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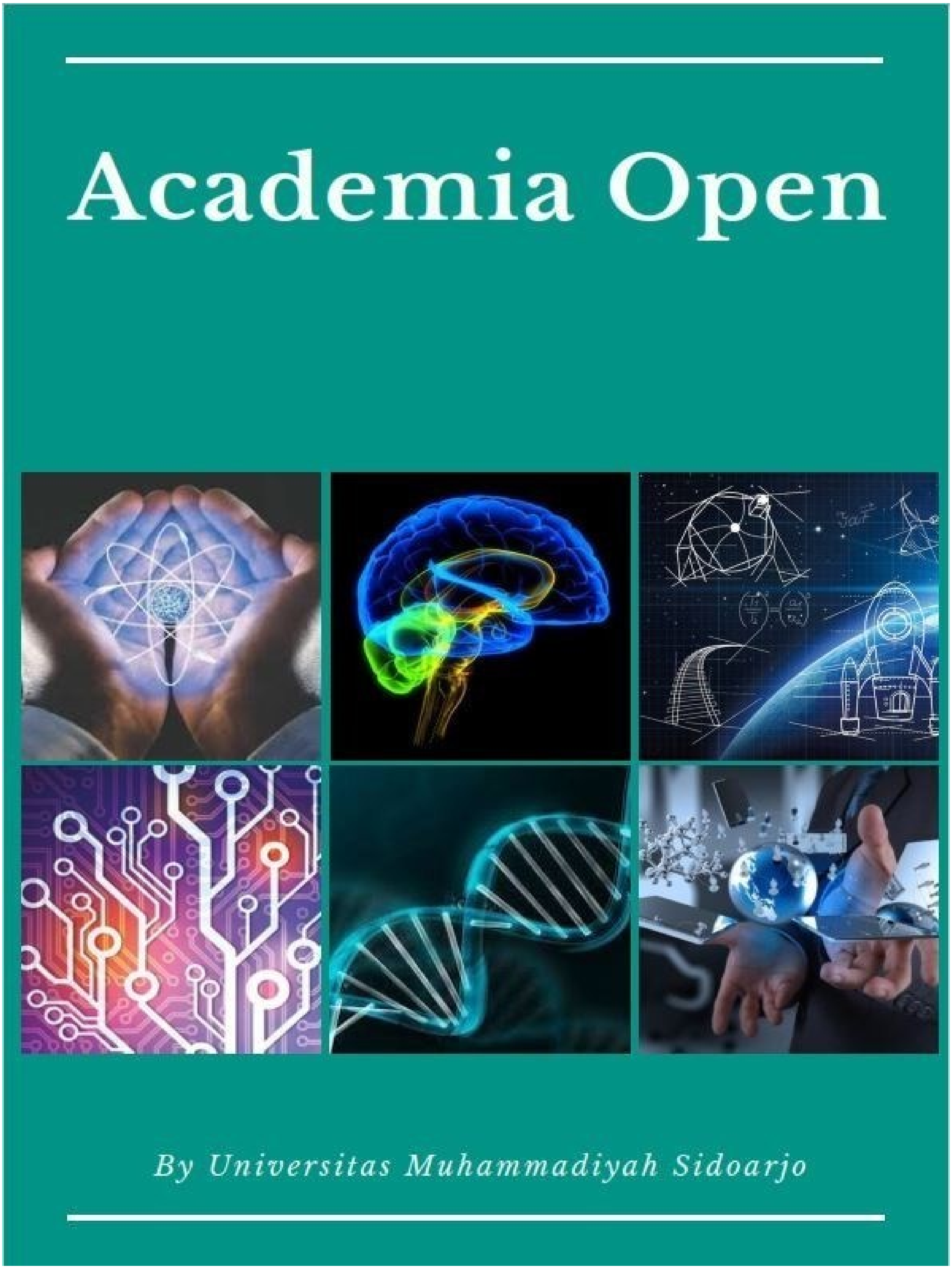

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Review Of Removal of Heavy Metal Ions from Water by Complexation-Assisted Ultrafiltration

Azeez Sakran Abed, azeezsakran@gmail.com,(1)
Department of Chemical Engineering, College of Engineering, University of Al-Muthanna, Iraq
Ahmed Hassan Ali, dr.ahmedha@mu.edu.iq,(2)
Department of Chemical Engineering, College of Engineering, University of Al-Muthanna, Iraq

