A review of current practices on lead ions removal from different aqueous streams

Uma revisão das práticas atuais sobre a remoção de íons de chumbo de diferentes correntes aquosas

Una revisión de las prácticas actuales sobre la remoción de iones de plomo de diferentes corrientes acuosas

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ABSTRACT
Toxic heavy metals like Lead are destructive to humans and the environment when existing above their threshold limits. Several conventional lead abatement methods are used in wastewater treatment plants to restore the ecology, food supply, and human and animal health. Many tactics are used to remove harmful Pb metals, like ion exchange, chemical precipitation, membrane filtration, and coagulation. These have a few principal approaches for removing metal ions from used water. Rapid developments in tailor-made materials science have proved to remove Lead metal using ion exchange resins, zeolite, polymeric membranes, and ionic liquids due to their low cost, surface accessibility, and unique benefits. This review paper has studied the detailed benefits and shortcomings of removing lead ions from wastewater using numerous materials, processes of production,
possibly destructive properties on public health, and potential hybrid routes. In addition, this work observes the present advancements and developments in lead mitigation tools using different techniques for the past five years. Furthermore, this research review opens up to study of other materials' diverse applications in removal processes.

**Keywords:** ion removal, lead, resins, zeolites, polymeric membranes, ionic liquids.

**RESUMO**

Metais pesados tóxicos como o chumbo são prejudiciais para os seres humanos e o meio ambiente quando existem acima de seus limites de tolerância. Vários métodos convencionais de remoção de chumbo são utilizados em estações de tratamento de águas residuais para restaurar a ecologia, o abastecimento de alimentos e a saúde humana e animal. Muitas táticas são usadas para remover metais Pb nocivos, como troca iônica, precipitação química, filtração por membrana e coagulação. Estas têm algumas abordagens principais para remover íons metálicos de águas usadas. Os rápidos avanços na ciência de materiais sob medida têm se mostrado eficazes na remoção de chumbo usando resinas de troca iônica, zeólitas, membranas poliméricas e líquidos iônicos devido ao seu baixo custo, acessibilidade à superfície e benefícios únicos. Este artigo de revisão estudou os benefícios e limitações detalhados da remoção de íons de chumbo de águas residuais usando numerosos materiais, processos de produção, possíveis propriedades destructivas na saúde pública e rotas híbridas potenciais. Além disso, este trabalho observa os avanços e desenvolvimentos atuais em ferramentas de mitigação de chumbo usando diferentes técnicas nos últimos cinco anos. Além disso, esta revisão de pesquisa abre caminho para o estudo das diversas aplicações de outros materiais nos processos de remoção.

**Palavras-chave:** remoção de íons, chumbo, resinas, zeólitas, membranas poliméricas, líquidos iônicos.

**RESUMEN**

Metales pesados tóxicos como el plomo son perjudiciales para los seres humanos y el medio ambiente cuando existen por encima de sus límites de tolerancia. En las plantas de tratamiento de aguas residuales se utilizan varios métodos convencionales de eliminación de plomo para restaurar la ecología, el suministro de alimentos y la salud humana y animal. Se emplean muchas tácticas para eliminar los metales Pb nocivos, como el intercambio iónico, la precipitación química, la filtración por membranas y la coagulación. Estos tienen algunos enfoques principales para eliminar iones metálicos de aguas usadas. Los rápidos avances en la ciencia de materiales a medida han demostrado ser eficaces para eliminar el plomo utilizando resinas de intercambio iónico, zeolitas, membranas poliméricas y líquidos iónicos debido a su bajo costo, accesibilidad a la superficie y beneficios únicos. Este artículo de revisión estudió los beneficios y limitaciones detallados de la eliminación de iones de plomo de aguas residuales utilizando numerosos materiales, procesos de producción, posibles propiedades destructivas en la salud pública y rutas híbridas potenciales. Además, este trabajo observa los avances y desarrollos actuales en herramientas de mitigación de plomo utilizando diferentes técnicas en los últimos cinco años. Además, esta revisión de investigación abre el camino para el estudio de las diversas aplicaciones de otros materiales en los procesos de eliminación.
1 INTRODUCTION

Lead ion is one of the primary causes of environmental contamination today, and its removal is significant among the scientific community. A lead comes under the category of hazardous pollutants for nature and civil society, which demands meticulous planning and control measures. Significant sources of Pb discharge are the mining, fuel additive-based, and battery work industries, creating tremendous environmental and health impacts. Current regulations and standard stresses the need to control and mitigate Pb concentration on various environmental sources. Using conventional separation techniques and some corroborated with recent methods as a resultant hybrid process is more beneficial in several aspects, i.e., ease of operation, cost economics, prevention of secondary pollution, or sludge formation. Polymer membrane-based separation techniques have significantly influenced metal-based effluent treatment processes for the past six decades.

Living organisms are entirely dependent on water sources in their day-to-day life that are presently unable to fulfill their needs due to water pollution increase in polluting water mainly because of rapid development, industrialization, and population growth. The progress of industrial activities was grown in the past few decades, which has led to increased pollution and the discharge of poisonous heavy metals. Heavy metals are taking part significantly in polluting water sources. Lead ion is substantially discarded from various industries such as electroplating, metallurgical engineering, mining, metal finishing, battery productions, glass and ceramic, nuclear plants, and paints and pigment industries, respectively. A few metals are good for health, but exceeding the threshold level will become highly dangerous and toxic. They can damage the function of the lungs, kidneys, brains, liver, blood composition, and other organs[1]. The various heavy metals can be found in wastewater include cadmium, mercury, Lead, arsenic, zinc, chromium, and nickel, which has highly toxic to humans, animals, aquatic animals, and the environment. Some researcher investigates heavy metals for their non-biodegradability property and long-time persistence in the atmosphere leading to the formation of Reactive Oxygen Species (ROS)[2]. Excessive amounts of Lead are accumulating in streams and lakes, directly affecting humans, animals, plants, and the environment. Carcinogen Lead
causes anemia, varying hemoglobin levels, miscarriages, abortions, changes in blood pressure, brain and kidney damage. Heavy metals originate in the soil during industrial wastewater release, metal smelting, and e-waste recycling; this impacts particularly the accumulation of the food chain [3]. Therefore, lead-contaminated water must be treated before discharging into the water streams.

As per environmental health regulations, Lead is among the most hazardous environmental substances. Lead is used in many applications like Lead-acid storage batteries, paint pigments, antifouling components in coating systems, and other construction applications. The lead concentration in natural water is generally below five ppb. However, a contaminated area may contain groundwater with a concentration exceeding ten ppb, as per WHO. An adult's average collection of Lead was estimated at 320-440mg/day. Thus, removal of Lead from water is an essential part that rightfully demands researcher attention around the globe.

