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High-performance polysulfone/NH_2-MIL-125 membranes for the rejection of toxic metals in aqueous solutions

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ABSTRACT

Water contamination is a significant environmental issue, and it is crucial to develop innovative technologies to address this problem. One such technology is the use of nanomaterials in polymeric membranes, which can help to purify water by eliminating pollutants and heavy metals. These membranes possess exceptional properties, including a large surface area, adjustable pore dimensions, and permeability selectivity, which make them effective in removing various contaminants from water. Nanoscale materials, like metal nanoparticles, nanofibers, graphene, and graphene oxide, and metal organic framework (MOF), are integrated into the membrane, which enhances its mechanical strength, separation efficacy, and adsorption capabilities. In the current investigation, we have successfully synthesized the metal-organic framework NH_2-MIL-125 and conducted preliminary research on its properties for heavy metal rejection (Pb^{2+} and Cd^{2+}) after incorporation into a polysulfone membrane. Field Emission Scanning Electron Microscopy (FESEM), X-ray Diffraction (XRD), Brunauer–Emmett–Teller (BET) analysis, an Electrokinetic Analyzer, and Fourier Transform Infrared Spectroscopy (FTIR) were used to study the membranes. Additionally, the membrane's water affinity, flow rate, and resistance to fouling were studied. The M-3 membrane with 3.0 % MOF incorporation showed a 99.10 % rejection for cadmium, and the M-3 membrane rejected 75.02% for lead at a feed concentration of 500 ppm.

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1. Introduction

As global freshwater demand has risen to its highest level in the past decade, and the subsequent decrease in freshwater levels both above and below the Earth's crust has diverted mankind's attention to invent new technologies for water purification. Among the different techniques explored in the field of water purification, membrane technology is found to be one of the most promising and successful techniques. Nanofiltration (NF), ultrafiltration (UF), Microfiltration (MF), and Reverse Osmosis (RO) are extensively applied techniques across various countries worldwide. There has been a great improvement in the quality of life with the help of polymer science, membrane technology, and development in engineering fields [1, 2].

Elements with atomic masses between 63.5 and 200.6 and a specific gravity greater than 5.0 are classified as heavy metals. Though biological entities require a trace amount of heavy metal for the body's functions, an excess amount of it leads to fatality. The main sources of non-essential heavy metals are various industrial sectors, and wastewater from these industries is often directly discharged into freshwater sources, leading to contamination of drinking water [3]. During the initial stage, humans can tolerate small amounts of heavy metals entering their bodies; however, severe repercussions will be observed due to long-term exposure or injection. Hence, the World Health Organization (WHO) has established maximum contamination levels (MCLs) for the percentage of heavy metals in water. Above 10 ppb, 3 ppb, 10 ppb, and 100 ppb for Lead, Cadmium, Arsenic, and Chromium in drinking water are considered to be highly unsafe for human consumption [4]. However, some of them require the body's nutrition, but the ionic form of these metals is toxic due to their non-decomposable and accession nature inside the body. Many health issues related to body organs, biological cycles, and physiology have been reported due to these heavy metals, which subsequently lead to fatal diseases like cancer, mutagenicity, or genotoxicity [5]. Numerous technologies have been developed for extracting heavy metals from wastewater. The universally developed techniques for elimination of contaminants from water, like adsorption[6-8], oxidation using various oxidants[9-11], membrane technology [12-14], ozonation[15-17], ion exchange[18, 19], chemical precipitation[20; 21], electrodialysis [22, 23], photo-catalytic degradation[24, 25], electrocoagulation[26-28], other techniques involving chemical and biological procedures[29-33] have been widely used across various sectors. Membrane technology has been extensively adopted in various industries due to its high-quality results, reduced chemical usage, low operating costs, decreased energy consumption, smaller footprint, and simplified scaling. The high operational costs, high waste generation, high energy consumption, and lower efficiency have led to a diversification of attention towards more efficient membrane technology [34]. Conventional membranes currently hold a predominant position in the water purification market; however, their selectivity, permeability, flux, stability, and high manufacturing costs make them less attractive for commercialization [35, 36]. These membranes are made up of various polymeric materials such as polyvinylidene fluoride (PVDF), polyether sulfone (PES), polypropylene (PP), polyvinyl chloride (PVC), polyacrylonitrile (PAN), polysulfone (PSF), polyamide, polyethylene (PE), and polyvinyl alcohol (PVA), based on the intended use[37]. The assimilation of nanoparticles into the membrane significantly enhances the membrane's ability to remove heavy metals[38].

Recently, several 2D and 3D nanomaterials have been incorporated into water purification techniques. This significant development in the field of nanomaterials is attributed to their exceptional physical and chemical properties, which significantly enhance the separation capabilities of polymeric membranes. The unique characteristics of nanomaterials present in polymeric membranes, such as their large surface area, adjustable pore sizes, and ability to selectively allow certain particles to pass through, have made significant advancements in removing various types of contaminants from water. The inclusion of nanoscale materials such as metallic nanocrystals, nanoscale fibers, Carbon nanostructures, and oxidized graphene has greatly improved membrane capabilities by enhancing mechanical strength, improving separation

efficiency, and increasing adsorption capabilities[39]. Different nanoparticles, such as metal-organic frameworks (MOFs)[40], covalent organic frameworks (COFs) [41], graphene oxide[42], zeolites[43], transition metal dichalcogenides[44] and MXenes [45] have been used in water purification.

Researchers in the field of water purification technology are increasingly interested in metal-organic framework-induced mixed matrix membranes. This is a result of the extensive surface area, multiple potential applications, and different pore sizes and functionalities of the nanofillers (MOFs). The organic ligand and the inorganic metal ion or cluster, which are the two components of MOFs, have a synergistic effect that provides exceptional properties, such as variable pore dimension, inner surface spaces, and massive porosity [46, 47]. The MOF-induced mixed matrix membranes have been synthesized and utilized in various applications, including gas separation, water treatment, and fluid separation. They have been used, especially in removing dense metals such as lead and arsenic, from effluent [37]. Titanium-based MOFs have been found to be highly beneficial in water purification technology. They have been widely used in the removal of heavy metals and dyes from industrial and other wastewater sources [48]. It has been reported that the modified NH_2-MIL-125, a titanium-centric metal-organic framework featuring an amine organic functional group, exhibits adsorption properties of 102.8 and 66.9 mg/g for lead and cadmium, respectively [49]. The MIL-125 MOFs were also found to enhance water flux and remove pesticides from wastewater resources [50, 51].

In our earlier work, polysulfone mixed matrix membranes containing MIL-125(Ti) were fabricated and evaluated for the removal of organic dyes (Reactive Black 5 and Reactive Orange 16) and heavy metals (lead and cadmium). The membranes exhibited rejection efficiencies of 90% for RB-5, 47% for RO-16, 89.33% for Pb(II), and 68.81% for Cd(II), confirming the potential of MIL-125(Ti) as a suitable additive for enhancing performance. The monographs describing the membrane morphology and performance are included in the previously published work [52]. Building on these findings, the present study investigates the use of the functionalized analogue, NH_2-MIL-125(Ti), in PSF-based mixed matrix membranes, explicitly targeting the removal of heavy metals. The incorporation of amino-functionalized MIL-125(Ti) significantly improved the rejection efficiency, achieving 99.1% for Pb(II) and 75.02% for Cd(II), thereby demonstrating the superior performance of the modified MOF compared to its parent structure.

There are reports of the usage of NH_2-MIL-125 for light-catalyzed decomposition of dyes [53], oil and water emulsion separation [54], gas separation [55], desalination [56], Medical [57], and heavy metal elimination [58]. In this research, the MOF has been synthesized using a solvothermal method [59]. The polymeric material Polysulfone (PSF) is a commercially available glassy material used for the construction of UF [60] and NF [61] membranes. These polymeric materials are highly resistant to thermal and chemical conditions, exhibiting excellent mechanical strength. They are hydrophobic, which causes an increase in membrane fouling [62]. Therefore, various routes have been employed to enhance the flux and removal efficiency, while also decreasing the fouling nature. This study focuses on fabricating NH_2-MIL-125/ PSF composite membrane and its efficiency in removing Pb^{2+} (lead) and Cd^{2+} (cadmium) heavy metals.

2. Materials and methods

2.1. Reagents

All reagents and compounds used were of laboratory-grade quality and were applied directly without further refinement. A polysulfone polymer possessing an approximate molar mass of 35 kDa was procured from Solvay Industry. 1-methyl-2-pyrrolidinone and poly(1-vinyl-2-pyrrolidone were purchased from Spectrochem, India. Fraction V bovine plasma protein was obtained through HiMedia industry. Titanium (IV) isopropoxide [$Ti(OCH(CH_3)_2)_4$, 95% purity], N, N-methanoyl dimethylamine, and benzene-1,4-dicarboxamide-2-amine were received from Merck India. Loba Chemie, India, delivered methyl alcohol, whereas cadmium nitrate tetrahydrate (98%) and lead nitrate (99.0%) were supplied by Sigma-Aldrich.

2.2. Synthesis of metal-organic framework NH_2-MIL-125(Ti)

The synthesis of NH_2-MIL-125 was conducted following the earlier reported technique with minor modifications [63]. In brief, 0.006 M 2-Amino Terephthalic acid was dissolved in N, N-dimethylformamide (DMF) and stirred for 10 minutes to obtain a clear solution. Then, about 0.003 M titanium isopropoxide was added slowly and stirred to create a homogeneous mixture. Then, approximately 25 mL of methanol was added to the reaction mass and stirred for 30 minutes to form a homogeneous mixture. Then, the reaction mixture is transferred to a 65 mL Teflon-coated stainless-steel autoclave and subjected to heating at 150 °C for a duration of 16 h. Once the reaction was complete, it was brought to room temperature and subsequently rinsed twice with 100 mL of DMF, followed by 100 mL of methanol. The resulting yellow-colored product was dried at 60 ℃ until it was free from solvents. The obtained material is used as a nano-additive with the PSF polymer to prepare the mixed matrix membranes. Figure 1 represents the synthetic route for the preparation of NH_2-MIL-125 [64], and Figure 2 depicts the structural representation of NH_2-MIL-125 [65].

