional groups [15], [48]	Reactive to sulfonic and amine functionalization [18]	Enhances surface functionality and adsorption via plasma-assisted doping [22], [48]

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Table 2. Comparison with Other MOF Reviews

Review	Focus	MOFs Covered	Gaps Addressed Here
Dutta et al. (2024) [72]	Water desalination	General MOFs	Integrated soil remediation, plasma enhancement
Rojas et al. (2022) [73]	MOFs in agriculture	MIL-101, ZIF-8	Scalability, field trials, regional applications
Khan et al. (2023) [74]	Photocatalytic degradation	UiO-66, others	Biochar hybrids for soil, magnetic composites

controlled surface and structural modifications [21, 22].

Plasma, a highly reactive species-containing ionized gas, is a very versatile tool for surface modification and functionalization [36]. Plasma treatment can selectively introduce defects in the MOF structure, improving adsorption capacities without compromising overall structural integrity or stability [23]. For instance, plasma-enhanced chemical vapor deposition (PECVD) of perfluoroalkanes can create fluorinated groups on MOF surfaces, greatly improving hydrophobicity, crucial for water stability and ion selectivity in desalination. Pore blockage needs to be carefully avoided by adjusting the plasma parameters. Recent studies also demonstrate that plasma-liquid interfaces can enable fast nucleation and growth of MOFs, allowing efficient framework incorporation of specific metal ions (e.g., Sc^{3+}), leading to enhanced properties like reactive oxygen species yield and effective bacteriostasis. This is a non-traditional, energy-efficient route to precision-engineer MOF surfaces and structures at the nanoscale [41, 24, 64]. Beyond surface modification, the nanoscale nature of MOFs makes it convenient for them to be integrated into other sophisticated materials and systems. This includes their incorporation into Thin-Film Nanocomposite (TFN) membranes and Mixed Matrix Membranes (MMMs) for radical enhancement of water flux and salt rejection. These MOF-based membranes create direct water channels, increasing water permeability without sacrificing high selectivity for ion removal [25]. The second key application in environmental remediation is the fabrication of MOF-biochar hybrids. Biochar, a carbonaceous product of biomass pyrolysis, improves the structure of the soil, water-holding capacity, and availability of nutrients, and supports favorable microbial populations [26, 27]. Loading MOFs onto biochar exhibits synergism and produces composites of high performance in reducing the mobility and bioavailability of salt ions like Na^+ and Cl^- in saline soils. The composite not only enhances the performance of MOFs but also addresses structural stability problems [28].

4. INTEGRATED REMEDIATION STRATEGY: WATER AND SOIL APPLICATIONS

The project utilizes the distinctive strengths of MOFs to offer an integrated, holistic remediation strategy for water desalination and soil salinity.

4.1 Water Desalination Systems

The project will develop and deploy MOF-based systems for effective water desalination with a focus on membrane technology, adsorption, and capacitive deionization.

MOF-Membrane Technology

It is a premise of this strategy that MOFs are incorporated in advanced membrane systems. Thin-Film Nanocomposite (TFN) membranes and Mixed Matrix Membranes (MMMs) using MOFs are developed to significantly enhance the efficiency of water purification [28]. Because MOFs are ordered porous, they form direct pathways for water through the membrane matrix, significantly increasing the permeability of water with high rejection rates. UiO-66 membranes, for instance, have shown 96% rejection of NaCl, while MIL-101(Cr) based TFN membranes have shown over 99% rejection of NaCl with 44% increased water permeance [30]. The extremely tunable pore size of MOFs like UiO-66 allows selective sieving, whereby water molecules can pass while efficiently rejecting larger salt ions and impurities [31].

Adsorption Systems

MOFs are excellent adsorbents for the selective elimination of salt ions from water. Their ultra-high surface area and tunable porosity allow high adsorption capacities and fast kinetics. For instance, MOF-808-EDTA, a thermo-regenerable salt adsorbent, has shown a desalination capacity as high as 9.4 mmol/g for NaCl with fast adsorption in 30 minutes [32, 66]. The underlying mechanisms of this outstanding performance involve selective ion sieving by accurately engineered nanochannels, favorable electrostatic interactions between the MOF matrix and target ions, and specific ligand-metal site coordination. These interactions provide efficient and targeted elimination of troublesome ions [67].