(1) Corresponding author

Abstract

The escalating contamination of water resources by heavy metal ions poses critical environmental and public health challenges, necessitating efficient remediation technologies. This review examines the application of Complexation-Assisted Ultrafiltration (CP-UF), alternatively termed Polymer-Enhanced Ultrafiltration (PEUF), as an advanced membrane-based separation process for removing toxic heavy metals from aqueous solutions. The study systematically analyzes two distinct approaches: synthetic polymers including Polyethylene Glycol (PEG 5000) and Diethylaminoethyl-cellulose (DEAE-cellulose) for zinc and cadmium removal, and natural biopolymer Carboxymethyl Cellulose (CMC) for copper, nickel, and chromium elimination. Through comprehensive evaluation of experimental data from ultrafiltration membrane systems operated under varying conditions, the research demonstrates that DEAE-cellulose achieves exceptional rejection rates up to 99% for Zn(II) at pH 9.0 and 300 kPa pressure, while CMC exhibits superior performance exceeding 97% rejection for Cu(II), Ni(II), and Cr(III) at neutral to alkaline pH conditions. Critical operational parameters including solution pH, applied transmembrane pressure, membrane molecular weight cut-off, and polymer concentration significantly influence both permeate flux and metal ion retention efficiency. The novelty of this work lies in the comparative assessment of synthetic versus natural polymeric ligands, revealing that amino-functionalized DEAE-cellulose forms stable coordination complexes through nitrogen electron donation, whereas CMC utilizes carboxyl and hydroxyl groups for metal binding in pH-dependent octahedral or square planar configurations. Furthermore, the study establishes the economic and environmental feasibility of polymer regeneration through pH adjustment or chemical cleaning cycles, enabling multiple reuse iterations. These findings advance membrane separation theory by validating osmotic pressure models in complexation-ultrafiltration systems and provide practical implications for industrial wastewater treatment, particularly for low-concentration heavy metal effluents where conventional precipitation methods prove inadequate, thereby supporting sustainable water resource management and regulatory compliance in chemical engineering applications.

Keywords : Filtration, Complexation-Ultrafiltration, Polymer-Enhanced Ultrafiltration (PEUF), Heavy Metal Removal, Water-Soluble Polymers

Highlight :

- DEAE-cellulose mencapai rejeksi 99% untuk Zn(II) pada pH 9,0 dengan tekanan 300 kPa
- CMC menghasilkan rejeksi >97% untuk Cu(II), Ni(II), dan Cr(III) pada pH ≥7
- Regenerasi polimer melalui penyesuaian pH memungkinkan penggunaan berulang dalam siklus pemisahan logam.

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Introduction

Separation processes have an incredible contribution to the chemical manufacturing, wherever they make 40–70% to together capital and operative expenses, of which filtration is one type[1]. Filtration may be described as the separation of solid impurities in a solid-fluid (gas or liquid) mixture to enhance the quality of filtered material by guiding the flow of the mixture over a supported cloth or mesh, known as filter[2]. particles suspended in liquor are partitioned via a permeable filtering intermediate. The hold-up with elements of interest goes into the housing of the filtration unit In most sophisticated filtering systems of air and liquids, the flow through the layer of filter material is enabled by providing a cross-layer draught with the help of a static pressure difference, the filter material of a filter is the most important and the most basic constituent of any filtering process choosing can,t be overestimated[3]. There is an establishment of a pressure difference which results the fluid to travel through small holes in a mesh or a bit of cloth that keep the big solid out particles; these, however, accumulate on the fabric as a spongy cake[4]. Filtration works solely on particle or droplet size (and, to an incomplete range, form), such that particles smaller than a specified size will pass through the barrier, and large particles will be held on or in the barrier for later removal[5]. Industrial filtration machines differ from laboratory filtration machines in the amount of material handled and in the requirement of low-cost process [4]. Arrangement of different particle separations according to the particle or molecular size is the overriding factor controlling the separated processes major separations operations of membranes, ultrafiltration (UF), microfiltration (MF) , Nanofiltration (NO)[6].

Ultrafiltration: The research pertaining to ultrafiltration has traditionally been linked with that of dialysis, along with, but to a lesser degree, osmosis and the issues surrounding the semi permeable membrane. Dialysis on collodion membrane artificial membranes was described by Fick while collodion membranes. [7].Ultrafiltration uses a very permeable film to filter water and micro solutes from macromolecules and colloids. The mean hole diameter of the membrane is in the 10–1000 °A range. Syntheses of the earliest ultrafiltration membranes were performed in the early 1900s from collodion (nitrocellulose) [8]. Ultrafiltration has a expansive variety of submissions both in chemistry and biology: in fractionation and analysis of disperse systems and in assessment of disperse systems. Of all the systems, the sol system is the best example demonstrating the ability to separate a colloid from a sol. As a matter of fact, it stands to reason that systems with a vapor demonstrate the same physicochemical standards [7]. Bubble point does not check ultrafiltration membranes. The pores are too small, and thus other approaches are utilized. Direct microscopic examination of the surface is unstable and difficult. Because they are so small, pores typically close when samples are dried for the electron microscope[9].