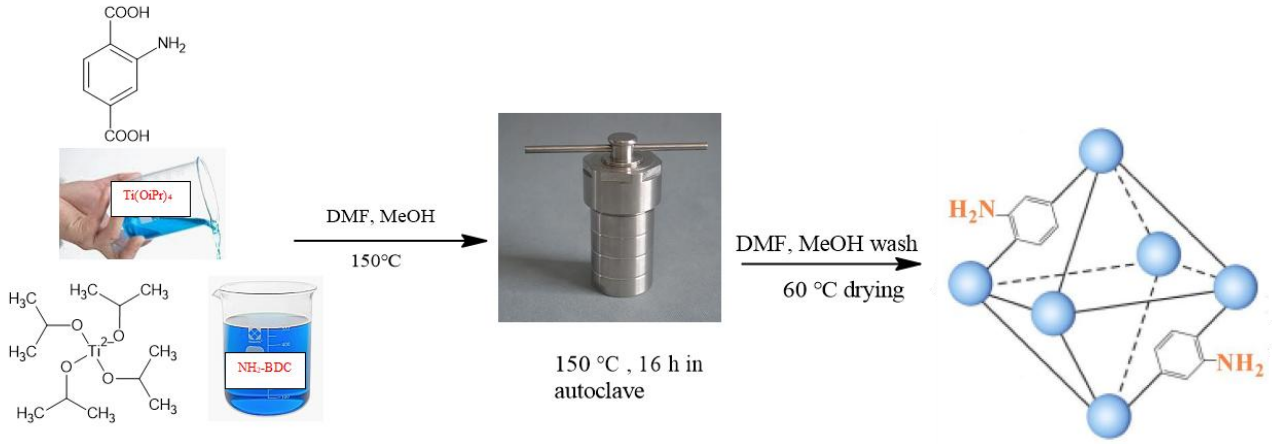

Fig. 1. Schematic representation of the route of synthesis of NH_2-MIL-125 MOF

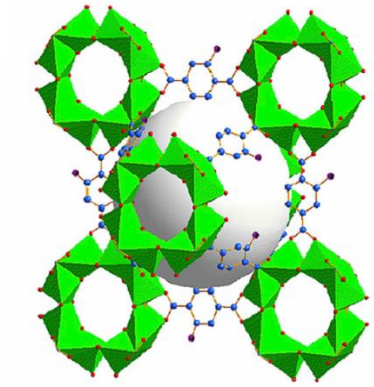

Fig. 2. Structure of NH_2-MIL-125

2.3. Fabrication of NH_2 - MIL-125/PSF composite films.

The NH_2-MIL-125/ PSF nanocomposite thin film was fabricated by a nonsolvent-induced phase separation method [66]. To initiate the experiment, the PSF material was desiccated at 60 ℃ under reduced pressure for one day to ensure that no moisture content remained. Then, fixed quantities of NH_2-MIL-125 (0 wt%, 0.5 wt%, 1 wt%, and 3 wt%) with respect to the weight of polymer were added to N-Methyl-2-pyrrolidone (NMP) solvent in a reagent bottle. The mixture was sonicated for 0.5 h at ambient temperature using a

40 kHz, 60W Spectra lab sonicator to get a clear dispersion.

Then, the PSF polymer and 1% Polyvinylpyrrolidone (PVP) were incorporated into the MOF solution in NMP and agitated at 60℃ for 1 day to obtain a transparent and consistent casting solution.

The dope solution was degassed to eliminate gas bubbles, and the polymer solution was then cast onto a transparent disc using a K-202 precision coating unit. The casted transparent panel was kept still for 10 s before being transferred to a coagulation chamber filled with water that had its minerals removed. The resulting membranes were left undisturbed in deionized water (DM) for 24 h. The specifics of the thin film formulation are provided in Table 1.

2.4. Description of NH_2 - MIL-125 and the blended nanocomposite films of NH_2 - MIL-125/PSF. Surface structures of NH_2 - MIL-125 and NH_2 -MIL-125/PSF composite membranes.

The morphological structure of the prepared nanocomposite and the mixed matrix membranes was analyzed using a Field Emission Scanning Electron Microscope (FESEM) instrument. The chemical composition of the sample was determined using energy-dispersive X-ray spectroscopy. The framework crystals were spread out on a graphite adhesive strip, and a fine coating of gold was applied to the surface. FESEM images were then taken for analysis. The thin film substance was dipped into cryogenic fluid for around one min, after which it was fractured using a knife-edge. Next, the material was mounted on a mounting platform, coated with gold colloids via a sputtering apparatus, and then studied for modifications observed across sections with the aid of an FESEM [67]. The size, structure, orientation, and extent of crystallinity, as well as information on unit cell dimensions, of the nanocomposite material were determined using X-ray Powder Diffraction (XRD) [62].

The occurrence of desired chemical groups in the nanocomposite and the proper blending of MOF into the polymeric membranes have been analyzed using FTIR and Attenuated Total Reflectance–Fourier Transform Infrared Spectroscopy (ATR-FTIR) techniques. About 0.02g of NH_2-MIL-125 was finely milled with anhydrous KBr particles to prepare the sample. The FTIR spectra for NH2-MIL-125 and the ATR-FTIR spectra of the blended membranes were also analyzed [68, 69].

The stability with respect to temperature has been investigated using a thermogravimetric analyzer. The cumulative pore space and mean pore radius for NH_2-MIL-125 have been calculated as per the reported methods. The interfacial extent per mass for a nanoscale particle plus hybrid polymer barriers was computed [70] and the pore volume (P_v) was also calculated through reported methods [71].

A contact angle analyzer was used to study the surface hydrophilicity of the prepared composite films. The hydrophilicity of the surface was measured using the KYOWA (Japan) surface wetting measurement instrument [72].

Table 1. Dope solution composition used in the preparation of mixed matrix membranes.

Membrane	PSF (g)	NMP (g)	PVP (g)	MIL-125 (Ti) wt%	MIL-125 (Ti) (g)
M-0	1.6	8.2	0.016	0	0
M-1	1.6	8.192	0.016	0.5	0.008
M-2	1.6	8.184	0.016	1	0.016
M-3	1.6	8.152	0.016	3	0.048

2.5. Investigation of water absorption and the pore structure of hybrid membranes.

The investigation of the membranes' ability to absorb water and their porosity levels was conducted following the established procedure [73].

A membrane with an area of 1 cm^2 was soaked in demineralized water for a duration of 24 h. Once the period was over, the membrane was removed from the liquid, and its moisture-laden weight was recorded. The wet film specimen was then placed in a vacuum oven at 60 °C for 24 h, after which its dry weight was noted. Based on this data, the percentage of water absorption was determined using the formula Eq. 1.

$$\% \text{ Water uptake} = \left(\frac{W_w - W_d}{W_w}\right) \times 100 \quad (1)$$

In the formula, the weight of the membrane in its dry state is considered W_d and the weight of the membrane in its wet state is regarded as W_w.
The determination of porosity has been carried out following Equation 2

$$\% \text{ Porosity calculation} = \left(\frac{C_w - C_d}{A \times \rho_w \times \delta}\right) \times 100 \quad (2)$$

where C_d refers to the dry mass of the prepared membrane, and C_w signifies the mass of the membrane when it is hydrated, ρ_d is the mass per unit volume of water (0.998 g cm^{-3}), A is the membrane area in wet condition (cm^2), and δ is the thickness of the membrane in wet condition.

2.6. Pure water permeability study of the fabricated membrane

Water filtration experiments were conducted in the laboratory to determine the pure water flux (PWF) of composite membranes made from pristine and MOF blends.
Circular membranes with a measuring area of 5 cm^2 were cut and placed in a sample holder for the compaction process at a pressure of 0.3 MPa for 30 minutes. Subsequently, the pressure was decreased to 0.2 MPa, during which the membranes were assessed for an additional 60 minutes. The inflow used was process water, and the flow rate of clean water was measured following Equation 3, as mentioned in prior research. [73].

$$\mathrm{Lw} = \frac{\mathrm{V}}{\mathrm{Mt}} \quad (3)$$

where, L_w represents the flow rate of pure water (L/m^2/h), V denotes the overall amount of liquid gathered, M refers to the effective membrane surface area and t indicates the duration of the experiment.