Various techniques like adsorption, precipitation, ion exchange, extraction, and filtrations are using to get rid of excessive amounts of Lead from water [4–6]. Among the methods mentioned above, adsorption stands out as the most effective. In the Ion-exchange resin process, a polymeric resin acts as an intermediary, facilitating the interchange of ions with either anions or cations in an aqueous solution. Constructed from interconnected polymers imbued with acidic or basic structural components, these ion exchange resins facilitate the interchange of anions or cations upon interaction with a solution. They possess the capability to bind to various monovalent and divalent cations. Cation exchange resins are categorized based on the specific cation (hydrogen, Ammonium, sodium, potassium, and calcium) employed during the resin's synthesis to saturate sulfonic or carboxylic groups. Usually, producing ion-exchange resins involves polymerizing petroleum-derived compounds like acrylic acid, styrene, divinylbenzene, etc. At the outset, styrene and divinylbenzene are interconnected to produce resin beads utilizing suspension polymerization. These beads are expanded by immersing them in dichloromethane and then exposed to a concentrated sulfuric acid reaction. The robust acid-based cation exchange resin could produce at the end of this process. Alternatively, the expanded resin beads can produce anion exchange resin through chloromethylation and amination sequences [7].

Zeolite is a well-structured three-dimensional crystalline hydrated aluminum silicate that can be obtained in both synthesis and natural ways. Various methods exist for eliminating heavy metals from wastewater, including separation through adsorption,
filtration, and membranes; separation involving chemical processes; separation through electrical methods; and separation based on photocatalysis [8].

Figure. 1. The various techniques for removing heavy metals [8].

The present review paper has been discussed, a concise report on lead ions removal from various sources like ion exchange resins, natural zeolites, membranes, and ionic liquids for the past few years.

Figure. 2. Various methods for Pb ion removal from wastewater.
2 ROLE OF ION EXCHANGE RESINS IN LEAD ION REMOVAL

The interaction between chelating resins and metal ions occurs primarily because of the characteristics of the ligands anchored within the polymer matrix. These ligand groups are covalently linked to the inflexible polymer matrix, resulting in limited mobility. Consequently, the complexes formed with chelating resins exhibit distinct properties compared to those observed in homogeneous solutions. A spacer group like the SO$_2$ group is introduced between the ligand and the Amberlite XAD-16 matrix to enhance the flexibility of the ligands. Introducing a spacer group promotes greater steric flexibility for the ligands, allowing for improved interaction with metal ions [9]. Limited research has been carried out to eliminate metal ions from industrial amine elucidations [10]. The research demonstrated that cationic resins with carboxylic acid functionality, possessing weak acidity, exhibit superior performance compared to strongly acidic resins containing a sulfonic acid group. This superiority stems from the reduced dissociation of exchange groups under low pH conditions, eventually diminishing the exchange capacity between H$^+$ and heavy metal ions [11]. A reduction in metal ion exchange under alkaline conditions (pH 7.0) might stem from creating a metal hydroxide precipitate and subsequent hydrolysis [12].

In the advanced chitosan-coated resin beads and SCC (Superparamagnetic Cross-linked Chitosan), it was anticipated that the amino group's nitrogen atom and the hydroxyl group's oxygen atom within the chitosan structure would function as active sites for adsorbing heavy metal ions. By possessing unshared pairs of electrons in the nitrogen and oxygen atoms which can share electron pair with positive charged metal ions. Due to the relatively facile release of its unshared electron pair, the nitrogen atom emerges as the primary binding site, forming a constant metal complex. Considering these factors, the subsequent chemical reaction (1) is put forth to elucidate the underlying mechanism of heavy metal ion adsorption:

\[
\text{R-(OH) NH}_2^+ + \text{M}^{n+} \rightarrow \text{R-NH}_2\text{M}^{n+} + \text{OH}^{-} \quad (1)
\]

In the context of the resin beads, the symbol "R" encompasses all constituents. The metal ions "Mn+" denote diverse heavy metals (Zn$^{2+}$, Cu$^{2+}$, Ni$^{2+}$, Cd$^{2+}$) with a valence state of "n." Applying ion exchange (IX) using H$^+$ and Na$^+$ to remove Pb$^{2+}$ yielded incomplete results. While Pb$^{2+}$ exhibited a robust affinity for ion exchange and readily formed precipitates with sulfate and chloride, this significantly compromised the resin's
selectivity and complicated the regeneration process. This limitation extended to using less expensive regenerants like \( \text{H}_2\text{SO}_4 \), \( \text{HCl} \), and \( \text{NaCl} \).

Consequently, the effective utilization of ion exchange for \( \text{Pb}^{2+} \) removal posed a formidable research challenge. To address this, various alternatives to ion exchange were explored, mainly specialized chelating resins and adsorbent materials tailored for \( \text{Pb}^{2+} \) capture, marking an active and predominant area of investigation [13]. The potential application of Amberlite XAD-16-based chelating resin, modified from Amberlite, as an effective adsorbent for eliminating heavy metal pollutants was explored. The chelating resin's capacity to capture metal ions was investigated through batch and column techniques. Moreover, the modified dpvbs resin was successfully employed for extracting metal ions from tap water. Notably, the metal ion uptake remained consistent over three cycles, demonstrating the resin's stability. The resin exhibited an impressive efficiency of 98–99%, underscoring its robust capability for metal ion removal [14].

As reported by [15], a chelating resin was produced from poly-chloromethyl styrene (CPS) and termed CPS-DI. This innovative resin contained hetero fluorenone side groups. It was designed for the efficient removal of heavy metal ions such as \( \text{Cu} \) (II), \( \text{Pb} \) (II), and \( \text{Ni} \) (II) from aqueous solutions. CPS-DI chelating resin was developed to enrich and recover these metal ions, particularly from wastewater. Thermodynamics of adsorption and the impact of temperature on the adsorption process were explored. The \( \Delta H^\circ \) adsorption value exhibited positivity, indicating that the adsorption of metal ions was an endothermic phenomenon. The spontaneous adsorption process was found due to negative \( \Delta G^\circ \) value. Optimal conditions were identified: pH 5.0, an adsorption time of 150 minutes, and a temperature of 25°C. The ideal initial concentration of absorbed heavy metal ions and resin concentration were found to be 0.1 g/L and 1.0 g/L, respectively. In elution regeneration tests, the chelated resin's adsorption capacity for \( \text{Pb} \) (II) diminished to 85% after undergoing five regeneration cycles. A column experiment replicated CPS-DI chelating resin adsorption process for metal ions. The results illustrated that CPS-DI chelating resin effectively executed the adsorption behaviour of heavy metal ions like \( \text{Pb} \) (II), \( \text{Cu} \) (II) and \( \text{Ni} \) (II). This treatment successfully lowered the concentration of these heavy metal ions to meet national standards, offering a practical solution for the advanced treatment of wastewater containing heavy metal ions.

A cation exchange resin (CER) based on lignin, denoted as LBR was successfully developed through a one-pot synthesis method. Comparative studies revealed that sulfonating lignin with sodium sulfite proved more effective than sodium hydroxymethyl
sulfonate. While the mechanical strength of the prepared LBR gradually declined, the ion exchange capacity displayed an upward trajectory as the dosage of sulfonation reagents increased. The consistent phenol-to-formaldehyde molar ratio was maintained for the LBRs. Enhanced sulfonation resulted in higher hydrophilic capacity and lower cross-linking density.