Capacitive Deionization (CDI) with MOFs

The study will further explore how Capacitive Deionization (CDI) systems can be upgraded by combining MOFs. CDI is a low-energy desalination technique and a promising one, and MOFs can significantly improve its ion removal rate and efficiency of desalination [33]. MOF-embedded cation-exchange membranes have shown over 99% Na^+ ion removal from mixed Na^+/Mg^{2+} and Na^+/Ca^{2+} solutions, outperforming commercial membranes [34]. Results in experiments indicate

that with the optimization of MOF-based CDI systems, very low energy consumption is achievable, which can be as low as 0.0089 W per gram of NaCl removed, especially when coupled with energy regeneration schemes. This is a very significant advancement over traditional CDI operations and much less than that required by reverse osmosis [35].

Energy Efficiency

One of the valuable advantages of MOF-based desalination units is that they consume much less energy compared to conventional technologies. Traditional reverse osmosis (RO) typically demands approximately 3-4 kWh/m^3 of treated water, whereas optimized MOF-based CDI processes decrease energy consumption to as low as 0.0089 Wh/g NaCl [36]. Besides, the project will explore the integrability of MOF-based desalination with renewable power sources, particularly solar thermal/electrical modules, in support of off-grid and sustainable water production [28]. Photoresponsive MOF PSP-MIL-53, for example, already showed capacity to desalinate water using sunlight, producing 139.5 L pure water per kilogram of MOF per day and regenerating within four minutes under sunlight exposure [37].

Magnetic MOF Nanocomposites in Water Treatment

Magnetic MOFs (e.g., Fe3O4@MIL-101, Fe-ZIF-8) enable easy separation via magnets, enhancing wastewater treatment. Applications include dye degradation (Fe-ZIF-8 for methylene blue, 98% removal under visible light) and heavy metal adsorption (Pb^{2+}/Hg^{2+} removal >90%). Synergies with photocatalysis and adsorption make them superior for recyclable systems [65] for Fe-ZIF-8.

4.2 Soil Salinity Remediation

The project extends its novel MOF application to the important field of soil salinity remediation, with a focus on MOF-biochar hybrid and overall nanomaterial applications.

MOF-Biochar Hybrids

The core of the soil remediation strategy is the design and application of MOF-biochar hybrids. Biochar, a rich carbon product from the pyrolysis of crop residues (typically 300-700°C) [38], is also renowned for its capability to improve soil structure immensely, increase water retention, increase nutrient availability, and boost the growth of healthy microbial communities [39]. An MOF-biochar blend produces a synergistic effect. These MOF hybrids, particularly MOF-biochar hybrids, have proven highly effective in controlling the mobility and bioavailability of detrimental salt ions, such as Na^+ and Cl^-, thereby directly improving the health and yield of crops [40]. By juxtaposition, not only is the performance of the MOFs enhanced but also the structural stability concerns associated with some MOFs [41, 68].

Mechanism of Action in Soil

Utilization of MOF-biochar hybrids can lead to measurable improvement in soil quality. Studies have shown that biochar treatments can reduce electrical conductivity (EC) and exchangeable sodium percentage (ESP) in saline-sodic soils and