2.7. Fouling resistivity study of the fabricated thin film membranes

The study investigated the antifouling properties of neat and hybrid thin films as per the previously reported method [74]. A 1000 ppm Bovine Serum Albumin (BSA) solution was used to conduct flux studies at a pressure of 0.2MPa. Firstly, the permeability of pure water (K_{w1}) in L/m^2/h was measured for 60 min. Then, the BSA permeability studies were conducted and reported as Kp in L/m^2/h. Subsequently, the membrane was rinsed extensively under a continuous flow of tap water for 20 minutes. Finally, pure water permeability (K_{w2}) in L/m^2/h was measured for an additional 60 min. The membrane's ability to resist fouling was determined using Equation 5.

$$\mathrm{FRR\%} = \left(\frac{K_{w2}}{K_{w1}}\right) \times 100 \quad (5)$$

The greater the Flux Recovery Ratio (FRR%), the more effective the material is against fouling. Likewise, the measurements for reversible fouling (R_r), irreparable fouling (R_{ir}), and overall fouling ratio (R_t) have been measured using Eqs. (6)-(8)

$$\mathrm{Rr}\ (\%) = \left(\frac{\mathrm{K_{w2} - K_p}}{\mathrm{Kw1}}\right) \times 100 \quad (6)$$

$$\mathrm{Rir}\ (\%) = \left(\frac{\mathrm{K_{w1} - K_{w2}}}{\mathrm{K_{w1}}}\right) \times 100 \quad (7)$$

$$\mathrm{Rt}\ (\%) = \left(\frac{\mathrm{K_{w1} - K_p}}{\mathrm{K_{w1}}}\right) \times 100 \quad (8)$$

2.8. Investigation of the removal of harmful heavy metal ions.

Removal analysis of harmful heavy metals was conducted using the dead-end filtration method. Solutions of lead(II) nitrate and cadmium(II) nitrate in water were prepared at a concentration of 500 ppm, complexed with 1 wt% Polyethyleneimine (PEI), and studied under a pressure drop across the membrane of 0.2 MPa for one hour. Although both lead and cadmium are divalent in nature, the difference in ionic size, speciation, and affinity towards PEI will lead to strong and stable PEI-Cd complexes compared to PEI-Pb complexes. The hydrodynamic radius is also larger for the former compared to the latter. The rate of rejection was assessed by analyzing the concentration of heavy metals in both the source fluid and the collected filtrate using Atomic Absorption Spectroscopy (AAS) equipment. The refusal rate was computed using Equation 9 [38].

$$\%\mathrm{R} = (1 - \frac{\mathrm{Np}}{\mathrm{Nf}}) \times 100 \quad (9)$$

where N_p denotes the level of the permeate solution, while N_f indicates the level of the feed solution

3. Results and discussion

3.1. Description of NH_2-MIL-125: High-Resolution Electron Beam Surface Imaging System (FESEM) analysis

The structural appearance of the manufactured nanoparticles has been studied using FESEM images, and their elemental composition has been identified with the help of Energy-Dispersive X-ray spectroscopy (EDX). The FESEM images show granular-shaped nanoparticles with smooth surfaces. The cylindrical "cake" like structures exhibit a length of 700-800nm with a thickness of 200 nm [52].

The nanoparticle's shape may vary depending on the concentration of the reactants and the solvents used during the synthesis [59]. The EDX spectrum showed (Figure 3) that the elemental composition is comprised of titanium, carbon, nitrogen, and oxygen, affirming the formation of NH_2-MIL-125.

3.2. Fourier Transform Infrared Spectroscopy (FTIR) analysis

The FTIR spectrum of NH_2-MIL-125 is shown in Figure 4, displaying the characteristic peaks. All of the spectra display distinctive vibrational bands in the 1400–1700 cm^{-1} region, characteristic of the carboxylate group within the titanium-linked metal-organic framework (MOF) architecture. The compound being analyzed exhibits several absorption bands in its infrared spectrum. Specifically, two absorption lines at approximately 1600 and 1500 cm^{-1} can be attributed to uneven oscillations of carbonyl stretching. Meanwhile, bands around 1440 and 1400 cm^{-1} indicate even oscillations of carbonyl stretching. Additionally, the band observed at 1250 cm^{-1} is attributed to the C–H symmetric stretching vibrations of the benzene ring. The region between 400 and 800 cm^{-1} features the vibrations of Ti–O–Ti–O. Finally, the bands at 3500 cm^{-1} and 3380 cm^{-1} indicate the presence of the NH_2 group [59].

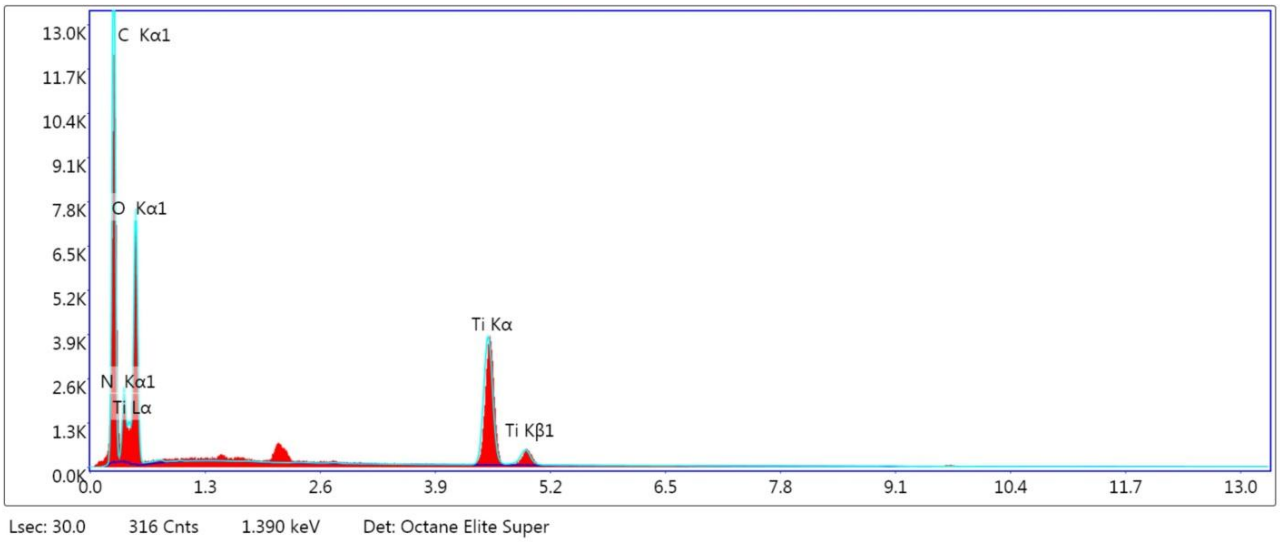

Fig. 3. Graphical representation of EDX analysis report of MIL-125(Ti)

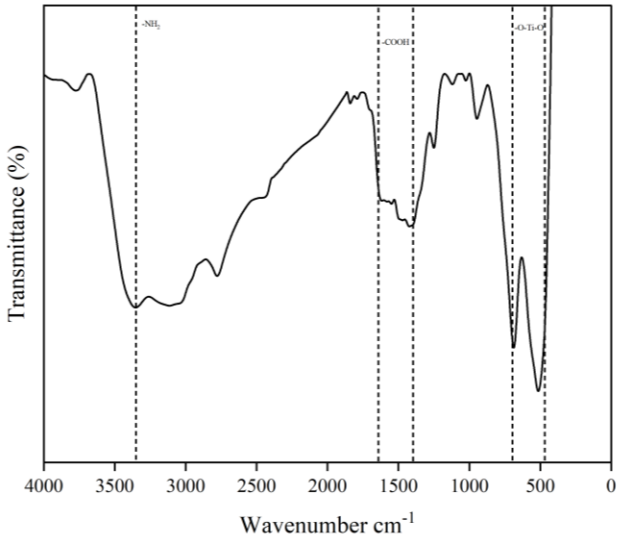

Fig. 4. IR spectrum of NH_2-MIL-125(Ti) crystals synthesized

3.3. Thermal Weight Measurement (TWM) and Differential Thermal Examination (DTE)

The heat solidity of the produced MOF material (Ti) was assessed using TWM and DTE measurements. The initial reduction in weight noted between 80 ℃ to 120 ℃ corresponds to trapped solvents and water traces. Upon further heating, the degradation of amino terephthalic acid starts at around 320℃ and goes up to 470℃, where the complete oxidation of organic linkers was observed [52]. Only the residue of metal oxide (TiO_2) will be observed above that temperature [59].

3.4. X-ray Powder Diffraction (XRD) Analysis

The crystal building of the synthesized nanomaterial was investigated using the Powder X-ray Diffraction (PXRD) technique.

From Figure 5, we can see all the crystalline patterns of the synthesized MOF. This structure consists of chains of corner-sharing TiO_6 octahedra with μ-OH groups, interconnected by NH_2-BDC molecules to form a 3D porous network. The sharp peaks at 2θ of 6.71^0, $9.58^{0,}$ and 11.58^0 indicate that NH_2-MIL-125 has been formed as reported in the literature [68].

3.5. Gas Adsorption Surface Area Method (BET Theory) Assessment

The nitrogen adsorption-desorption isotherm of NH_2-MIL-125 metal-organic framework and the corresponding aperture dimension distribution are studied. BET measurements indicated that the available surface area was 1042.04 m²/g.

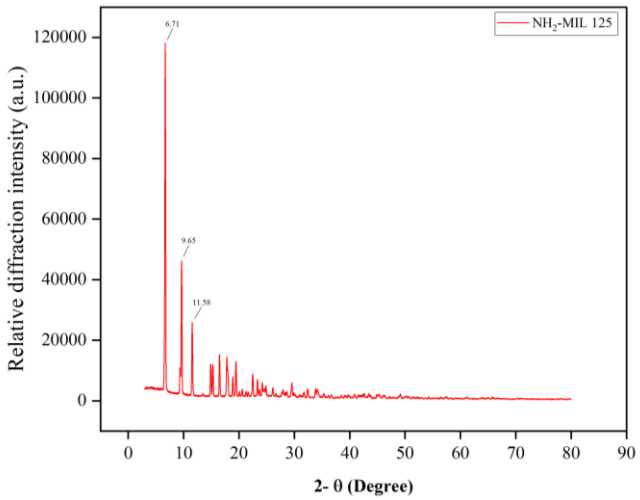

Fig. 5 The XRD pattern of NH_2-MIL-125

The adsorption pore diameter is found to be 1.4 nm, and for desorption, it is found to be 1.94046 nm. The pore volume is found to be 0.5 cm³/g. The graph indicates a type-III adsorption isotherm, which is flat due to the superposition of adsorption and desorption isotherms, mostly occurring in micropores [75].

The Barrett–Joyner–Halenda (BJH) pore size distribution of the synthesized MOF was similar to previously reported work [52]. The maximum point at 2.7 nm suggests a structure with tiny pores [76, 77].