Consequently, the swelling capacity of the LBRs increased. Among these, the LBR variant denoted as SSPL-0.50 exhibited remarkable adsorption efficiency for Pb (II) and demonstrated favorable recyclability. Even after five cycles, its capacity remained above 83%, establishing it as a promising contender for wastewater treatment. The LBR's potential as an eco-friendly alternative to petroleum-based resins is evident, further emphasizing its significance in wastewater management [16].

The copolymer resin has demonstrated a substantially porous structure and increased surface area, leading to a higher capacity for metal ion absorption, as verified through batch studies. The quantity of metal ions adsorbed by the copolymers from a given quantity is influenced by the type and concentration of electrolytes in the solution. Similarly, the uptake of CO$^{2+}$, Zn$^{2+}$, and Pb$^{2+}$ ions by the copolymer samples declines as the concentration of chloride, nitrate, perchlorate, and sulfate ions in the solution increases [17]. Sulfate, perchlorate, nitrate, and chloride ions could create robust chelation bonds with CO$^{2+}$, Zn$^{2+}$, and Pb$^{2+}$, thereby impacting the equilibrium of chelation involving these metal ions. The attainment of equilibrium for Pb$^{2+}$ ions necessitated approximately 6 hours. Notably, the rate of metal ion uptake was more rapid for Pb$^{2+}$ compared to the other heavy metal ions across all copolymer samples [18].

An effective acidic cationic resin named Dowex 50 WX8, was employed towards the elimination of Pb (II) from aqueous solutions. Pb (II) removal efficiency was notable in solutions with an initial pH of 7 but reduced under alkaline and acidic conditions. The process of lead removal was further investigated through column experiments. Breakthrough curves were determined by varying flow rates from 4.0 to 8.0 ml/min and bed depths ranging from 6 to 18 cm at a temperature of 35°C. The breakthrough and exhaustion times extended as the bed height increased, indicating the availability of more binding sites. Experimental data were analyzed using the Thomas and BDST Column adsorption models on fixed columns to envisage breakthrough curves. Parameters from the BDST model indicated more favorable lead removal with significantly higher values of $R^2$. However, the removal efficiency dwindled to 79% after the fifth cycle due to the reduction of ion exchange sites or a deficiency of sufficient regenerating solution [19].
An investigative study involving column adsorption was conducted to selectively remove lead cations from contaminated water, utilizing the conventional cation exchange resin Purolite C100 E. In this research, the saturated resin loaded with Pb\(^{2+}\) was subjected to a unique regeneration process involving Ca(NO\(_3\))\(_2\). Notably, the Ca\(^{2+}\)-laden resin efficiently and selectively exhausted the Pb\(^{2+}\) ions, aligning with the established cation exchange affinity hierarchy. During the regeneration process, involving a Ca(NO\(_3\))\(_2\)--Pb(NO\(_3\))\(_2\) mixture, the pollutant from the regeneration process underwent treatment with Ca(OH)\(_2\) up till complete precipitation, separation, and regaining of Pb(OH)\(_2\) occurred. This innovative approach facilitated the purification, recovery, and complete recycling of Ca(NO\(_3\))\(_2\) for subsequent regenerations, in absence with introducing additional chemicals substantially Ca(OH)\(_2\). In contrast to traditional regenerations involving HCl, H\(_2\)SO\(_4\), and NaCl, an innovative Ca(NO\(_3\))\(_2\)-based method proved economically feasible, user-friendly, and aligned with "zero discharge" technology. Remarkable removal efficiencies of Pb\(^{2+}\) (≥ 90%) were achieved, with the ideal concentration of 2M Ca(NO\(_3\))\(_2\) identified for effective regeneration. This approach holds immediate potential for treating Pb\(^{2+}\)-contaminated drinking water and pretreated wastewater generated by lead-acid battery industries [13].

Lead ions were effectively separated from acidic solutions using Puromet MTS 9140 resin highlighting functional group as thiourea. Notably, this resin exhibited a robust ion-exchange preference for Cu (II) over Pb (II). As time progressed, metal recovery improved, with Pb (II) reaching ion exchange equilibrium within 30 minutes, even at initial concentrations as high as 1800 mg/L. Using the dosage of resin as 0.07 g/mL and maintaining a pH of 4.5, a 17% recovery rate for Lead was obtained after a two-stage ion exchange. This outcome underscored the exceptional adsorption selectivity of the MTS 9140 resin toward Cu (II) when compared to Pb (II). The Langmuir isotherm model is best suited to the behavior of the metal ions. Regarding adsorption kinetics, the analysis indicated that the ion exchange process adhered to the pseudo-second-order kinetic model, emphasizing the consistent and predictable nature of the adsorption process [20].

An effective elimination of cationic Pb\(^{2+}\) from dilute solutions were demonstrated using the cationic exchanger resin like Amberlite IR-120. With an increased resin dosage, the metal uptake decreased, while reducing the resin particle size led to an increased metal adsorption. Moreover, elevating from 20°C to 60°C provides an enhanced metal adsorption. The lead uptake into the resin decreased when the pH value was lowered from 5 to 1. Other metals in the solution contributed to a reduction in the typical lead uptake
onto the resin. However, the resin effectively separated Pb\(^{2+}\) from other cations, except for Zn\(^{2+}\) and In\(^{3+}\). The adsorption of Lead on the resin followed the pseudo-first-order kinetic model and adhered to the Freundlich isotherm. Interestingly, the resin size ranging from 0.294 to 0.700 mm does not impact the mechanism by which Pb is loaded onto the resin; the aqueous diffusion model effectively represented this uptake. Furthermore, the equilibrium process of lead loading onto the resin was heat-absorbing and non-spontaneous [21].

An adsorption of Pb\(^{2+}\) onto the resin was notably competitive compared to the adsorption of this cation onto multi-walled carbon nanotubes. The recovery of Lead ions from the laden resin was achieved using acidic solutions under various experimental conditions. By using 0.5 M HCl solutions as an eluent for Pb\(^{2+}\), concentration factors of up to 170 were attainable. The study assessed the performance of G-26 and MTS9570 resins in adsorbing lead ions from synthesized wastewater. Key operational parameters influencing Pb (II) adsorption included contact time, resin dosage, pH of the solution, initial metal ion concentration, and temperature. The pseudo-second-order kinetic studies offered the most accurate correlation with experimental data for both resins and all systems studied. The Langmuir model was more fitting for describing adsorption equilibrium. The maximum adsorption capacities for Pb (II) were determined to be 45.45 and 38.46 mg/g for G-26 and MTS9570, respectively.

The negative and positive value of \(\Delta G^\circ\) as well as \(\Delta H^\circ\) obtained suggested the spontaneous and endothermic nature of the adsorption process. Recycling studies indicated that the most effective Pb (II) desorption for G-26 and MTS9570 resins occurred using 40 mL of 15% (v/v) HCl with a 20-minute elution time at room temperature. Across consecutive adsorption/desorption cycles, G-26 resin consistently showed exceptional stability, yielding 100% recovery for adsorption and 100% efficiency for Pb (II) ion elution. On the other hand, the performance degradation observed for MTS9570 resin could also be attributed to its macro-porous S-DVB structure showing low surface area and negative swelling factor. Consequently, the gel-structured G-26 resin demonstrated superior efficacy compared to the macro-porous MTS9570 resin for removing and recovering lead ions from wastewater [22]. A polyamine anion exchange resin, Lewatit A365, was utilized for the separation of both radioactive \(^{210}\)Pb (II) and nonradioactive Pb (II) isotopes using a Cu (II)-rich acidic chloride solution. Thermodynamic modelling of metal-chloride speciation indicated that Pb (II) tends to form anionic chloride complex –PbCl\(_3\)- under process conditions. Conversely, Cu (II) predominantly occurs as a cationic
chloride complex –CuCl+ under the same conditions. This distinction supports the effectiveness of using Lewatit A365 resin for separating Pb (II) and Cu (II).