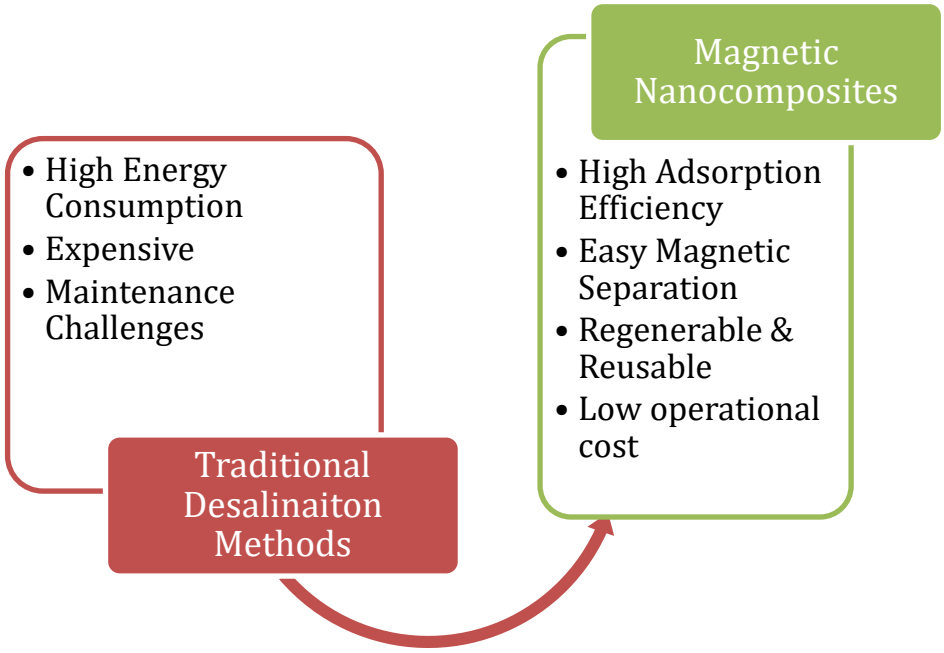

Fig. 5. Comparison of desalination methods vs. magnetic MOF nanocomposites

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create more favorable growth conditions for vegetation [76]. The adsorption and ion-exchange capabilities of MOFs coupled with the porous nature of biochar enhance the water-holding capacity and nutrient retention capability of the soil [42]. Such an enhanced soil environment, in turn, enhances crop yields and facilitates healthy root growth even under stressful conditions of salinity [43]. For instance, application of biochar has been shown to increase surface area and root length in rice plants cultivated under heat stress, leading to elevated dry weight. Wheat yield in Armenia is greatly reduced when the concentration of soil solution exceeds 4 mS/cm, and ameliorant application can lead to higher yields (e.g., 3.4 t/ha on improved soil) [44].

Nanomaterials in Soil Remediation

Besides MOF-biochar composites, nanotechnology as a whole has much potential for soil remediation. Nanomaterials such as carbon nanotubes, nanosilica, and nano-biochar have been proven to improve soil fertility, water retention, and structural stability [45]. Nanomaterials also have the potential to detoxify heavy metals in contaminated soils, allowing plants to thrive in poor conditions. This is suggestive of a diversified nanotechnology solution to soil health.

Relevance of Field Trial

Although much of the research on MOFs and biochar for environmental remediation is done at the laboratory level, the success of this project ultimately lies in proving efficacy in field conditions. The project acknowledges the need to transition from lab-scale soil leaching simulators to full field trials. Past field trials, such as subsurface drip irrigation (SDI), have measured high soil desalination (15.33% to 26.96% increase) rates and enhanced fungal communities in the soil, making practical application very significant [46]. The vision of MOFs harvesting water from desert air has already been fulfilled in field trials, demonstrating the feasibility of the materials under challenging conditions and their capacity to greatly increase water productivity (over a liter per kilogram of MOF per day). Such emphasis on field testing is necessary to translate laboratory success into real, effective solutions for agricultural communities [47].

5. IMPLEMENTATION AND SCALABILITY

Effective implementation and widespread application of this MOF-based remediation technology rely on robust methodology and a well-defined route to scalability and cost-effectiveness.

5.1 Methodology and Experimental Design

The project methodology is founded on robust scientific principles, such as material synthesis, effective characterization, and multi-stage testing.

MOF Synthesis

The MOF syntheses targeted (ZIF-8, UiO-66, MIL-101) will primarily employ mechanochemical and hydrothermal approaches, the methods of choice owing to scalability and green synthesis possibilities. The methods allow for good structural and property control of MOFs. A central field will be pre-functionalization of MOFs with tailor-made functional groups, i.e., sulfonic (SO_3H) or amino ($-NH_2$) groups, to enhance their ion selectivity and adsorption capacity [48,49]. Furthermore, novel plasma-assisted synthesis routes will also be explored. Plasma-assisted processes offer the advantage of high reaction rates (e.g., one-hour laser-induced synthesis of Zn-based MOFs) and the ability to introduce controlled defects or surface modifications that enhance MOF properties for water treatment [50]. This can lead to more stable and robust materials that are crucial for sustained use.

Characterization

High-end analytical suites will be employed for comprehensive MOF characterization. X-ray Diffraction (XRD) will identify crystallinity and phase purity, and Brunauer-Emmett-Teller (BET) measurement will quantify surface area and pore volume [51]. Fourier-Transform Infrared (FTIR) spectra will identify functional groups, and Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS) will provide morphology and elemental composition information. Thermogravimetric Analysis (TGA) will analyze thermal stability [52]. These characterization tests are important in material quality assurance as well as structure-property relation determination.

Adsorption & Membrane Testing

The performance of the MOFs will be rigorously tested by batch and flow-through tests with mock saline water (NaCl, $CaCl_2$). Adsorption isotherm modeling (Langmuir, Freundlich) will be used to determine the adsorption mechanisms and capacities [53]. Pilot systems on a laboratory scale will be constructed for membrane applications, including column adsorption reactors and mixed-matrix MOF-polymer membranes for forward osmosis (FO) and thin-film composite (TFC) applications [54]. These systems will confirm the performance of the MOFs under continuous flow conditions, which will mimic actual operating conditions.