3.6. Examinations of the structure of blended membranes Assessment using a Field Emission Scanning Electron Microscope (FESEM)

The surface topography of the original (M-0) and MOF-doped films was analyzed using the FESEM technique. The images show a top dense layer and a porous sublayer attributed to asymmetric membranes. The neat film (M-0) shows tiny digit extensions, and as we increase the percentage composition of nano components, the finger-like projections and the macrovoids increase from M-1 to M-3. The increase in spongy structure and macrovoids is owing to hydrophilic carboxylate groups and amino groups of MOF. The addition of a pore-generating agent, PVP, to the casting solution accelerates the phase inversion process, resulting in larger macrovoids. The EDX analysis (Figure 6 (a, b, c, d)) shows the occurrence of Nitrogen, Oxygen, Sulphur, Carbon, and Titanium on the membrane matrix of composite membranes, showing the successful incorporation of nanoparticles on the membrane surface [73, 78].

3.7. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The various functional moieties present in the PSF polymer and the incorporated MOF have been analyzed using the FTIR technique [53, 69]. Figure 7 shows the grouped spectrum of neat and mixed matrix thin films.

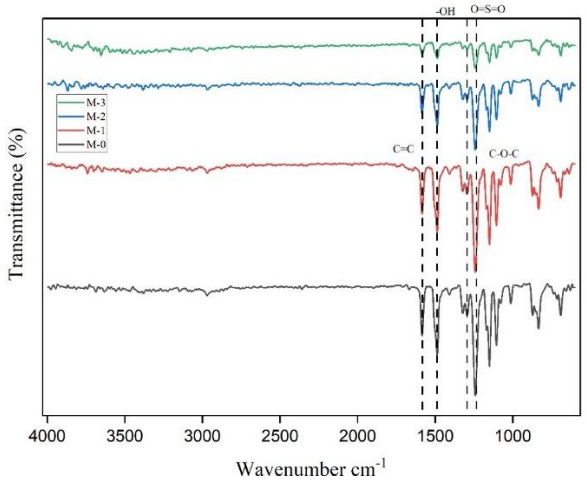

Fig. 7. The stacked FTIR spectra of both pristine and composite membranes

The peaks around 3400 cm^{-1} are attributed to the vibration of -OH and -NH groups. The maximum observed at 1590 cm^{-1} is linked to C=C vibrations, while the prominent absorption peak at 1490 cm^{-1} is associated with -OH deformation. The resonance bands detected at 1300 cm^{-1} and 1350 cm^{-1} are associated with the stretching frequencies of the O=S=O group. The primary Ti-related peaks are observed in the region between 400 and 800 cm^{-1}. The Ti-O stretching vibration is observed at 650-800 cm-1, and the Ti-O-Ti bridging vibrations are observed at 650-800 cm^{-1}. The Ti-O-Ti bridging stretching mode is also observed at 424 cm^{-1} [79-81].

3.8. Contact angle measurements

The surface absorbency, hydrophobicity, and hydrophilicity of the prepared membranes have been investigated using contact angle analysis. By employing the sessile drop technique, the contact angle is measured to determine the preferential wetting of a given membrane by water. The neat thin film M-0 exhibited a surface wettability measurement of 85.1^0, while M-1 produced 75.5^0, M-2 showed 69.9^0, and M-3, with the least droplet interface angle of 65.5^0. This indicates that the addition of nanoparticles has enhanced the water-attracting properties of the fabricated membranes [82].

3.9. Clean water flow analysis

Filtration studies have been conducted to assess the pure water permeability of the original and nanocomposite membranes. The M-3 film exhibited a maximum flux of 202.69 $L/m^2/h$ after 60 mins, while the original membrane M-0 displayed a flux of 44.57 $L/m^2/h$ after 60 mins.

3.10. Antifouling nature of membranes

During filtration studies, scientists consider fouling of prepared membranes a major issue. Several factors, including pore plugging, narrowing, and the formation of protein cake, cause this fouling. These factors are of major concern when preparing membranes for commercialization [83]. The M-3 film demonstrated the most significant resistance to membrane fouling.

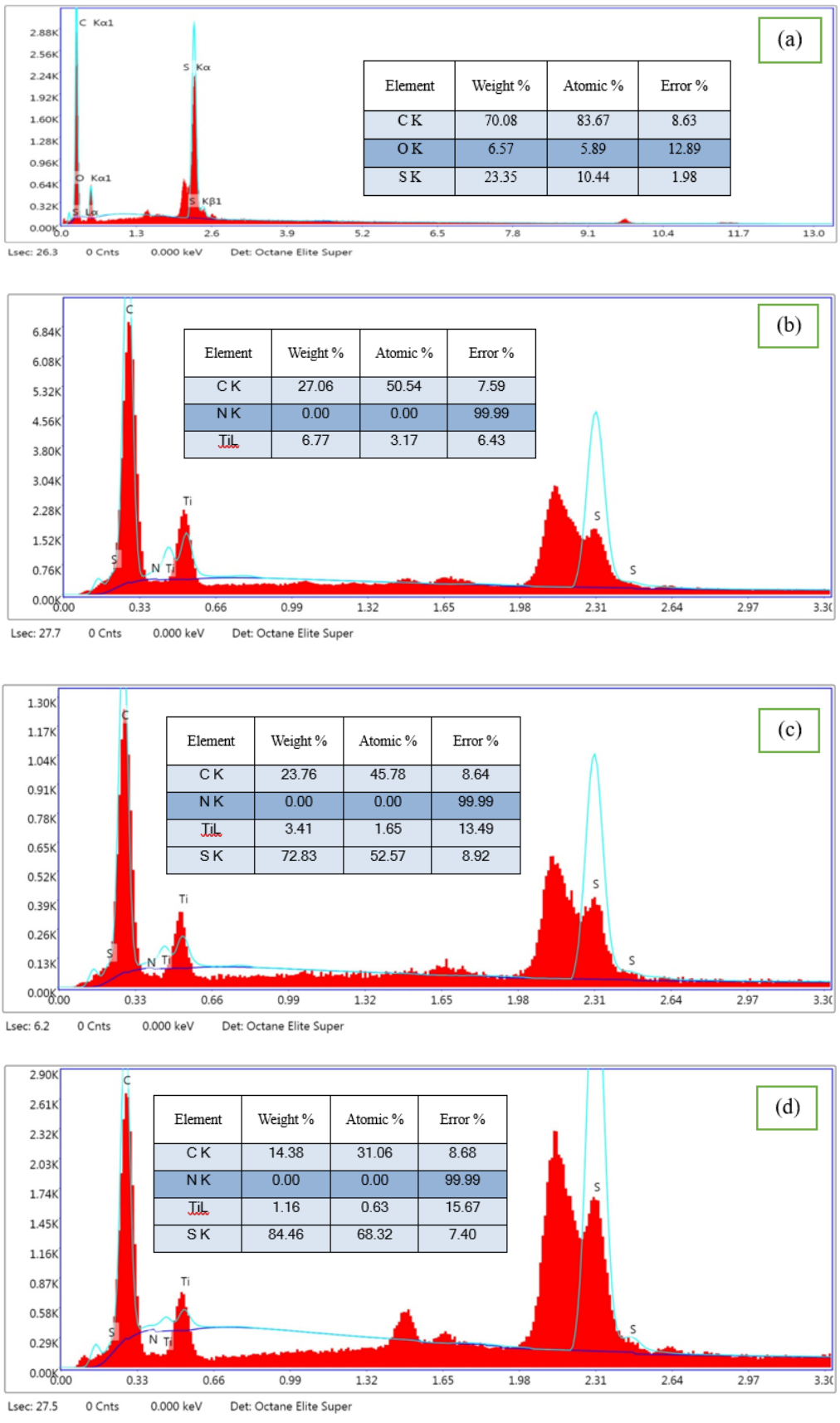

Fig. 6. The EDX outcomes for (a) M-0, (b) M-1, (c) M-2, and (d) M-3 are provided.

3.11. Investigation of moisture absorption and void space analysis

The effect of nanoparticles on the synthesized mixed matrix membranes is collectively displayed in Table 2.

The water uptake increased by 21.93% when transitioning from the pristine to the M-3 membrane, with the M-3 membrane exhibiting the maximum porosity.

The same trend has also been observed in contact angle measurements. The homogeneous distribution of MOF on the membrane matrix has led to the formation of more pores and voids, which in turn leads to an increase in flux, water uptake, and porosity values [84].

The MOF membrane has a relatively uniform and sturdy porosity, but the shape of its pores seems to be irregular and elongated.

These asymmetrical pore structures, which can resemble finger-like or spongelike projections, have the potential to boost mass transfer and, as a result, improve rejection efficiency [52]. The MOFs made of terephthalic acid and 2-amino terephthalic acid efficiently interact with membranes by acting as pore-forming agents [85].

3.12. Heavy metal rejection studies of membranes

In this study, pristine and MOF-amalgamated mixed matrix membranes were used to investigate the rejection capabilities at varying concentrations of MOFs.

The rejection studies have been depicted using a bar graph for lead and cadmium for different membranes.

Figure 8 displays the details of the rejection study. In this study, the M-3 composite film with 3.0% MOF incorporation exhibited a 99.10% rejection for cadmium and a 75.02% rejection for lead. In the investigation of heavy metal filtration, agents such as polyethyleneimine (PEI) are employed to enhance the particle size of the metals, resulting in improved rejection rates.

The rejection percentage has increased by approximately 14% from the pristine membrane to the 3% MOF-induced membrane for cadmium and lead.

The removal of toxic ions by membranes is more likely to depend on the size exclusion mechanism. Adsorption may contribute to the rejection of metal ions due to weak molecular forces, hydrogen interactions, and ionic attraction [86].

The concentration of the feed solution used in the research is set at 500 parts per million, and as the feed concentration increases, the percentage rejection decreases.

The reduced availability of several active adsorption sites is the reason behind this [13, 87]. A comparative statistical rejection study is presented in Table 3.