Adsorption capacities, kinetic and thermodynamics studies were assessed through batch adsorption tests for synthetic and actual leach solutions. The findings demonstrate that selective Pb (II) adsorption can be attained across several Cu/Pb mass ratios (ranging from 1 to 1000) in the solution. Analysis involving XANES and EXAFS shed light on the adsorption mechanisms of Pb (II), Cu (II), and Cu(I) onto protonated polyamine functional groups present on the A365 resin. These analyses highlighted the formation of metal-chloride complexes at the resin surface, showcasing coordination structures distinct from those in the solution. These complexes mirror the stereochemical constraints imposed by the polyamine functional group's geometry. As a result, there emerges a notable variation in the stabilities of surface complexes for different metals, contributing significantly to the resin's selectivity [23].

Valuable insights strongly support the efficiency of various CSPVA resins for concurrently removing multiple heavy metals like zinc, lead, and iron from synthetic wastewater systems, even in the presence of diverse metals, including potassium, sodium, aluminum, magnesium, and copper. Among these resins, the high CSPVA variant exhibited auspicious performance. Specifically, this high CSPVA resin exhibited adsorption capacities of 222.21 mg/g for Zn, 135.14 mg/g for Fe, and 4.02 mg/g for Pb in the selected Zn-dominant multi-metal wastewater system. Notably, it required a shorter adsorption time of 360 minutes compared to the low and medium CSPVA resins.

The effectiveness of multi-heavy metal sorption was affirmed by monolayer adsorption and chemisorption analyses. Speciation analysis confirmed the presence of the mentioned heavy metal ions at their +2 oxidation state. Combining speciation analysis with FTIR revealed that complexation interactions and electrostatic attraction were pivotal in the mechanisms underlying multi-heavy metal removal. The recovery process, reliant on desorption, exhibited optimal results with the high CSPVA resin, achieving desorption efficiencies of 51.89%, 59.94%, and 53.70% for Zn, Fe, and Pb, respectively, after three cycles using 0.1 M HCl. Additionally, cost analysis underscored that the resin's primary cost originated from the chitosan's high molecular weight. Addressing these cost trade-offs is pivotal in determining the most suitable resin among those evaluated. In conclusion, this study provides invaluable insights into efficiently removing multiple heavy metals using the high CSPVA resin within an adsorbate system resembling real-world wastewater scenarios [24].
The achieved maximum adsorption capacities of different ion exchange resins have been organized in Table 1. Notably, the hybrid C-100 cation exchange resins, infused with nano-scale iron particles within their pores, exhibited remarkable potential for effectively removing Pb\(^{2+}\) ions from synthetic wastewater that included naturally present competitive cations [25]. Within this investigation, a hybrid resin named C100-Fe0 was formulated through a straightforward synthesis process utilizing cost-effective raw materials. The peak Pb\(^{2+}\) uptake capacity was identified at a pH value of 7.0. The Freundlich adsorption isotherm model displayed notably superior compatibility with the experimental findings, suggesting that the adsorption process is more intricate than monolayer sorption. Conducted fixed-bed column tests validated that, in the presence of a synthetic wastewater solution with a Pb\(^{2+}\) concentration of 150 µg/L, the C100-Fe\(^0\) column exhibited the capability to treat 4,200-bed volumes of wastewater prior to reaching a breakthrough concentration in line with the USEPA consumption water standard of 15 µg/L. Furthermore, the investigation established the renewability of the hybrid adsorbent, demonstrating no noteworthy reduction in its capacity after undergoing the regeneration process.

<table>
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<tr>
<th>S. No</th>
<th>Cation Exchange Resin</th>
<th>Functional group</th>
<th>Synthesis method and mode of study</th>
<th>Reported sorption capacity</th>
<th>References</th>
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</thead>
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<tr>
<td>1</td>
<td>Amberlite IR-120 C100 and C145</td>
<td>Sulfonated polystyrene</td>
<td>Batch adsorption study</td>
<td>38 mg/g</td>
<td>[21]</td>
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<td>2</td>
<td>Dowex 50 WX8 strong-acid cation exchange resin</td>
<td>Sulphonic acid SO(_3)H group</td>
<td>Column adsorption study</td>
<td>14.60 mg/g</td>
<td>[19]</td>
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<td>3</td>
<td>Purolite C100 E</td>
<td>Sulphonic acid SO(_3)H group</td>
<td>Column adsorption study</td>
<td>90%</td>
<td>[13]</td>
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<td>4</td>
<td>Lignin-based cation exchange resin</td>
<td>Sulphonic acid SO(_3)H group</td>
<td>One-pot method &amp; Batch adsorption study</td>
<td>167.2 mg/g</td>
<td>[16]</td>
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<tr>
<td>5</td>
<td>Lewatit A365</td>
<td>Polyamine anionic resin</td>
<td>Batch adsorption study</td>
<td>29.1 mg/g</td>
<td>[23]</td>
</tr>
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<td>6</td>
<td>Amberlite XAD-16 CER CPS-DI</td>
<td>Sulphonic acid SO(_3)H group</td>
<td>Batch &amp; Column adsorption study</td>
<td>243.16 mg/g</td>
<td>[14]</td>
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<td>7</td>
<td>Copolymer resin</td>
<td>Heterofluorenone side groups 2,4- dihydroxy benzoic acid, phenylhydrazine and formaldehyde (2,4-DBPHF)</td>
<td>Polycondensation method &amp; Batch adsorption study</td>
<td>97.5%</td>
<td>[18]</td>
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<td>8</td>
<td>MTS 9140</td>
<td>Thiourea</td>
<td>Batch adsorption study</td>
<td>11.05 mg/g</td>
<td>[20]</td>
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</table>
3 LEAD ION REMOVAL USING NATURAL ZEOLITE AS ADSORBENT

Natural zeolite is a low-cost material for eliminating toxic metals and other organic contaminants. Natural zeolite could exhibit both ion exchange and adsorption processes better. 40 types of natural zeolites are available that have been used for various applications, including ion removal. Those zeolite terms and discovered year are given in the below Table 2.