Filtration of heavyweight metallic ions was attempted via employing complexation with ultrafiltration operations:

One promising method of removing heavy metals from water was the complexation-membrane filtration method which outperformed the traditional techniques of precipitation and ion exchange. During the last ten years, the above topic has been widely researched and many papers have been published[10]. The complexation–filtration method has several advantages that include the selective binding which leads to the high separation selectivity and the small - dynamism supplies of these procedures. Aquatic - solvable polymeric ligands consume found to remain very active in rejecting trace metals from the water through the membrane processes in both aqueous and industrial waste water. But still, the selection of water-soluble macroligands is a crucial factor for technology advancement. Carboxylic or amine containing polymers have been widely researched for this application[11]. The interaction of polymer and metal ions usually involves several weak binding forces like coordination bonds, hydrogen bonds, charge-transfer interaction, and hydrophobic interaction. The weak interactions, however, are important, and they work together and change over time. This work is a screening test for applicability in addition effectiveness of certain a selection of macroligands-polyethylene glycol 5000 , HO-(CH2CH2O)n-H and dextrin-for the elimination of zinc and cadmium ions from water [12]. On the one hand, the global demand for heavyweight metallics compounds continues to rise due to the fast-growing modern industrial activities, and on the additional ,the regulations regarding hardwearing metals are getting more and more rigorous worldwide. The water-soluble polymers of varying functionalities have found their way into different separation processes like adsorption, precipitation, coagulation/flocculation, and membrane filtration for the removal of heavy metals from sewage[14,15]. It is a highly efficient method for removing heavy metals from wastewater at quite low concentrations, making it a very good option for the traditional processes used for the removal and recovery of these metals. Furthermore, the technique can sometimes even selectively separate certain metal types within a mixture[16]. The use of water-soluble polymeric ligands has revealed their capability of being very efficient in removal tracing metals from water and industrial wastewater with help of the membrane processes. But, selecting the correct water-soluble macroligands is critical for the success of this technology. The use of biopolymer macroligands that have the capacity of complexation of heavy metals, such as chitosan, have been investigated in numerous experiments[11,17].

Materails and Method

All chemicals used in this study were of element score. Normal clarifications with focusing of 50 mg dm^{-3} were equipped via attenuated of 50 cm^3 standard clarification of cadmium and zinc having 1 g (2.032 g of CdCl2.1/2H2O and 2.084 g of ZnCl2 in distilled water to 1 dm^3. The DEAE-cellulose was equipped at a focusing of 0.5 g dm^{-3}, HO-(CH2CH2O)n-H 5000 at a concentrated of 10 g dm^{-3} and polysaccharide at a focusing of 3.5 g dm^{-3}, via disintegrating 0.5 g, 10g and 3.5 g in purified water. The attenuated sourness and norms were made by attenuated 36.5% HCl and NaOH -monohydrate with water. For cadmium and zinc microscopic assimilation spectroscope capacities, a Pye Unicam SP9 atomic absorption spectroscope was used., which was outfitted with the deep cathode uplighters for cadmium at 228.8 nm and zincum at 213.9 nm. The diagnostic standard solutions and their respective calibration values ranged from 10.0 to 70.0 mg dm^{-3} in the instance of metals and from 1.00 to 7.00 mg dm^{-3} in the instance of their respective calibration. The determination of the pH of the solutions was done using an pH metrics with a glass electrode. A Millipore 8050 laboratory ultrafiltration cell was used for the membrane filtration experiments, and it was stirring magnetically at 300 rpm. The details of the UF cell are given in Table1. The synthetic (200) and (450) membranes and the polysulfonamide Vladipor membranes were the membranes used with a 13 kDa cutoff. Pressure used was regulated by nitrogen gas at 100-400 kPa. The whole experiment took place at chamber temperature. For each test, 25 cm^3 sample from the at work product was used. The pH of the solution was altered by partial neutralization with Hydrogen Chloride and Sodium Hydroxide. Next, the complexing mediator was additional and the mixture was moved for 60 min at that time filtered. More blending time indicated 1 houre got enough for the complexation achieve its equilibration. The focusing of the huge metallic ionic then the ultrafiltration process were analysed with AAS. Among the UF cells, particularly the Millipore 8050 type, were our options of the shortest list[13]. The metallics standard solutions for Cu(II), Ni(II), and Cr(III) were made at a focusing of 1000 mg/L and the metals were drawn from these sources. The metals compounds with $[C_6H_7O_2(OH)_2OCH_2COONa]_n$ (CMC, viscidity 25–75 m Pa s) as a water-solvable polymer. The pH values of the waterborne solutions were controlled with 1 M Hydrogen chloride and 1 M Caustic soda. The ultrafiltration trials were conducted via means of a membrane system featuring a polyethersulfone membrane with a cut-off of 10,000 Da. The 5 L solution having different focusing of metallic and CMC was mixed to enable the formation of the metal-CMC complex. Then, the solution was transferred to the device technique for the ultrafiltration process to start. The operating pressure was adjusted to 1 bar and a pervade run rate of 7.5 L/H was established. Initially, together pervade and retentate were returning to the vessel container so that steady-state operation could be reached. The monitoring and adjustment of the solution's pH level were done by a pH meter. A sample for metal analysis was taken after the solution had been circulated for 10 min at a fixed pH. The permeate water was afterward collected into separate containers for subsequent runs, each of 1 L every 8 min. Metal analysis models that gathered from the pervade and retentate. Once the experiment was completed, the membrane was washed with warm water and then, pursuant to the membrane industrialist's orders, the water solution was circulated for two runs, thus immediately regenerating the film. In the initial cycle, 1 g of sodium hydrosulfite was enhanced, and 5% NaOH was used to raise the pH of the solution to about 9. In the second run, 5% citric acid was used to neutralize the solution. [18].