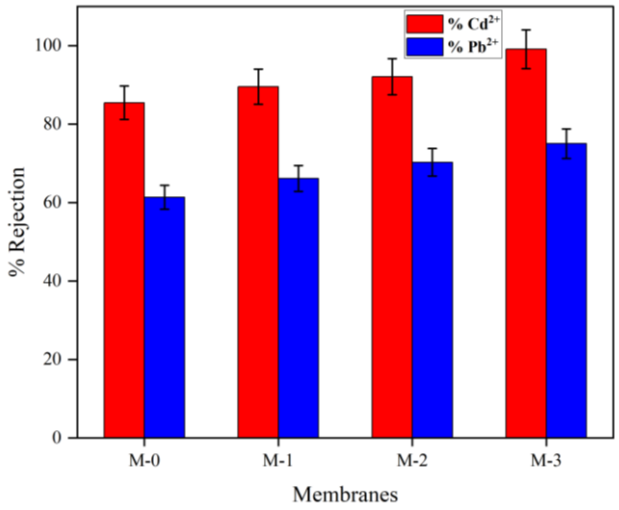

Fig. 8. Heavy metal rejection studies of membranes

Table 2. Membrane properties

Membranes	PWFL/m²/h	Water uptake (%)	Porosity (%)	FRR (%)	Rt (%)	Rrev (%)	Rirr (%)
M-0	44.57	51.79	193.07	81.57	40.64	8.32	18.42
M-1	99.75	69.72	198.13	88.13	24.2	9.57	11.86
M-2	89.14	69.47	220.44	89.27	19.14	12.33	9.57
M-3	202.68	73.72	337.34	90.42	19.04	22.51	10.72

Table 3. Comparison of membrane performance with other reported polysulfone membranes

Entry	Polymer	Nanofiller	Operating conditions	Heavy metal	Feed (ppm)	Removal (%)	Reference
1	Polysulfone	Sulfonated polyimide	4.0 bar, Dead-end filtration	Lead and Cadmium	500	97.6 and 92.2	[88]
2	Polysulfone	Titania nanotubes and magnetite oxide hybrid nanoparticles	Cross-flow filtration	Lead and Cadmium	-	98 and 98	[89]
3	Polysulfone	MOF-5@GO	2.0 bar, Cross-flow filtration	Lead and Cadmium	-	99 and 99	[90]
4	Polysulfone	GO, ZnO, NiO	2.0 bar	Lead and Cadmium	200	30.81 and 35.48	[91]
5	Polysulfone	Mesoporous Mg-Al-Ti ternary composite oxide	-	Lead and Cadmium	-	90 and 90	[92]
6	Polysulfone	Multiwalled carbon nanotubes and polyethylenimine	0.2 bar, Dead-end filtration	Lead and Cadmium	-	96.2 and 93.87	[93]
7	Polysulfone	Multiwall carbon nanotubes and chitosan	6.0 bar, Dead-end filtration	Lead	10	71.3	[94]
8	Polysulfone	Jute copper nanocomposite	-	Lead and Cadmium	1	85.2 and 84.3	[95]
9	Polysulfone	montmorillonite	1.0 bar dead end	Lead and Cadmium	5	3 and 12	[96]
10	Polysulfone	sodium dodecyl sulfate	2.0 bar, Dead-end filtration	Lead	50	90.52	[97]
11	Polysulfone	Carbon nitride	RO	Lead and Cadmium	-	95 and 80	[98]
12	Polysulfone	Al–Ti_2O_6	RO	Lead and Cadmium	-	99 and 98	[99]
13	Polyether sulfone	-	Cross-flow filtration	Lead and Cadmium	10	99 and 78	[87]
14	Chitosan-Polysulfone	Dendritic mesoporous silica nanoparticles	Dead-end filtration	Lead and Cadmium	20	88 and 97	[100]
15	Polysulfone	NH_2-MIL-125	2.0 bar, Dead-end filtration	Lead and Cadmium	500	75.02 and 99.10	In this study

4. Conclusion

The novelty of this study lies in the use of the amino-functionalized metal–organic framework, NH_2-MIL-125(Ti), as a filler in polysulfone mixed matrix membranes for heavy metal removal. While our earlier work employed the parent MIL-125(Ti) MOF for dyes (RB-5, RO-16) and metal ions (Pb^{2+}, Cd^{2+}) rejection, the present investigation focuses exclusively on Pb^{2+} and Cd^{2+} separation using the functionalized analogue.

The incorporation of $–NH_2$ groups not only enhanced the interaction between the MOF and the polymer matrix but also improved the affinity toward heavy metal ions, resulting in significantly higher rejection efficiencies (99.1% for Cd^{2+} and 75.02% for Pb^{2+}) compared to the previously reported values (89.33% and 68.81%, respectively, for MIL-125(Ti)). This work, therefore, demonstrates the superior performance of functionalized MOFs in mixed-matrix membranes and provides new insights into the role of linker

modification in enhancing membrane-based water purification.

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Author's contribution

Shivarama B. conducted the experiments and prepared the original draft of the manuscript. **Arun M. Isloor** supervised the overall research work. **Chivukula Suryanarayana Murthy** provided technical inputs and guidance. **Balakrishna Prabhu** assisted with technical analysis and assisted in carrying out selected characterization studies. All authors reviewed and approved the final manuscript.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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References

[1] Fane, A. G., Wang, R., & Hu, M. X. (2015). Synthetic Membranes for Water Purification: Status and Future. *Angewandte Chemie International Edition*, *54*(11), 3368-3386. https://doi.org/10.1002/anie.201409783

[2] Magara, Y., Kunikane, S., & Itoh, M. (1998). Advanced membrane technology for application to water treatment. *Water Science and Technology*, *37*(10), 91-99. https://doi.org/10.1016/S0273-1223(98)00307-2

[3] Srivastava, N. K., & Majumder, C. B. (2008). Novel biofiltration methods for the treatment of heavy metals from industrial wastewater. *Journal of Hazardous materials*, *151*(1), 1-8. https://doi.org/10.1016/j.jhazmat.2007.09.101

[4] Abdullah, N., Yusof, N., Lau, W. J., Jaafar, J., & Ismail, A. F. (2019). Recent trends of heavy metal removal from water/wastewater by membrane technologies. *Journal of Industrial and Engineering Chemistry*, *76*, 17-38. https://doi.org/10.1016/j.jiec.2019.03.029

[5] Birniwa, A. H., Habibu, S., Abdullahi, S. S. a., Mohammad, R. E. A., Hussaini, A., Magaji, H.,...Jagaba, A. H. (2024). Membrane technologies for heavy metals removal from water and wastewater: A mini review. *Case Studies in Chemical and Environmental Engineering*, *9*, 100538. https://doi.org/10.1016/j.cscee.2023.100538

[6] Ince, M., & Kaplan İnce, O. (2017). [An Overview of Adsorption Technique for Heavy Metal Removal from Water/Wastewater: A Critical Review]. *International Journal of Pure and Applied Sciences*, *3*(2), 10-19. https://doi.org/10.29132/ijpas.358199

[7] Thakur, A., Kumar, A., & Singh, A. (2024). Adsorptive removal of heavy metals, dyes, and pharmaceuticals: Carbon-based nanomaterials in focus. *Carbon*, *217*, 118621. https://doi.org/10.1016/j.carbon.2023.118621

[8] Zaimee, M. Z., Sarjadi, M. S., & Rahman, M. L. (2021). Heavy Metals Removal from Water by Efficient Adsorbents. *Water*, *13*(19). https://doi.org/10.3390/w13192659

[9] Bolisetty, S., Peydayesh, M., & Mezzenga, R. (2019). Sustainable technologies for water purification from heavy metals: review and analysis [10.1039/C8CS00493E]. *Chemical Society Reviews*, *48*(2), 463-487. https://doi.org/10.1039/C8CS00493E

[10] Guo, X., Yang, Z., Dong, H., Guan, X., Ren, Q., Lv, X., & Jin, X. (2016). Simple combination of oxidants with zero-valent-iron (ZVI) achieved very rapid and highly efficient removal of heavy

metals from water. *Water Research*, *88*, 671-680. https://doi.org/10.1016/j.watres.2015.10.045

[11] Li, X., Liu, H., Zhang, Y., Mahlknecht, J., & Wang, C. (2024). A review of metallurgical slags as catalysts in advanced oxidation processes for removal of refractory organic pollutants in wastewater. *Journal of Environmental Management*, *352*, 120051. https://doi.org/10.1016/j.jenvman.2024.120051

[12] D, M. S., Isloor, A. M., Nayak, S. S., Venktesh, M., & Shetti, V. (2025). Polydopamine functionalized halloysite nanotubes incorporated polyethersulfone hollow fiber membranes for the removal of arsenic (as-v) from water. *Advances in Environmental Technology*, *11*(3), 266-282. https://doi.org/10.22104/aet.2025.7186.1978

[13] Ibrahim, G. P. S., Isloor, A. M., Inamuddin, Asiri, A. M., Ismail, A. F., Kumar, R., & Ahamed, M. I. (2018). Performance intensification of the polysulfone ultrafiltration membrane by blending with copolymer encompassing novel derivative of poly(styrene-co-maleic anhydride) for heavy metal removal from wastewater. *Chemical Engineering Journal*, *353*, 425-435. https://doi.org/10.1016/j.cej.2018.07.098

[14] Kumar, M., Isloor, A. M., Nayak, M. C. S., Todeti, S. R., Padaki, M., & Ismail, A. F. (2023). Hydrophilic polydopamine/polyvinylpyrrolidone blended polyphenylsulfone hollow fiber membranes for the removal of arsenic-V from water. *Journal of Environmental Chemical Engineering*, *11*(5), 110358. https://doi.org/10.1016/j.jece.2023.110358

[15] Honarmandrad, Z., Javid, N., & Malakootian, M. (2020). Efficiency of ozonation process with calcium peroxide in removing heavy metals (Pb, Cu, Zn, Ni, Cd) from aqueous solutions. *SN Applied Sciences*, *2*(4), 703. https://doi.org/10.1007/s42452-020-2392-1