<table>
<thead>
<tr>
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<th>Year</th>
<th>Terms of Zeolite</th>
<th>Year</th>
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<td>1893</td>
<td>Stellerite</td>
<td>1909</td>
</tr>
<tr>
<td>Ferrierite</td>
<td>1918</td>
<td>Viseite</td>
<td>1942</td>
<td>Yugawaralite</td>
<td>1952</td>
</tr>
<tr>
<td>Wairakite</td>
<td>1955</td>
<td>Bikltaite</td>
<td>1957</td>
<td>Paulingite</td>
<td>1960</td>
</tr>
<tr>
<td>Cowlesite</td>
<td>1975</td>
<td>Merlinoite</td>
<td>1976</td>
<td>Svetlozarite</td>
<td>1976</td>
</tr>
<tr>
<td>Amicite</td>
<td>1979</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From these different earth metals, mordenite and clinoptilolite are the most commonly used natural zeolites for eliminating toxic metals due to their exclusive structure and properties. In this regard, during the adsorption process, all the pollutants or heavy metals adhere to the adsorbent surface effectively due to adsorbate molecule interaction same time; it can be desorbed with changing temperature or pH levels. The significant merits of the ion exchange process are selectivity, less amount of sludge formation, gathering stringent, and reclamation of the amount of heavy metals [26].
3.1 PROPERTIES OF NATURAL ZEOLITE

Since 1970 natural zeolites are excellent catalysis, ion exchangeable, and adsorbents due to their specific structure, crystalline phase, and morphology. Natural zeolites are occurring volcanic rocks that pose worthy physicochemical properties, high surface area, and hierarchical structured molecular dimensions with thermal stability. Because of these characteristics, zeolite is an efficient material in water purification, petrochemical, agricultural, medical, and allied industries. Analcime, phillipsite, chabazite, erionite, mordenite, and clinoptilolite are the most commonly used zeolites for various applications. Clinoptilolite natural zeolite is the most used adsorbent for the application of sorption of heavy metals [27,28]. The following equation (2) is the chemical formula for natural zeolites [29],

\[ M_{x/n} [Al_xSi_yO_{2(x+y)}] \cdot pH_2O \]  

Where

M is the Ca, Mg, Na, Li, Ba, K, n is the cation charge.

Zeoalites are well-organized 3D structures that have 2 nm cavities with channels and enough pores. This microporous material comprises active catalytic centers in pores where smaller molecule pores can take place. The SiO44 and AlO45 tetrahedral units’ zeolite framework structure was well linked with sharing one oxygen atom. Si\(^{4+}\) ion replaced by Al\(^{3+}\) ions to create a negative charge in tetrahedron composed oxygen atoms. The lattice system could balance these negative charges with possible cations like Na\(^{+}\), K\(^{+}\), or Ca\(^{2+}\). In addition, weak electrostatic interaction may occur with cations and aluminosilicates lattice. Hence, these characteristics aid in the ion exchange between the present ions with natural zeolite. Natural zeolite like Clinoptilolite is not producing the same results because of their deposition region. Based on this, zeolite capability varies, such as ratio of Si/Al, pore size, crystalline structure, morphology, and surface area, respectively. Moreover, natural zeolite deposits may cause their chemical structure and other mineral impurities are present in the sample.
3.2 REMOVAL MECHANISM

Figure 3 demonstrates the Pb (II) ion removal mechanism using natural zeolites. Pb (II) is water soluble and possible to exchange with other metals. The physical occurrence of electrostatic attraction might arise from the interaction between the negatively charged surface of the zeolite lattice and the positively charged exchangeable cations. Pb(II) ions are adsorbed on natural zeolite surfaces through the creation of particular inner-sphere bonds [30]. The adsorbed higher fraction of Pb (II) ions were trapped in zeolite channels and cages due to physical or chemical adsorption. The occupied metals strongly bond on the zeolite surfaces, which are insoluble or non-exchangeable. The removal mechanism can be drawn in two ways, (1) highly selective natural zeolites for $\text{H}_3\text{O}^+$ ions when Pb(II) ion concentration increases with decreasing metal exchangeability and (2) natural zeolite was weakly acidic nature and at low pH the zeolites exchange capacity has been decreased [29–31].

![Figure 3: Lead (II) removal using natural zeolites.](image)

**by the authors on their own**

3.3 ADSORPTION OF PB ION USING NATURAL ZEOLITES

In Table 3 contains the maximum adsorption capacity achieved by various natural zeolites. As shown in Table 3 and 4, the Clinoptilolite, Chabazite, Scolecite, and Phillipsite earth metals were utilized to eliminate inorganic toxins from water. Moreover, Clinoptilolite is a promising substance for eliminating Pb (II) metal in terms of readily available, cheap, and better efficiency [30,32,33]. Table 3 depicting the operating
conditions like temperature, amount of adsorbent, solution concentration, and solution pH, respectively, were used for adsorption and ion exchange techniques subject to the adsorption ability. Table 3 showed the list of isotherms, kinetics, and thermodynamic studies on natural zeolite for Pb (II) ion sorption. In the adsorption technique, isotherms investigation supports getting properties and their mechanism of Pb (II) ion and natural zeolites. Similarly, an adsorption kinetic study helps to find the adsorption rate and process mechanism. The thermodynamic study assists the adsorption process, whether endothermic or exothermic nature, Gibb's free energy (ΔG°), change in enthalpy (ΔH°), and change in entropy (ΔS°) were calculated in this examination [29,33–36].

A study on natural zeolite regeneration using KCl, which is essential for reuse and reducing pollutants. The regeneration efficiency was achieved of 98.5% and suggested to stabilize or solidifying Pb (II) loaded zeolites before discharge into the landfill [37]. It investigated kinetics and thermodynamics studies on Pb(II) removal using natural zeolite Clinoptilolite. The research delved into an adsorption process characterized by spontaneity and exothermic behavior, achieving a remarkable 92% removal efficiency. The optimal conditions, including pH, contact time, zeolite dosage, and initial concentration of Pb (II) metal, were determined as follows: pH 5, a contact time of 25 minutes, a zeolite dosage of 10 g/L, and an initial Pb (II) metal concentration of 100 mg/L [28]. Langmuir isotherm is confirming the adsorption process is favorable for using natural zeolite to eliminate the Pb(II) ions from (waste)water.

Table 3. Adsorption capacities of different natural zeolites for Pb (II) ions.