Table 1 : The UF cell Millipore 8050 characteristics[13].

parameter	value
Cell capability	50 CM^3
Minimal procedure volume	2.5 CM^3
Notional film diameter	43 MM
Efficient film region	13.4 CM^2
Retenting volume	0.5 CM^3
Maximum operational pressure	5 Bar
pH operational variety	2 – 10

Effect of practical pressure

The pressure was assessed at the constant focusing of heavy metal ions 50.0 mg dm^{-3} and pH 9.0. The changes in the flux values are shown in Figure. 1a and 2a depending the impact of pressure application on the flux of pure water and different agent complexes. The solvent's flux is lower in all instances than that of pure water. For dextrin, however, the increase in pressure results in the flux to rise almost linearly. While for the case of the flux versus pressure curve of PEG5000 and DEAE23 complexes,

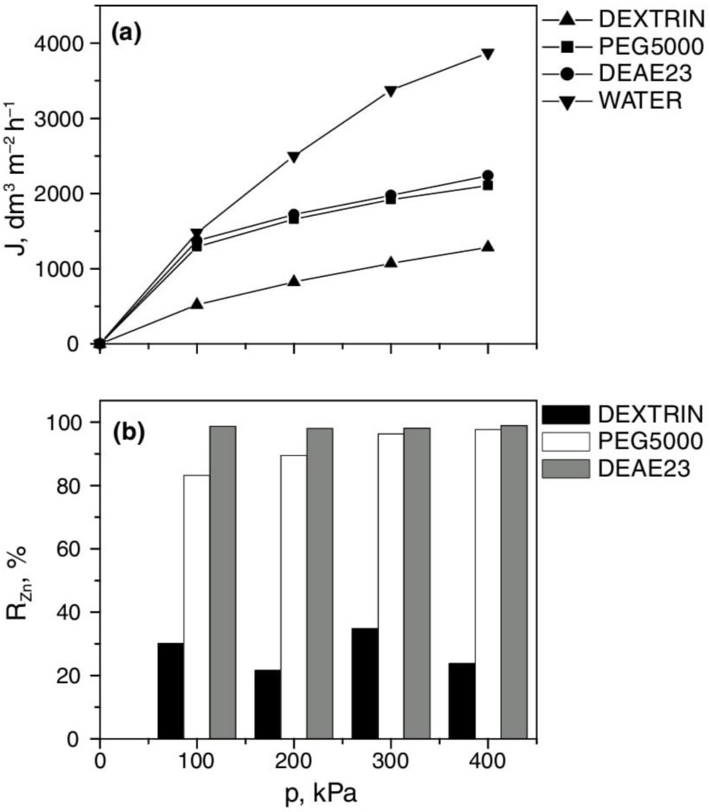

Figure 1: how pressure impacts (a) flow rate and (b) Zn(II) removal from various KMe ligands (synthetic film (0.2) and pH = (9.0) [13].