[16] Ikhlaq, A., Aslam, T., Zafar, A. M., Javed, F., & Munir, H. M. S. (2019). Combined ozonation and adsorption system for the removal of heavy metals from municipal wastewater: effect of COD removal. *Desalination and Water Treatment*, *159*, 304-309. https://doi.org/10.5004/dwt.2019.24164

[17] Zhu, Y., Luo, H., Wang, T., Zhou, J., Zhu, Y., & Hou, J. (2024). Advanced treatment of landfill leachate by catalytic ozonation with MnCeOx/γ-Al2O3 catalyst. *Surfaces and Interfaces*, *46*, 104113. https://doi.org/10.1016/j.surfin.2024.104113

[18] Al-Enezi, G., Hamoda, M. F., & Fawzi, N. (2004). Ion Exchange Extraction of Heavy Metals from Wastewater Sludges. *Journal of Environmental Science and Health, Part A*, *39*(2), 455-464. https://doi.org/10.1081/ESE-120027536

[19] Dąbrowski, A., Hubicki, Z., Podkościelny, P., & Robens, E. (2004). Selective removal of the heavy metal ions from waters and industrial wastewaters by ion-exchange method. *Chemosphere*, *56*(2), 91-106. https://doi.org/10.1016/j.chemosphere.2004.03.006

[20] Benalia, M. C., Youcef, L., Bouaziz, M. G., Achour, S., & Menasra, H. (2022). Removal of Heavy Metals from Industrial Wastewater by Chemical Precipitation: Mechanisms and Sludge Characterization. *Arabian Journal for Science and Engineering*, *47*(5), 5587-5599. https://doi.org/10.1007/s13369-021-05525-7

[21] Singhal, A., Parihar, A., Khare, V., Tripathi, G. K., & Khan, R. (2024). Chemical Approaches to Remediate Heavy Metals. In *Remediation of Heavy Metals* (pp. 123-147). https://doi.org/https://doi.org/10.1002/9781119853589.ch7

[22] Arana Juve, J.-M., Christensen, F. M. S., Wang, Y., & Wei, Z. (2022). Electrodialysis for metal removal and recovery: A review. *Chemical Engineering Journal*, *435*, 134857. https://doi.org/10.1016/j.cej.2022.134857

[23] Bunani, S., Abbt-Braun, G., & Horn, H. (2024). Heavy Metal Removal from Aqueous Solutions Using a Customized Bipolar Membrane Electrodialysis Process. *Molecules*, *29*(8). https://doi.org/10.3390/molecules29081754

[24] Malato, S. (2008). Removal of Emerging Contaminants in Waste-water Treatment: Removal by Photo-catalytic Processes. In Barceló, D. & Petrovic, M. (Eds.), *Emerging*

Contaminants from Industrial and Municipal Waste: Removal Technologies (pp. 177-197). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-79210-9_5

[25] Massoudinejad, M., Keramati, H., & Ghaderpoori, M. (2020). Investigation of photo-catalytic removal of arsenic from aqueous solutions using UV/H2O2 in the presence of ZnO nanoparticles. *Chemical Engineering Communications*, *207*(11), 1605-1615. https://doi.org/10.1080/00986445.2019.1674813

[26] Bazrafshan, E., Mohammadi, L., Ansari-Moghaddam, A., & Mahvi, A. H. (2015). Heavy metals removal from aqueous environments by electrocoagulation process– a systematic review. *Journal of Environmental Health Science and Engineering*, *13*(1), 74. https://doi.org/10.1186/s40201-015-0233-8

[27] Solis-Marcial, O. J., Talavera-López, A., Ruelas-Leyva, J. P., Hernández-Maldonado, J. A., Najera-Bastida, A., Zarate-Gutierrez, R., & Serrano Rosales, B. (2024). Clarification of Mining Process Water Using Electrocoagulation. *Minerals*, *14*(4). https://doi.org/10.3390/min14040412

[28] Un, U. T., & Ocal, S. E. (2015). Removal of heavy metals (Cd, Cu, Ni) by electrocoagulation. *International Journal of Environmental Science and Development*, *6*(6), 425–429. https://doi.org/10.7763/ijesd.2015.v6.630

[29] Bang Mo, K. (1984). Membrane-based solvent extraction for selective removal and recovery of metals. *Journal of Membrane Science*, *21*(1). https://doi.org/10.1016/S0376-7388(00)83060-4

[30] Černá, M. (1995). Use of solvent extraction for the removal of heavy metals from liquid wastes. *Environmental Monitoring and Assessment*, *34*(2), 151-162. https://doi.org/10.1007/BF00546029

[31] Gavrilescu, M. (2004). Removal of Heavy Metals from the Environment by Biosorption. *Engineering in Life Sciences*, *4*(3), 219-232. https://doi.org/10.1002/elsc.200420026

[32] Sarker, A., Masud, M. A. A., Deepo, D. M., Das, K., Nandi, R., Ansary, M. W. R.,...Islam, T. (2023). Biological and green remediation of heavy metal contaminated water and soils: A state-of-the-art review. *Chemosphere*, *332*, 138861. https://doi.org/10.1016/j.chemosphere.2023.138861

[33] Wingenfelder, U., Hansen, C., Furrer, G., & Schulin, R. (2005). Removal of heavy metals from mine waters by natural zeolites. *Environmental Science and Technology*, *39*(12). https://doi.org/10.1021/es048482s

[34] Ibrahim, S., Mohammadi Ghaleni, M., Isloor, A. M., Bavarian, M., & Nejati, S. (2020). Poly(Homopiperazine–Amide) Thin-Film Composite Membrane for Nanofiltration of Heavy Metal Ions. *ACS Omega*, *5*(44), 28749-28759. https://doi.org/10.1021/acsomega.0c04064

[35] Khraisheh, M., Elhenawy, S., AlMomani, F., Al-Ghouti, M., Hassan, M. K., & Hameed, B. H. (2021). Recent Progress on Nanomaterial-Based Membranes for Water Treatment. *Membranes*, *11*(12), 995. https://doi.org/10.3390/membranes11120995

[36] Mamah, S. C., Goh, P. S., Ismail, A. F., Suzaimi, N. D., Yogarathinam, L. T., Raji, Y. O., & El-badawy, T. H. (2021). Recent development in modification of polysulfone membrane for water treatment application. *Journal of Water Process Engineering*, *40*, 101835. https://doi.org/10.1016/j.jwpe.2020.101835

[37] Bassyouni, M., Abdel-Aziz, M. H., Zoromba, M. S., Abdel-Hamid, S. M. S., & Drioli, E. (2019). A review of polymeric nanocomposite membranes for water purification. *Journal of Industrial and Engineering Chemistry*, *73*, 19-46. https://doi.org/10.1016/j.jiec.2019.01.045

[38] Syed Ibrahim, G. P., M. Isloor, A., Al Ahmed, A., & Lakshmi, B. (2017). Fabrication and Characterization of Polysulfone-Zeolite ZSM-5 Mixed Matrix Membrane for Heavy Metal Ion Removal Application. *Journal of Applied Membrane Science & Technology*, *18*(1). https://doi.org/10.11113/amst.v18i1.17

[39] Noah, N. M. (2023). Current Status and Advancement of Nanomaterials within Polymeric Membranes for Water Purification. *ACS Applied Nano Materials*.

https://doi.org/10.1021/acsanm.3c04110

[40] Jafarian, H., Dadashi Firouzjaei, M., Aghapour Aktij, S., Aghaei, A., Pilevar Khomami, M., Elliott, M.,...Rahimpour, A. (2023). Synthesis of heterogeneous metal organic Framework-Graphene oxide nanocomposite membranes for water treatment. *Chemical Engineering Journal*, *455*, 140851. https://doi.org/10.1016/j.cej.2022.140851

[41] Asif, M. B., Kim, S., Nguyen, T. S., Mahmood, J., & Yavuz, C. T. (2024). Covalent Organic Framework Membranes and Water Treatment. *Journal of the American Chemical Society*, *146*(6), 3567-3584. https://doi.org/10.1021/jacs.3c10832

[42] Wang, X., Zhao, Y., Tian, E., Li, J., & Ren, Y. (2018). Graphene Oxide-Based Polymeric Membranes for Water Treatment. *Advanced Materials Interfaces*, *5*(15), 1701427. https://doi.org/10.1002/admi.201701427

[43] Yin, J., & Deng, B. (2015). Polymer-matrix nanocomposite membranes for water treatment. *Journal of Membrane Science*, *479*, 256-275. https://doi.org/10.1016/j.memsci.2014.11.019

[44] Wang, Z., Sim, A., Urban, J. J., & Mi, B. (2018). Removal and Recovery of Heavy Metal Ions by Two-dimensional MoS2 Nanosheets: Performance and Mechanisms. *Environmental Science & Technology*, *52*(17), 9741-9748. https://doi.org/10.1021/acs.est.8b01705

[45] Lim, G. P., Soon, C. F., Al-Gheethi, A. A., Morsin, M., & Tee, K. S. (2022). Recent progress and new perspective of MXene-based membranes for water purification: A review. *Ceramics International*, *48*(12), 16477-16491. https://doi.org/10.1016/j.ceramint.2022.03.165

[46] Mehrifar, Y. F., Ghasemi Koozekonan, A. F., Rashidi, M. A. F., Arab, N. F., & Farhang Dehghan, S. F. (2024). A review on H2S adsorption by metal-organic frameworks for air purification application. *Advances in Environmental Technology*, *10*(3), 270-296. https://doi.org/10.22104/aet.2024.6818.1863

[47] Zhou, H. C., Long, J. R., & Yaghi, O. M. (2012). Introduction to metal-organic frameworks. *Chemical Reviews*, *112*. https://doi.org/10.1021/cr300014x