Soil Leaching Simulators & Field Trials

For soil remediation, laboratory-scale soil leaching simulators will be utilized to find the effectiveness of MOF-biochar hybrids in soil salinity prevention and promotion of soil health. This stage is crucial for establishing performance under changing environmental conditions and determining the impact on crop production. Earlier field tests, e.g., subsurface drip irrigation, achieved high soil desalination rates (15.33% to 26.96% increase)

and improved fungal communities in soil. One's vision of MOFs harvesting water from desert air is already a reality in field demonstrations demonstrating their practicability under harsh conditions [55,56].

Regeneration & Cycling

Their long-term viability and sustainability are highly dependent on cyclic efficiency and regeneration stability. The project will evaluate a range of regeneration protocols including electro-regeneration, mild thermal desorption, pH swing, and water flushing. Performance retention will be conducted for 50–100 cycles of adsorption-regeneration to ensure that materials have sustained high efficiency and structural integrity under operating conditions. For example, MOF-808-EDTA showed no apparent capacity loss after 10 consecutive adsorption-regeneration cycles [57].

Computational Modeling

DFT and MD simulations will predict the ion transport mechanisms and atomic-level profile of MOF-water interactions. Computational tools will provide fundamental insights into MOF behavior, guiding material design and optimization to achieve improved performance.

5.2 Scalability and Cost-Effectiveness

To transform scientific discoveries into broadly accepted solutions, scalability and cost-effectiveness are addressed.

Scalable Synthesis

One of the most important challenges in the Metal-Organic Frameworks market is the high cost of production and restrictions in MOF synthesis on a large scale [58]. Traditional synthesis methods generally employ expensive metal precursors, complex organic linkers, and energy-intensive processing [59]. The project will focus on effective synthesis methods, including solvent-free methods, mechanochemical processes, and green synthesis with bio-based precursors. Continuous-flow synthesis methods will be explored since they have been shown to synthesize MOFs like ZIF-8 on a kilogram scale per day. It has been shown that the cost of MOF production can be significantly reduced, even down to below $10/kg for multi-ton synthesis (e.g., 2.5 tons/year) or below $30/kg for some MOFs like MIL-100(Fe) at industrial scale, particularly with wise selection of synthetic pathways such as aqueous-based synthesis over solvothermal processes. Collaborations between academia and industry, and also governmental efforts, are necessary in driving innovation and cost reduction in MOF manufacturing [60].

Waste Management

Waste management is included in the project sustainability. Reusability of MOFs for multiple cycles with minimal loss of performance is a vital advantage. The project will also explore the means to incorporate MOF systems into zero-liquid-discharge or brine valorization pathways for low environmental impact from concentrated salt solution [61,62].

Economic Benefits

The successful application of this technology is expected to achieve significant economic benefits. For agriculture, the reclamation of salt-affected land and provision of desalinated water will lead to increased agricultural productivity and better crop yields. For example, the use of reclaimed water for irrigation is estimated to generate significant value (e.g., EUR 10,003/ha) and create new jobs in the agricultural industry (e.g., 922 new jobs per 19.5 hm^3 of reclaimed water). Sustainable agricultural production approaches, such as good water use and soil health, have already led to an increased ability to produce food and better livelihoods for farmers in terms of greater productivity and reduced costs of production [63]. Efforts directed towards the restoration of degraded land and enhancement of irrigation schemes have recorded promising yields and income security for farmers. The project's emphasis on low-cost, decentralized solutions, such as greywater treatment for irrigation, also indicates its economic feasibility and potential to help reduce overall water supply costs [63].

6. CONCLUSION

This review underscores the transformative potential of ZIF-8, UiO-66, and MIL-101 in addressing water scarcity and soil salinization through integrated, sustainable approaches. By leveraging plasma-functionalized MOF-biochar hybrids, these materials offer energy-efficient desalination and remediation, applicable in arid regions like Armenia and the UAE for enhanced food security and environmental health. Future work should prioritize large-scale field trials to realize global impact.

Conflict of Interest

The authors declare no conflict of interest.

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Author's Contributions

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Data Acquisition: Gevick Davoodi, Laya Anjo, Gurgen Yeghiazaryan
Data Analysis or Interpretation: Gevick Davoodi, Laya Anjo
Manuscript Drafting: Gevick Davoodi, Laya Anjo, Gurgen Yeghiazaryan
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All authors have approved the final manuscript and are responsible for all aspects of the work.

AI Statement
The authors confirm that no AI tools or services were used during the preparation of this work.

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