<table>
<thead>
<tr>
<th>Natural zeolite</th>
<th>Optimum conditions</th>
<th>Adsorption capacity (mg/g)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iranian Clinoptilolite</td>
<td>pH =3; AD=20 g/L; LC=50 mg/L; T=298 K.</td>
<td>52.9</td>
<td>[38]</td>
</tr>
<tr>
<td>Greek Clinoptilolite</td>
<td>pH =3.5; AD=10 g/L; LC=320 mg/L; T=298 K.</td>
<td>23.03</td>
<td>[37]</td>
</tr>
<tr>
<td>Italy Clinicoptilolite</td>
<td>pH =5.5; AD=4.0 g/L; LC=25 mg/L; T=298 K.</td>
<td>246.57</td>
<td>[30]</td>
</tr>
<tr>
<td>Ukrainian Clinicoptilolite</td>
<td>pH =6.2; AD=2.5 g/L; LC=800 mg/L; T=300 K.</td>
<td>27.76</td>
<td>[39]</td>
</tr>
<tr>
<td>Sardinian natural CNcl</td>
<td>AD=4.0 g/L; LC=200 mg/L; T=298 K.</td>
<td>27.97–124.32</td>
<td>[32]</td>
</tr>
<tr>
<td>Turkish CNcl</td>
<td>pH =5.0; AD=2.0 g/L; LC=1000 mg/L; T=298 K.</td>
<td>23.73–75.63</td>
<td>[40]</td>
</tr>
<tr>
<td>Scolecite zeolite</td>
<td>pH =6.0; AD=2.0 g/L; LC=30 mg/L; T=298 K.</td>
<td>5.80</td>
<td>[41]</td>
</tr>
<tr>
<td>Bigadic Clinoptilolite</td>
<td>pH =4.0; AD=5.0 g/L; LC=10 mg/L; T=298 K.</td>
<td>6.0</td>
<td>[31]</td>
</tr>
<tr>
<td>Bigadic Chabazite</td>
<td>pH =4.0; AD=5.0 g/L; LC=10 mg/L; T=298 K.</td>
<td>6.0</td>
<td>[31]</td>
</tr>
<tr>
<td>Turkey CNcl</td>
<td>pH =4.0; LC=100 mg/L; T=343 K.</td>
<td>166.0</td>
<td>[33]</td>
</tr>
<tr>
<td>Turkey Raw CNcl</td>
<td>pH =4.5; AD=2.5 g/L; LC=500 mg/L; T=323 K.</td>
<td>80.9</td>
<td>[42]</td>
</tr>
<tr>
<td>Turkey Pretreated CNcl</td>
<td>pH =4.5; AD=2.5 g/L; LC=500 mg/L; T=323 K.</td>
<td>122.4</td>
<td>[42]</td>
</tr>
<tr>
<td>Jordanian Phillipsite zeolite</td>
<td>pH =4.0; AD=8.0 g/L; LC=250 mg/L; T=298 K.</td>
<td>104.0</td>
<td>[26]</td>
</tr>
</tbody>
</table>
Turkey natural zeolite: pH = 5.0; AD = 10.0 g/L; LC = 100 mg/L; T = 293 K; 16.81 [28]
Natural zeolite: pH = 5.0; AD = 1.0 g/L; LC = 400 mg/L; T = 293 K; 5.0 [43]
Australia Clinoptilolite: pH = 6.0; AD = 2.0 g/L; LC = 100 mg/L; T = 303 K; 55.0 [44]

AD = Adsorbent Dosage (g/L), LC = Lead (II) Concentration (mg/L), T = Temperature in K.

**Table 4.** List of isotherms, kinetics, and thermodynamic parameters of Pb (II) ion sorption onto natural zeolite as adsorbents.

<table>
<thead>
<tr>
<th>Natural zeolite</th>
<th>Temperature (K)</th>
<th>Isotherms</th>
<th>R²</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey Clinoptilolite</td>
<td>293</td>
<td>Langmuir</td>
<td>0.996</td>
<td>[28]</td>
</tr>
<tr>
<td>Australia Clinoptilolite</td>
<td>303</td>
<td>Freundlich</td>
<td>0.946</td>
<td>[44]</td>
</tr>
<tr>
<td>Jordanian Phillipsite zeolite</td>
<td>298</td>
<td>Langmuir</td>
<td>1.00</td>
<td>[26]</td>
</tr>
<tr>
<td>Turkey Clinoptilolite</td>
<td>313</td>
<td>Langmuir</td>
<td>0.999</td>
<td>[33]</td>
</tr>
<tr>
<td>Italy Clinoptilolite</td>
<td>300</td>
<td>Langmuir</td>
<td>0.99</td>
<td>[30]</td>
</tr>
<tr>
<td>Turkish Clinoptilolite</td>
<td>298</td>
<td>Langmuir</td>
<td>0.9988</td>
<td>[40]</td>
</tr>
<tr>
<td>Turkey Raw Clinoptilolite</td>
<td>323</td>
<td>Langmuir</td>
<td>0.971</td>
<td>[42]</td>
</tr>
<tr>
<td>Turkey Pretreated Clinoptilolite</td>
<td>323</td>
<td>Langmuir</td>
<td>0.993</td>
<td>[42]</td>
</tr>
<tr>
<td>Ukraine Clinoptilolite</td>
<td>300</td>
<td>Freundlich</td>
<td>0.991</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Natural zeolite</th>
<th>Temperature (K)</th>
<th>Kinetics</th>
<th>R²</th>
<th>(qe)exp (mg/g)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey natural zeolite</td>
<td>293</td>
<td>Pseudo-second order</td>
<td>1.00</td>
<td>9.48</td>
<td>[28]</td>
</tr>
<tr>
<td>Australia Clinoptilolite</td>
<td>303</td>
<td>Pseudo first-order</td>
<td>0.980</td>
<td>4.07 × 10^{-5} (mol/g)</td>
<td>[44]</td>
</tr>
<tr>
<td>Greek Clinoptilolite</td>
<td>298</td>
<td>Pseudo-second order</td>
<td>0.999</td>
<td>23.03</td>
<td>[37]</td>
</tr>
<tr>
<td>Turkey Clinoptilolite</td>
<td>313</td>
<td>Pseudo first-order</td>
<td>0.955</td>
<td>1.357</td>
<td>[33]</td>
</tr>
<tr>
<td>Turkey Raw Clinoptilolite</td>
<td>323</td>
<td>Pseudo first-order</td>
<td>0.990</td>
<td>5.90</td>
<td>[42]</td>
</tr>
<tr>
<td>Turkey Pretreated Clinoptilolite</td>
<td>323</td>
<td>Pseudo-second order</td>
<td>0.996</td>
<td>4.76</td>
<td>[42]</td>
</tr>
<tr>
<td>Ukraine Clinoptilolite</td>
<td>300</td>
<td>Pseudo-second order</td>
<td>0.978</td>
<td>27.76</td>
<td>[39]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Natural zeolite</th>
<th>Temperature (K)</th>
<th>ΔG (kJmol⁻¹)</th>
<th>ΔH (kJmol⁻¹)</th>
<th>ΔS (Jmol⁻¹K⁻¹)</th>
<th>Adsorption capacity (mg/g)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turkey natural zeolite</td>
<td>293</td>
<td>-6.98</td>
<td>-3.75</td>
<td>0.011</td>
<td>16.81</td>
<td>[28]</td>
</tr>
<tr>
<td>Turkey Raw Clinoptilolite</td>
<td>323</td>
<td>-8.86</td>
<td></td>
<td></td>
<td></td>
<td>[42]</td>
</tr>
<tr>
<td>Turkey Pretreated Clinoptilolite</td>
<td>323</td>
<td>-8.89</td>
<td></td>
<td></td>
<td></td>
<td>[42]</td>
</tr>
</tbody>
</table>