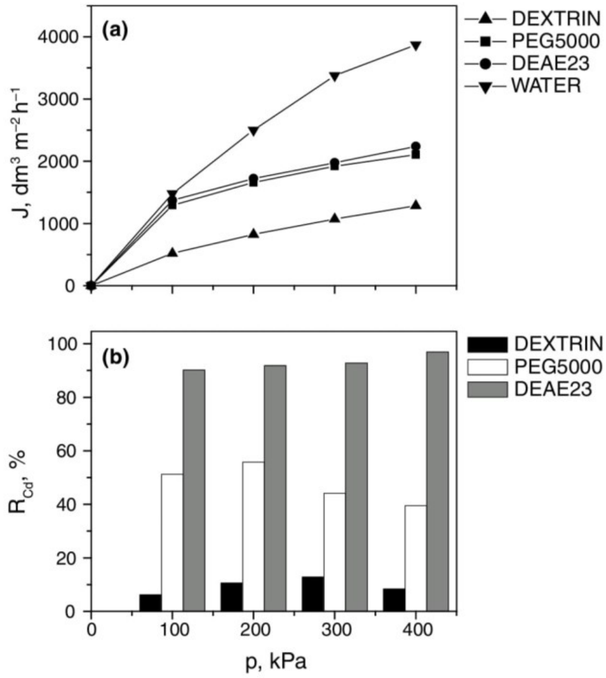

Figure.2.impact of pressure on Cd(II) (a) flow and (b) holding of various complexing managers together (synthetic membrane 0.2 and pH=9.0) [13].

no sharp change is seen at the points where the fluidity is silent a minor purpose of pressure in the case of upper pressure. This denotes the presence of rumination polarization, but not to the extent that it would create a plateau which would suggest that the gel-polarization effects are dominating in the case of polymers for the studied pressure range. The osmotic pressure model is somewhat applicable but with caution [19]. The osmotic force perfect takes into account solute strength at film superficial as a role of all differences counting the practical pressure, whereas the gel-polarization perfect is based on the assumption that emulsion focusing is unaffected by effective positions [20]. Thus, the flux (J) can be articulated with the following equation

$$J = \frac{Pt - f(CB\exp(\frac{J}{K}))}{RM} \qquad (1)$$

In this context, PT is the pressure difference across the membrane, CB is the focusing of solute in the feed solution , k is the coefficient of substance transmission, and RM is the film resistance. Such observation is supported by Fig. 1b and Fig. 2b since the retaining factors of the complexes were still significant. Fig. 1b indicates that the retaining coefficient of zinc compound with DEAE23 remains nearly unchanged with the rise in practical pressure. The retaining of the compound with PEG5000 shows a slight rise that corresponds with the increase in the applied pressure. As for the case of the dextrin complex, the different sizes of the particles make the pressure's effect on the retention to be more pronounced. The configuration of the molecule is an important factor in determining retentivity. A linear molecule is capable of passing over a membrane, whereas rotund (not necessarily larger) particles might be kept. The reasoning behind this is that lineal, water-solvable polymer particles are capable to slip through the film holes at increased pressure [21] The retaining of cadmium ions at various pressures exhibits a pattern alike (Fig. 2b). The cadmium complex with DEAE23's retention coefficient is rather firmly controlled by the pressure. It is observed that the retaining of multiplexes with PEG5000 and dextrin reduces rather as the pressure increases[13].

Effect of pH

Influence of pH value was examined in the variety of 2.0-9.0, with 50.0 mg dm^{-3} heavy metal concentration, and 300 kPa pressure. The denial factors of zincum and cadmium ions without then with unlike complexing elements. pH are depicted in Figure. 3. The retention of metal varies a lot with the pH because of a stronger interaction with the polymer ligands. The minor denial of zincum ions in the lack of elements at pH 2.0 as can be, probably, partially accredited to the attendance of some ultra-fine holes in the film [22]. On the other hand, there is no retaining for cadmium composites with Full macroligands at pH 2.0. The low holding of zincum ions that is seen among pH 2 and 6 is attributable to the dissolution of metal hydroxyl complexes in the solution. As the pH increases, the retaining of cadmium rises awfully slow.At high pH, particles of metallic hydroxyl complex start to agglomeration, and larger atoms which are disallowed via the film are formed, especially in the situation of zincum[13]. The influence of pH on the separation of metallic Ionian from water consuming the polyethersulfone ultrafiltration membrane is illustrated in Figure. 6. The pH variety studied that 3-9, the CMC/ metallic rate that 100, and the pressure applied was 1bar. It is observed that the rejection rate of metallic ions enhanced with the increase of pH until the maximum values at pH ≥ 7. The denial rates for Cu (II), Ni (II), and Cr (III) ions were 97.6%, 99.1%, and 99.5% at pH 7, respectively. This phenomenon is due to the stable of the M−CMC compounds formed while are pH-reliant. Metal denial is largely affected by the pH since there is more tying with the polymer linking at upper pH standards. At little pH, CMC has a weak affinity towards metal ions because of the attendance of Positively charged particles, and thus, the stable of the compounds is low (Figure. 6). Increasing pH boosts the attraction and stable of CMC– metallic compounds [24].