[48] Khosravi, M. J., Hosseini, S. M., & Vatanpour, V. (2022). Polyamidoamine dendrimers-Mil-125(Ti) MOF embedded polyethersulfone membrane for enhanced removal of heavy metal, antibiotic and dye from water. *Journal of Environmental Chemical Engineering*, *10*(6), 108644. https://doi.org/10.1016/j.jece.2022.108644

[49] Abdelhameed, R. M., Ismail, R. A., El-Naggar, M., Zarie, E. S., Abdelaziz, R., & El Sayed, M. T. (2019). Post-synthetic modification of MIL-125 with bis-quinoline Mannich bases for removal of heavy metals from wastewater. *Microporous and Mesoporous Materials*, *279*, 26-36. https://doi.org/10.1016/j.micromeso.2018.12.018

[50] Shahid, M. U., Najam, T., Islam, M., Hassan, A. M., Assiri, M. A., Rauf, A.,...Nazir, M. A. (2024). Engineering of metal organic framework (MOF) membrane for waste water treatment: Synthesis, applications and future challenges. *Journal of Water Process Engineering*, *57*, 104676. https://doi.org/10.1016/j.jwpe.2023.104676

[51] Yang, C., Wang, J., Yan, W., & Xia, Y. (2022). Facile synthesis disposable MOF membrane filter: Growth of NH2-MIL-125 (Ti) on filter paper for fast removal of organophosphorus pesticides in aqueous solution and vegetables. *Food Chemistry*, *389*, 133056. https://doi.org/10.1016/j.foodchem.2022.133056

[52] Shivarama, B., Isloor, A. M., Murthy, C. S., Prabhu, B., & Rashid, S. A. (2025). A polysulfone/MIL-125(Ti) mixed matrix membrane for removing toxic dyes and heavy metals from water. *Applied Nanoscience*, *15*(3), 20. https://doi.org/10.1007/s13204-025-03095-w

[53] Ahmadi, A., Sarrafzadeh, M. H., Mohamadi, M., Mahdigholian, Z., & Hosseinian, A. (2020). Investigation on polysulfone blended NH2-MIL125 (Ti) membrane for photocatalytic degradation of Methylene Blue dye. *Journal of Water and Environmental Nanotechnology*, *5*(3), 234-245. https://doi.org/10.22090/jwent.2020.03.004

[54] Zhu, X., Yu, Z., Liu, Y., Li, X., Long, R., Wang, P., & Wang, J. (2021). NH2-MIL-125@PAA composite membrane for separation of oil/water emulsions and dyes. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *630*, 127542. https://doi.org/10.1016/j.colsurfa.2021.127542

[55] Ding, S. H., Oh, P. C., Mukhtar, H., & Jamil, A. (2024). Influence of NH2-MOF addition into PVDF and estimation of CO2 gas transport through membrane. *Materials Today: Proceedings*, *96*, 11-16. https://doi.org/10.1016/j.matpr.2023.08.145

[56] Bayrami, A., Bagherzadeh, M., Navi, H., Nikkhoo, M., & Amini, M. (2022). Zwitterion-functionalized MIL-125-NH2-based thin-film nanocomposite forward osmosis membranes: towards improved performance for salt rejection and heavy metal removal [10.1039/D2NJ02608B]. *New Journal of Chemistry*, *46*(31), 15205-15218. https://doi.org/10.1039/D2NJ02608B

[57] Tarkhani, M., Mousavi, S. A., Asadollahi, M., Bastani, D., & Pourasad, F. (2023). Investigating the effect of zirconium-based and titanium-based metal–organic frameworks nanoparticles on the performance of polysulfone hollow fiber mixed matrix membrane for dialysis application. *Polymer Engineering & Science*, *63*(3), 986-1000. https://doi.org/10.1002/pen.26259

[58] Jun, B.-M., Al-Hamadani, Y. A. J., Son, A., Park, C. M., Jang, M., Jang, A.,...Yoon, Y. (2020). Applications of metal-organic framework based membranes in water purification: A review. *Separation and Purification Technology*, *247*, 116947. https://doi.org/10.1016/j.seppur.2020.116947

[59] Hu, S., Liu, M., Li, K., Zuo, Y., Zhang, A., Song, C.,...Guo, X. (2014). Solvothermal synthesis of NH2-MIL-125(Ti) from circular plate to octahedron [10.1039/C4CE01545B]. *CrystEngComm*, *16*(41), 9645-9650. https://doi.org/10.1039/C4CE01545B

[60] Moideen K, I., Isloor, A. M., Ismail, A. F., Obaid, A., & Fun, H.-K. (2016). Fabrication and characterization of new PSF/PPSU UF blend membrane for heavy metal rejection. *Desalination and Water Treatment*, *57*(42), 19810-19819. https://doi.org/10.1080/19443994.2015.1106985

[61] Pereira, V. R., Isloor, A. M., Bhat, U. K., Ismail, A. F., Obaid, A., & Fun, H.-K. (2015). Preparation and performance studies of polysulfone-sulfated nano-titania (S-TiO2) nanofiltration membranes for dye removal [10.1039/C5RA07994B]. *RSC Advances*, *5*(66), 53874-53885. https://doi.org/10.1039/C5RA07994B

[62] Ibrahim, G. P. S., Isloor, A. M., Inamuddin, Asiri, A. M., Ismail, N., Ismail, A. F., & Ashraf, G. M. (2017). Novel, one-step synthesis of zwitterionic polymer nanoparticles via distillation-precipitation polymerization and its application for dye removal membrane. *Scientific Reports*, *7*(1), 15889. https://doi.org/10.1038/s41598-017-16131-9

[63] Gómez-Avilés, A., Peñas-Garzón, M., Bedia, J., Dionysiou, D. D., Rodríguez, J. J., & Belver, C. (2019). Mixed Ti-Zr metal-organic-frameworks for the photodegradation of acetaminophen under solar irradiation. *Applied Catalysis B: Environmental*, *253*, 253-262. https://doi.org/10.1016/j.apcatb.2019.04.040

[64] Fu, Y., Zhang, K., Zhang, Y., Cong, Y., & Wang, Q. (2021). Fabrication of visible-light-active MR/NH2-MIL-125(Ti) homojunction with boosted photocatalytic performance. *Chemical Engineering Journal*, *412*, 128722. https://doi.org/10.1016/j.cej.2021.128722

[65] Fan, Y.-H., Zhang, S.-W., Qin, S.-B., Li, X.-S., & Qi, S.-H. (2018). An enhanced adsorption of organic dyes onto NH2 functionalization titanium-based metal-organic frameworks and the mechanism investigation. *Microporous and Mesoporous Materials*, *263*, 120-127. https://doi.org/10.1016/j.micromeso.2017.12.016

[66] Shenvi, S., Ismail, A. F., & Isloor, A. M. (2014). Enhanced Permeation Performance of Cellulose Acetate Ultrafiltration Membranes by Incorporation of Sulfonated Poly(1,4-phenylene ether ether sulfone) and Poly(styrene-co-maleic anhydride). *Industrial*

& *Engineering Chemistry Research*, *53*(35), 13820-13827. https://doi.org/10.1021/ie502310e

[67] Hebbar, R. S., Isloor, A. M., Ananda, K., & Ismail, A. F. (2016). Fabrication of polydopamine functionalized halloysite nanotube/polyetherimide membranes for heavy metal removal [10.1039/C5TA09281G]. *Journal of Materials Chemistry A*, *4*(3), 764-774. https://doi.org/10.1039/C5TA09281G

[68] Hussain, M. Z., Bahri, M., Heinz, W. R., Jia, Q., Ersen, O., Kratky, T.,...Xia, Y. (2021). An in situ investigation of the thermal decomposition of metal-organic framework NH2-MIL-125 (Ti). *Microporous and Mesoporous Materials*, *316*, 110957. https://doi.org/10.1016/j.micromeso.2021.110957

[69] Kumar, R., Isloor, A. M., Ismail, A. F., Rashid, S. A., & Ahmed, A. A. (2013). Permeation, antifouling and desalination performance of TiO2 nanotube incorporated PSf/CS blend membranes. *Desalination*, *316*, 76-84. https://doi.org/10.1016/j.desal.2013.01.032

[70] Muelas-Ramos, V., Belver, C., Rodriguez, J. J., & Bedia, J. (2021). Synthesis of noble metal-decorated NH2-MIL-125 titanium MOF for the photocatalytic degradation of acetaminophen under solar irradiation. *Separation and Purification Technology*, *272*, 118896. https://doi.org/10.1016/j.seppur.2021.118896

[71] Wu, S., Xing, X., Wang, D., Zhang, J., Chu, J., Yu, C.,...Li, Z. (2020). Highly Ordered Hierarchically Macroporous MIL-125 with High Specific Surface Area for Photocatalytic CO2 Fixation. *ACS Sustainable Chemistry & Engineering*, *8*(1), 148-153. https://doi.org/10.1021/acssuschemeng.9b04829

[72] Hebbar, R. S., Isloor, A. M., Ismail, A. F., Shilton, S. J., Obaid, A., & Fun, H.-K. (2015). Probing the morphology and anti-organic fouling behaviour of a polyetherimide membrane modified with hydrophilic organic acids as additives [10.1039/C5NJ01095K]. *New Journal of Chemistry*, *39*(8), 6141-6150. https://doi.org/10.1039/C5NJ01095K

[73] Panchami, H. R., Isloor, A. M., & Ismail, A. F. (2022). Improved hydrophilic and antifouling performance of nanocomposite ultrafiltration zwitterionic polyphenylsulfone membrane for protein rejection applications. *Journal of Nanostructure in Chemistry*, *12*(3), 343-364. https://doi.org/10.1007/s40097-021-00416-7

[74] Hebbar, R. S., Isloor, A. M., Prabhu, B., Inamuddin, Asiri, A. M., & Ismail, A. F. (2018). Removal of metal ions and humic acids through polyetherimide membrane with grafted bentonite clay. *Scientific Reports*, *8*(1), 4665. https://doi.org/10.1038/s41598-018-22837-1