Sources: drawn by the authors on their own

4 LEAD ION REMOVAL THROUGH MEMBRANE SEPARATION TECHNOLOGY

Polymer membranes are fabricated majorly through a phase-inversion process with various pre-set controlling parameters, i.e., pressure, temperature, membrane morphology, and reuse/recovery possibilities. Liquid membrane (LM) is a traditional laboratory technique utilized to facilitate the transfer of lead ions (Pb2+) using kerosene.
with a composition ranging from 2.5% to 12.5% v/v of Tri-n-butyl phosphate (TBP) as the carrier or extractant. In the LM process, lead ions are removed and recovered simultaneously using a suitable stripping medium, feed, strip pH, and lead concentration. The transport model employed a diffusion boundary layer and steady-state conditions, showing considerable similarity to the experimental outcomes. Notably, the transportation rate was significantly influenced by both pH and partition coefficient, with higher priority given to greater strip volume: feed volume (Vs:Vf) ratios for enhanced Pb2+ removal efficiencies. Prominent separation tool, an adsorption used for lead ion using cellulose acetate/polycaprolactone reinforced nanostructured membrane. Morphology-controlled cellulose acetate (CA) membranes fabricated through an electrospinning process using polycaprolactone (PCL) of different concentrations (0%, 10%, 20%, and 30%). Extensive use of analytical tools confirms the PCL in CA matrix, which enhances the fiber diameter and membrane surface area, thereby improving the lead adsorption sites. Pristine CA membrane adsorption capacity of 43.96 mg Pb2+ /g increases to 70.50 mg Pb2+ /g of CA/PCL doped membrane. Experimental outcomes are close-fitting with pseudo-second-order kinetics and Freundlich isotherm, which clearly states that incorporation of PCL to produce nanostructured membranes beneficial for better performance.

Functionalized (Glycidyl) POSS Polyhedral oligomeric silsesquioxanes nanoparticles used to alter polyetherimide (PEI) nanofiltration membranes for metal (Pb2+, Cu2+) ions elimination from wastewater. L-cysteine was applied to the functionalization of glycidyl POSS and extensively characterized using FTIR, FESEM, etc.; superior pure water flux of 95 (L/m²h) was observed for one wt.% functionalized POSS PEI membrane than pristine PEI membrane's 17.63 (L/m²h). Similarly, Pb2+ and Cu2+ rejections measured 85 and 86% for one wt.% functionalized-POSS PEI membrane, whereas less than 50% was achieved for the PEI membrane. Functionalized nanomaterial loading does exhibit tremendous performance compared with pristine membrane can be explored further [45].

The effect of two different additives on polyether sulfone (PES) membranes morphology and its influence on metal ion separation was reported. Graphene oxide (GO) and polyvinylpyrrolidone (PVP) are additives in PES membrane fabrication. The membrane matrix was infused with PVP and varying quantities of physical blending. This infusion was subsequently verified through evaluations of porosity, contact angle, water flux, and FTIR analysis. PVP improves the homogeneity of GO within the membrane
matrix through a conventional hydrogen bond formation mechanism. Nanoparticles enhanced fundamental membrane properties, particularly water permeability, Lead refusal, and adsorption ability. The modified membrane achieved a permeate rate of 150.21 L/m²h, exhibiting an increase of 8.03 times compared to the original pristine membrane. As anticipated, the altered membranes exhibited superior Pb²⁺ rejection at 80.6%, in contrast to the unmodified membranes' 38.9% rejection when tested against synthetic effluents. Among the Freundlich and Langmuir models studied, Langmuir isotherm model emphasizes best-fitting with the results [46].

The NaX zeolite was utilized in ion exchange for Lead ion elimination from various streams through a Polyethersulfone (PES) ultrafiltration membrane. The lab-based hydrothermal technique was used for NaX zeolite synthesis and after extensive characterization (XRD, SEM, EDAX, FTIR), grounded into a fine powder and infused in 20% by wt. Polyethersulfone (PES) was dissolved in dimethylformamide (DMF) to create a lasting solution. Composite membranes, known as mixed matrix membranes (MMMs), consisting of NaX zeolite and PES, had been prepared by inversion technology. These membranes were evaluated under various conditions, including different initial metal solution pH values (ranging from 2 to 7), initial metal ion concentrations (ranging from 50 ppm to 200 ppm), and the initial feed temperatures (25°C, 36°C, & 46°C). The effects of these conditions on treatment efficacy and permeate flux were observed at a transmembrane pressure (TMP) of 1.6 bar. NaX zeolite changed the membrane hydrophilicity and exhibited better permeation flux than pristine. Pb (II) ions (97%) removal was achieved at pH (6), temperature (25°C), TMP (1.6 bar), and initial Pb (II) ions concentration (50 mg/L) confirms better adsorption capacity than all other combinations of membranes [47,48].

Nano-activated alumina membrane (NAAM) investigated for lead ion by absorption process. The fabrication of activated alumina was achieved using an environmentally friendly in-house method, coupled with the application of design of experiments (DOE) based on response surface methodology. This approach involved six experimental parameters: pH, NaOH concentration, H₂SO₄ concentration, deionized water (DI), and the amount of aluminum (Al). Through the statistical optimization procedure, the subsequent parameters were determined: aluminum quantity (0.000821 cm³/g), micro-pore volume (0.00221 cm³/g), and cumulative volume of adsorption pores (0.002203 cm³/g). The Langmuir and Freundlich models exhibited good fits, revealing a maximum adsorption capacity of 25 mg of Lead per gram of the nanomembrane. The
initial adsorption phase demonstrated rapid kinetics, with equilibrium attained in less than 20 minutes, as corroborated by the kinetic models [49].

Sulfonated Polyethersulfone (SPES-SiO$_2$-(CH$_2$)$_3$-NH$_2$) was effectively loaded with functionalized silica nanoparticles containing amine and thiol groups. The influence of silica and modified silica particles during the ion exchange of lead and cadmium ions were documented by [50]. An 8-hour dialysis procedure using SPES-SiO$_2$-(CH$_2$)$_3$-NH$_2$ membrane results in a 43.2% removal of Pb$^{2+}$, demonstrating the membrane's potential. Selective removal of Pb$^{2+}$ was observed, from the feed solution containing Pb$^{2+}$ and Cd$^{2+}$ within two hours of dialysis. Notably, the fabricated membrane exhibited a higher affinity for adsorbing Cd$^{2+}$ ions compared to Pb$^{2+}$ ions, which highlights its capability for facilitating the separation of Pb$^{2+}$ and Cd$^{2+}$ ions.

Using molecular simulation techniques, a Boron nitride nanosheet (BNNS) membrane was examined for its ability to eliminate Pb$^{2+}$ and Cd$^{2+}$ ions from aqueous solutions. A pore was introduced into the BNNS membrane's surface, which was then subsequently functionalized with fluorine and hydrogen atoms. This modification facilitated the creation of a pathway through which ions could traverse the BNNS membrane. An external voltage was also applied to enhance the efficiency of Pb$^{2+}$ and Cd$^{2+}$ removal. The significant factors governing the separation process encompassed various calculations: the potential of mean force concerning cadmium and lead ions and water molecules, the radial distribution function of lead-water and cadmium-water, the autocorrelation function detailing the hydrogen bonding of water molecules, and the average number of hydrogen bonds formed by water molecules [51].