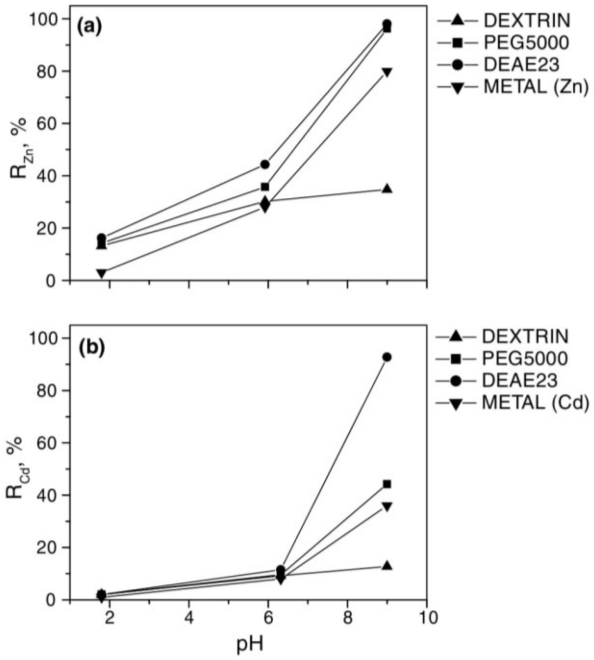

Figure 3. The effect of the pH on the adsorption of Zn(II) (Part (a) and Cd(II) (Part (b) by varying get levels for complexing agents (synthetiic membrane 0.2 and p=300 kPa) [13].

If there are any agents present, the retention of the ions will be less at a pH lower than 5.0, and it will decrease, the rivalry of H^+ by divalent metallic ions to promise with the ligand has been suggested at low pH. Retaining coefficients for zincum complexes with PEG5000 and DEAE23 are 96% and 99% severally at pH = 9.0, but with dextrin, they remain small. At PH equal 9.0, the retaining amount of the cadmium complex with DEAE23 is elevated (95%), but it stays low for PEG5000 and dextrin. The best retaining coefficients for the two metals were figured out with DEAE23. The contact between the amino groups of DEAE23 and the metal ions is basically forming a stable complex with the metal ions during the involvement of the allowed electron combine from the nitrogen atom. This is the reason that the pH greatly affects the stability of the complexes. Under low pH conditions, most of the amino collections are protonated, therefore the empathy of the amino groups for the metallic ions is weak and the constancy of the compound is small. An increase in pH results in the higher empathy and constancy of the polymer– iron complexes. At a pH greater than 6 for both metals, the incidence of dextrin decreases the retaining factor in comparison to the retaining of metallic ions without any agent. Dextrin may coordinate with metal hydroxides, and this has already been noted in the earlier sections. Above neutral pH, dextrin molecules interact with metal hydroxyl complexes, and this interaction prevents the agglomeration of hydroxyl particles. The interaction of dextrin with metals gives rise to the formation of small particles, which can easily penetrate through the membrane, thus lowering the retaining coefficients. According to Figure 3, for both metals, a reduction in pH results in abridged retaining, and at very little pH, the majority of metallic ions remain uncomplexed. This shows the possibility of re-use of the polymeric agents through the separation process by making the adjustment of pH[13].

Effect of membrane type

At a focusing of 50.0 mg dm^{-3} of heavy metal ions, 300 kPa pressure and pH 9.0, the membrane type effects were fixed to be investigated. The purified water flux was expected to decrease with the shrinking of membrane pore diameter for both metals, the ultrafiltration membrane showing the lowest values (Figure. 4a and 5a).Thus, the PSA membrane although having very high retaining coefficients is not recommendable for extensive petition. The retaining coefficients were very similar due to the minute variances in the hole size of the synthetic membranes. The lowest retaining coefficient for zincum was obtained with dextrin as the complexing agent which was responsible for its low molecular weight. Polyethylene glycol and diethylaminoethyl cellulose were observed to be more effective complexing agents with a constant value of retention coefficient at all three membranes as illustrated in Figure. 4b. The retaining coefficient of cadmium complex with dextrin is very low irrespective of the kind of membrane used in the experiment. Polyethylene glycol was indicated as a more effective complexing agent and the retention was higher than with dextrin, but the highest retaining coefficient was achieved using diethylaminoethyl cellulose as shown in Figure. 5b. The evidence given has corroborated that, after the macroligands had linked the ions, the method was feasible for the segregation of Zincum and cadmium. The various factors such as flow of clean water and retaining factors of Zincum (II) and Cadmium (II) compounds rely upon on the complexing factor, pH , and applied pressure that studied. The authors stated that the process could be described with some caution using the osmotic pressure perfect ultimately. In the complexation–filtration procedure parity a powerful impact of pH on metallic ionian compounds retaining that noticed. Via varying the pH standards, it is probable to either separate metallic Ionian compounds with in height retaining factors or to break down the macroligand compounds that might product in obtaining the focused metallic in the feeding and the complexing mediator used being the regenerated one. It is exposed that the linkage procedure that further effective in alkaline situations compared to impartial or sour ones .The lowly retaining factors were gotten with dextrin as predictable owed to its low molecular weight. Polyethylene glycol was a better complexing . Agent but the maximum retaining factor was using diethylaminoethyl cellulose (95% for cadmium and 99% for zincum). Removal of Zincum(II) is more effective than that of Cd(II) because of its higher coordination ability with macroligands[13]. The conditions of the ultrafiltration membrane that was used can be found in Table 1. The ultrafiltration membrane is made of hydrophilic polyethersulfone polymer. It is meant to eliminate particulates from solutions during the general filtration process[18].