[75] Wang, Y., Chen, J., Zhang, X., Yang, Y., Yang, Q., Liu, X.,...Zhang, X. (2022). N-doped rutile TiO2/C hybrids with enhanced charge transfer capability derived from NH2-MIL-125(Ti) for the photocatalytic degradation of tetracycline. *Materials Research Bulletin*, *155*, 111968. https://doi.org/10.1016/j.materresbull.2022.111968

[76] Sohail, M., Yun, Y.-N., Lee, E., Kim, S. K., Cho, K., Kim, J.-N.,...Kim, H. (2017). Synthesis of Highly Crystalline NH2-MIL-125 (Ti) with S-Shaped Water Isotherms for Adsorption Heat Transformation. *Crystal Growth & Design*, *17*(3), 1208-1213. https://doi.org/10.1021/acs.cgd.6b01597

[77] Wen, G., & Guo, Z. (2018). Facile modification of NH2-MIL-125(Ti) to enhance water stability for efficient adsorptive removal of crystal violet from aqueous solution. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *541*, 58-67. https://doi.org/10.1016/j.colsurfa.2018.01.011

[78] Rajashekhara, P. H., Isloor, A., & Ismail, A. F. (2022). One-step synthesis and characterization of hydrophilic polymer microspheresimmobilized with polyphenylsulfone ultrafiltration membranes for protein rejection application. https://doi.org/10.21203/rs.3.rs-1331802/v1

[79] Krakowiak, R., Frankowski, R., Mylkie, K., Kotkowiak, M., Mlynarczyk, D. T., Dudkowiak, A.,...Goslinski, T. (2022). Titanium(IV) oxide nanoparticles functionalized with various meso-porphyrins for efficient photocatalytic

degradation of ibuprofen in UV and visible light. *Journal of Environmental Chemical Engineering*, *10*(5), 108432. https://doi.org/10.1016/j.jece.2022.108432

[80] Omer, A. M., Abd El-Monaem, E. M., El-Subruiti, G. M., Abd El-Latif, M. M., & Eltaweil, A. S. (2021). Fabrication of easy separable and reusable MIL-125(Ti)/MIL-53(Fe) binary MOF/CNT/Alginate composite microbeads for tetracycline removal from water bodies. *Scientific Reports*, *11*(1), 23818. https://doi.org/10.1038/s41598-021-03428-z

[81] Zhao, Y., Cai, W., Chen, J., Miao, Y., & Bu, Y. (2019). A Highly Efficient Composite Catalyst Constructed From NH2-MIL-125(Ti) and Reduced Graphene Oxide for CO2 Photoreduction [Original Research]. *Frontiers in Chemistry*, *Volume 7 - 2019*. https://doi.org/10.3389/fchem.2019.00789

[82] Kumar, M., Isloor, A. M., Somasekhara Rao, T., Ismail, A. F., Farnood, R., & Nambissan, P. M. G. (2020). Removal of toxic arsenic from aqueous media using polyphenylsulfone/cellulose acetate hollow fiber membranes containing zirconium oxide. *Chemical Engineering Journal*, *393*, 124367. https://doi.org/10.1016/j.cej.2020.124367

[83] Nabe, A., Staude, E., & Belfort, G. (1997). Surface modification of polysulfone ultrafiltration membranes and fouling by BSA solutions. *Journal of Membrane Science*, *133*(1), 57-72. https://doi.org/10.1016/S0376-7388(97)00073-2

[84] Almanassra, I. W., Jaber, L., Chatla, A., Abushawish, A., Shanableh, A., & Ali Atieh, M. (2023). Unveiling the relationship between MOF porosity, particle size, and polyethersulfone membranes properties for efficient decontamination of dye and organic matter. *Chemical Engineering Journal*, *471*, 144616. https://doi.org/10.1016/j.cej.2023.144616

[85] Karthik, G., Vinothkumar, K., Mohan, S., & Balakrishna, R. G. (2024). Synergy of Ligands in Tailoring the Photocatalytic Properties of Zirconium Metal–Organic Framework-Impregnated Membranes for Water Treatment. *Industrial & Engineering Chemistry Research*, *63*(15), 6743-6753. https://doi.org/10.1021/acs.iecr.4c00215

[86] Alshahrani, A. A., AlQahtani, M., Almushaikeh, A. M., Hassan, H. M. A., Alzaid, M., Alrashidi, A. N., & Alsohaimi, I. H. (2022). Synthesis, characterization, and heavy-ion rejection rate efficiency of PVA/MWCNTs and Triton X-100/MWCNTs Buckypaper membranes. *Journal of Materials Research and Technology*, *18*, 2310-2319. https://doi.org/10.1016/j.jmrt.2022.03.099

[87] Hadi, S., Mohammed, A. A., Al-Jubouri, S. M., Abd, M. F., Majdi, H. S., Alsalhy, Q. F.,...Figoli, A. (2020). Experimental and theoretical analysis of lead Pb2+ and Cd2+ retention from a single salt using a hollow fiber PES membrane. *Membranes*, *10*(7). https://doi.org/10.3390/membranes10070136

[88] Jafar Mazumder, M. A., Raja, P. H., Isloor, A. M., Usman, M., Chowdhury, S. H., Ali, S. A.,...Al-Ahmed, A. (2020). Assessment of sulfonated homo and co-polyimides incorporated polysulfone ultrafiltration blend membranes for effective removal of heavy metals and proteins. *Scientific Reports*, *10*(1), 7049. https://doi.org/10.1038/s41598-020-63736-8

[89] Soo, K. W., Wong, K. C., Goh, P. S., Ismail, A. F., & Othman, N. (2020). Efficient heavy metal removal by thin film nanocomposite forward osmosis membrane modified with geometrically different bimetallic oxide. *Journal of Water Process Engineering*, *38*, 101591. https://doi.org/10.1016/j.jwpe.2020.101591

[90] Mondal, M., & Indurkar, P. D. (2024). Heavy metals remediation using MOF5@GO composite incorporated mixed matrix ultrafiltration membrane. *Chemical Engineering Journal*, *494*, 153155. https://doi.org/10.1016/j.cej.2024.153155

[91] Maqbool, A., Shahid, A., Jahan, Z., Bilal Khan Niazi, M., Ali Inam, M., Tawfeek, A. M.,...Saeed Akhtar, M. (2023). Development of ZnO-GO-NiO membrane for removal of lead and cadmium heavy metal ions from wastewater. *Chemosphere*, *338*, 139622.

https://doi.org/10.1016/j.chemosphere.2023.139622

[92] Banerjee, S., Das, A., Das, R., & Bhattacharjee, C. (2024). Mesoporous Mg–Al–Ti composite oxide incorporated mixed matrix ultrafiltration membrane with superior multi-heavy metal removal capacity, anti-fouling & anti-microbial property. *Journal of Membrane Science*, *703*, 122836. https://doi.org/10.1016/j.memsci.2024.122836

[93] Mistry, P., & Murthy, C. N. (2023). Positively Charged Polysulfone and Polyether Sulfone Mixed Matrix Membranes Modified with Polyethylenimine: Enhancing Heavy Metal Rejection and Antifouling Properties. *ACS ES and T Water*, *3*(12). https://doi.org/10.1021/acsestwater.3c00585

[94] Refaat Alawady, A., Ali Alshahrani, A., Ali Aouak, T., & Mohamed Alandis, N. (2020). Polysulfone membranes with CNTs/Chitosan biopolymer nanocomposite as selective layer for remarkable heavy metal ions rejection capacity. *Chemical Engineering Journal*, *388*, 124267. https://doi.org/10.1016/j.cej.2020.124267

[95] Prajapati, H., Gosai, J., Chaudhari, N., & Busupalli, B. (2025). Jute-Copper Nanocomposite Embedded PSf Membrane for Sustainable and Efficient Heavy Metal Removal from Water Sources. *Langmuir*, *41*(1). https://doi.org/10.1021/acs.langmuir.4c03847

[96] Said, K. A. M., Amin, M. A. M., Luisa, J., Chee, D. N. A., Yakub, I., Rahman, M. R.,...Kueh, A. B. H. (2023). Impact of Montmorillonite Clay on Polysulfone Mixed Matrix Membrane for Heavy Metal Adsorption. *Water, Air, & Soil Pollution*, *234*(4), 275. https://doi.org/10.1007/s11270-023-06275-y

[97] Ismail, N. Q., Yusoff, A. H., Shoparwe, N. F., Yusof, N. N., Noorazlan, M., Ameram, N., & Fares, M. M. (2024). The effect of Sodium Dodecyl Sulfate on Polysulfone membrane for Pb (II) ions removal in an aqueous solution. *Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex use of mineral resources*, *334*(3), 26-36. https://doi.org/10.31643/2025/6445.25

[98] Nadig, A. R., Naik, N. S., Padaki, M., Pai, R. K., & Déon, S. (2021). Impact of graphitic carbon nitride nanosheets in mixed- matrix membranes for removal of heavy metals from water. *Journal of Water Process Engineering*, *41*, 102026. https://doi.org/10.1016/j.jwpe.2021.102026

[99] Sunil, K., Karunakaran, G., Yadav, S., Padaki, M., Zadorozhnyy, V., & Pai, R. K. (2018). Al-Ti2O6 a mixed metal oxide based composite membrane: A unique membrane for removal of heavy metals. *Chemical Engineering Journal*, *348*, 678-684. https://doi.org/10.1016/j.cej.2018.05.017

[100] Alotaibi, K. M., Shukla, A. K., Alshahrani, A. A., Alzhrani, E. M., Alotaibi, S. S., & Alswieleh, A. (2025). Layer-by-Layer Assembled Nanocomposite Membranes with Functionalized Dendritic Mesoporous Silica Nanoparticles for Selective Heavy Metal Removal. *ACS Omega*, *10*(26). https://doi.org/10.1021/acsomega.5c02486.

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