CMC–metallic Ionian compounds

CMC forms compounds with transition metallic Ionian, such as Cr(III) , Ni(II) , Cu(II). Cr(III) , Ni(II) complexes have ether-oxygen of hydroxyl group as their tying locations, while in the case of the Cu(II) complexes, the band locations are the oxygen of ethoxyl collections and major alcoholic particle of glucopyranose hoops. This compounds will predominantly have an octahedral pattern with Cr(III) and Ni(II), while a quad flattened formation would be anticipated in the case of Cu(II)[23].

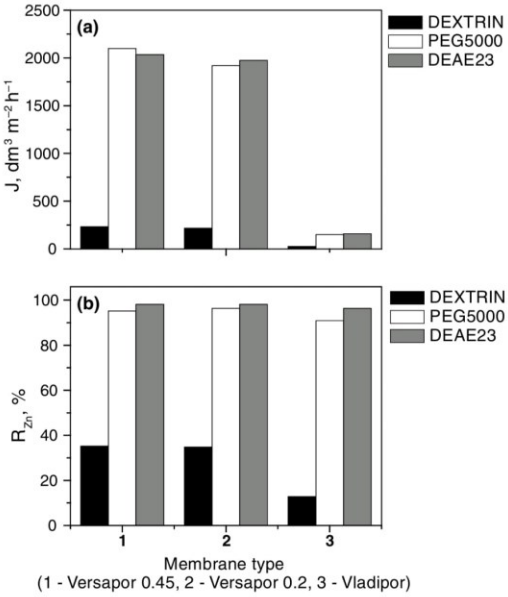

Figure. 4. Influence of Film on the (a) Flux and (b) percentage of Zincum retention ultizing diverse complexing factors (p =(300) kPa and pH=(9.0)) [13].

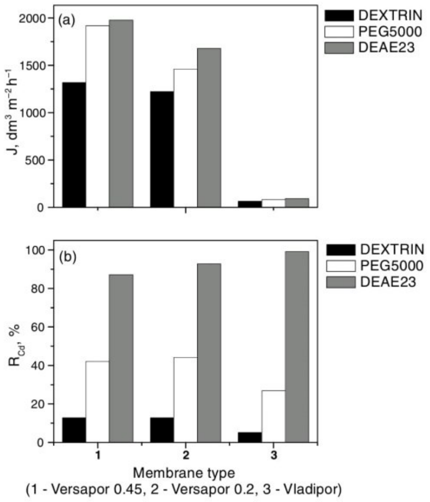

Figure. 5 portrays the impact that the membrane had on the (a) flow and (b) retaining of Cadmium(II) ions through the use of various complexing agents under the following conditions: pressure, p = (300 kPa) and pH = (9.0) [13].

Table2: Specifications of the ultrafiltration membrane used in CMC experiments

Membrane surface area	0.26 $M^{2.}$
Molecular weight cut-off	10 MWCO, KDA
Module length	364 MM
Flow rate for velocity of 1 m/s	690 L/H
Maximum pressure	3 BAR
Maximum temperature	70 °C

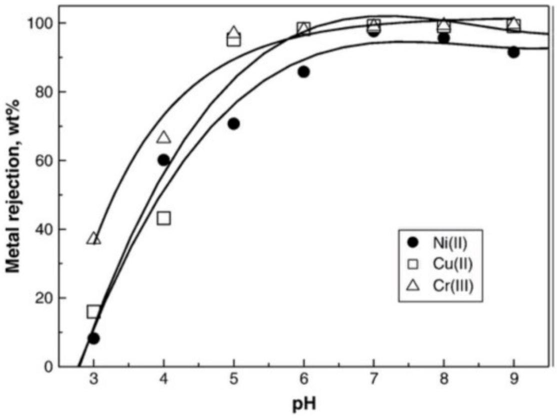

Figure. 6. Influence of (pH) on degree of separation of Ni (II), Cu (II), and Cr (III) from water using a polyether sulfone ultrafiltration membrane. (CMC=1 g/L, metal ion conc.=10 mg/L, p=1 bar) [18].

In the review, one may effectively gather and recall the two viable usages of the PEUF technique for evaluating in comparison.

Table3: Comparison between synthetic polymer-based and natural polymer-based PEUF methods

Criterion	Method 1 (Synthetic Derivatized Polymers)	Method 2 (Natural-based Polymer: CMC)
Polmers used	PEG 5000,DEAE-cellulose Dextrin	CMC (Carboxymethyl Cellulose)
Target Metals	Zn(II),Cd(II)	Cu(II), Ni(II), Cr(III)
Removal Efficiency	High with DEAE-cellulose (up to 99% for Zn)	Very High with CMC (>97% for all metals at pH ≥7)
PH Influence	High efficiency in alkalir conditions (pH 9.0)	High efficiency at near-neutral to alkaline pH (27)
Reusbility Potential	Demonstrated through pH adjustment (comple dissociation at low pH)	Demonstrated through chemical cleaning cycles (NaOH and Citric Acid)
Key Finding	Molecular weight and functional group of the polymer are critical.	CMC forms stable, pH-dependent complexes with high rejection rates

Future suggestions for optimizing the pH parameter in the first method (using synthetic polymers like PEG 5000 and DEAE-cellulose for Zn(II) and Cd(II) removal) include exploring pH ranges beyond 9.0, such as 10-11, to enhance complex stability while monitoring hydroxide precipitation risks. Automated pH control systems with real-time feedback could minimize variability during operation, improving rejection rates above 99% for DEAE-cellulose complexes. Incorporating buffering agents like phosphate at pH 8-9 would stabilize conditions for industrial scalability. For the second method (using natural CMC biopolymer for Cu(II), Ni(II), and Cr(III) removal), future work should test pH values up to 10 with CMC concentrations optimized at 1-2 g/L to push rejection beyond 99.5% without excessive fouling. Hybrid pH adjustment with mild chelators during regeneration cycles (e.g., citric acid at pH 3-4 followed by NaOH) could extend membrane life and polymer reusability over 10 cycles. Machine learning models predicting pH-flux relationships based on metal-CMC speciation would refine operational windows for wastewater variability.

Table 4: Comparative Summary of Two PEUF Methods for Heavy Metal Remval

Aspect	First method suggestions	Second method suggestions
pH Range Extension	9.0-11.0 with DEAE focus	7.0-10.0 with CMC dosing
Control Tech	Real-time sensors	Buffers + ML prediction
Regeneration	Low pH dissociation	Acid-base cycles

Conclusion

This review on complexation-assisted ultrafiltration (also termed Polymer-Enhanced Ultrafiltration, PEUF) demonstrates its effectiveness as an advanced membrane-based technology for removing heavy metal ions like Zn^{2+}, Cd^{2+}, Cu^{2+}, Ni^{2+}, and Cr^{3+} from aqueous solutions, addressing critical wastewater treatment challenges in chemical engineering. Key findings reveal that synthetic polymers such as DEAE-cellulose achieve rejection rates up to 99% for Zn^{2+} and 95% for Cd^{2+} at pH 9 and moderate pressures (300 kPa), outperforming PEG 5000 and dextrin due to stronger coordination via amino groups, while natural biopolymer carboxymethyl cellulose (CMC) yields 97-99.5% rejection for Cu^{2+}, Ni^{2+}, and Cr^{3+} at near-neutral pH 7.Operational parameters profoundly influence performance: rejection and permeate flux increase with pH due to enhanced complex stability, though low pH enables polymer regeneration via dissociation; applied pressure boosts flux linearly up to gel polarization limits, modeled by osmotic pressure equations; and tighter membranes (e.g., 13 kDa polyethersulfone) maximize retention but reduce flux. Membrane type and polymer molecular weight also matter, with hydrophilic polysulfone variants balancing efficiency and fouling resistance.As a student reviewer, PEUF stands out for its selectivity, low energy use, and reusability (via pH swings or NaOH/citric acid cleaning over multiple cycles), surpassing traditional methods like precipitation in treating low-concentration effluents from industrial sources. Future optimizations could integrate real-time pH sensors, machine learning for speciation prediction, and hybrid buffers to exceed 99.5% rejection scalably, paving the way for sustainable water purification in chemical processes. This technology aligns with growing regulatory demands, underscoring the need for further pilot-scale studies on multi-metal wastewaters.

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