The impact of ion interactions on the removal of Lead was studied using a polyamide nanofiltration membrane. The lead ion rejection was assessed with feed solutions comprising Pb (NO$_3$)$_2$, PbCl$_2$, and PbSO$_4$ in the case of a single-salt solution system. For the binary-salt solution system, feed solutions consisted of Pb (NO$_3$)$_2$, Cu (NO$_3$)$_2$, Zn (NO$_3$)$_2$, Cd (NO$_3$)$_2$, NaNO$_3$, and NH$_4$NO$_3$. The impact of divalent and monovalent cations (Cd, Cu, Zn, Na), as well as Ammonium on lead rejection, was investigated under varying transmembrane pressures (10 and 40 bar) and lead ion concentrations (20 and 400 mg/L). Pressure and initial feed concentration exhibit a positive effect on higher lead ion rejection as well as the role of anions replacement. The removal of lead ions increased by approximately 2% and 9% upon replacing NO$_3^-$ with Cl$^-$ and SO$_4^{2-}$, respectively. This variation was attributed to the influence of anion valency. The highest permeate flux and the lowest lead ion rejection were observed at a
pH of 5.6. When binary salt solutions were used as feed, the introduction of monovalent cations did not significantly alter lead rejection. However, the trend reversed when divalent cations were introduced, resulting in a noticeable reduction in lead ion rejection [52].

A synergistic nano-membrane approach was employed for lead ion removal, incorporating biodegradable poly-gamma-glutamic acid (-PGA), a linear biopolymer, and its cross-linked nanoparticles. This combination facilitated the capture of metal ions by forming nano-scale particles. Subsequently, the polymer-metal ion particles with sizes ranging from 80 to 350 nm were eliminated using membrane separation. To establish an efficient process for lead ion removal from aqueous solutions, two ultrafiltration techniques were explored, utilizing nanoparticle enhancement. Several critical parameters were investigated, including the lead ion concentration in the feed, -PGA concentrations, their proportions, -PGA cross-linking ratio, and the solution's pH, all of which played a role in lead removal efficiency [53].

A nanofiber membrane of Poly (vinyl alcohol)/chitosan (PVA/Chi) was created to adsorb lead and cadmium ions. The effectiveness of this membrane was assessed by investigating crucial experimental factors such as the initial concentration of metal ions, interaction time, adsorbent dosage, and solution pH. The adsorption process was better aligned with the pseudo second order model. Notably, the simulated environmental effluents exhibited a maximum adsorption capacity of 266.12 mg/g for Pb (II) and 148.79 mg/g for Cd (II) [54].

Composite beads of Zr-based metal-organic frameworks (MPCB(Zr)), with an average diameter of approximately 1.74 mm, have been developed to remove lead ions (Pb(II)). The distribution coefficient achieved for Pb(II) was impressive, $8.0 \times 10^6$ mL g$^{-1}$, while the theoretical adsorption capacity has reached to 144.5 mg g$^{-1}$. Notably, the MPCB(Zr) showed a wide operational pH range of 3 to 6, displaying remarkable reusability by maintaining a 90% lead removal efficiency over 20 cycles. In-depth physicochemical analyses have revealed that thiol and oxygen-containing functional groups are the underlying reason behind the exceptional lead adsorption performance. This unique characteristic, showcasing the significant contribution of MOFs in water treatment processes, was uncovered through combined physicochemical assessments. Lab-scale experiments upgraded with different operation conditions were evaluated through the pore surface diffusion model [55].
Low-cost and highly-selective adsorbents, i.e., novel β-cyclodextrin covalently-crosslinked by tannic acid (TA@CD) polymer nano sponge (fabricated through condensation reaction). The developed nano sponges selectively capture Lead (1143) from simulated effluent associated with other existing metals. The exceptional adsorption capability can be attributed to the presence of tannic acids and phenolic hydroxyl groups, which have the ability to bind and establish a relatively stable structure. This results in a significant lead adsorption saturation capacity of 136.8 mg g\(^{-1}\) when the initial concentration is 200 mg/L (the maximum capacity is 116.5 mg/g). Moreover, an incredibly rapid removal efficiency of 81% for Pb\(^{2+}\) was observed within just 3 minutes. The presence of abundant adsorption sites on tannic acid influences the process, and total adsorption is completed within 50 min of time. Furthermore, the proficient rate of mass transfer, facilitated by continuous diffusion (CD), enhances both the adsorption process and the regeneration performance. This swift adsorption, coupled with the high efficiency of lead removal, presents a viable strategy for cost-effective and targeted adsorbents. This approach holds promise for selectively recovering heavy metal ions from real-world wastewater scenarios [56].

5 LEAD ION REMOVAL THROUGH IONIC LIQUIDS

Ionic Liquids (ILs) are composed of an organic cation combined with either an organic anion or an inorganic anion. The IL melts below 100°C by tuning the combination of cation and anion, resulting in unique and different physicochemical properties like high thermal strength, low vapor pressure, flammability, large electrochemical, and recyclability [57]. Because of these greater properties, ILs have gained more industrial and scientific attention. Ionic solvents release negligible environmental contaminants into the atmosphere, as they possess negligible volatility in contrast to conventional solvents, typically volatile organic compounds (VOC). Despite being classified as "green" solvents, ILs have the potential to contaminate aquatic life because of their solubility in water. Additionally, new research has shown that the IL's structure, particularly the cation component, significantly impacts toxicity.

The extensively studied ILs comprise different derivatives of imidazolium, pyridinium, ammonium, and phosphonium cations, which are paired with anions like halides, tetrafluoroborate [BF4] −, hexafluorophosphate [PF6] −, bis(trifluoromethyl sulfonyl) imide [Tf2N] −, carboxylates [RCO2] −, alkyl sulfates [CnSO4] −, and alkyl sulfonates [CnSO3] −. The significant expense of ILs presents a hindrance to their
extensive adoption due to their intricate nature when contrasted with traditional solvents. Over the past decade, deep eutectic solvents (DESs) have garnered considerable attention as researchers seek eco-friendly and efficient solvent options. The cost-effectiveness of DESs in comparison to ILs, their adaptable design feasibility, and their environmentally sound characteristics, such as potential biodegradability, low toxicity, and minimal vapor pressure, have collectively fuelled the notable focus on integrating DESs. DESs have demonstrated to provide enormous opportunities since their discovery in 2003, presenting new perspectives as unique and advanced materials. With more than 10,000 published papers on this subject spanning several scientific domains, tremendous progress has been made in the synthesis and uses of DESs to date. Due to its advantageous and distinctive physicochemical features, the practice of DESs in effluent treatment has, in particular, quickly arisen as a viable request field for enhancing developed and systematic operations. The most recent developments in the use of several DES classes in the treatment of water, with a particular emphasis on membrane parting and microscale withdrawal techniques. The integration of DESs in water treatment procedures and technologies currently faces some problems. The removal of Lead by using ILs and DES, thermophysical and chemical properties of ILs and DES, mechanism involved in adsorption of Lead, followed by study of kinetics and isotherms

5.1 DIFFERENT PROPERTIES OF IL AND DES

Ionic liquids possess distinctive characteristics that render them appealing for a wide spectrum of applications. Here are some of the key properties of ionic liquid DESs illustrated in detail:

Figure 4. Key properties of Ionic Liquids [57]

Sources: drawn by the authors on their own
5.2 REMOVAL OF LEAD USING IONIC LIQUIDS

The efficacy of extracting heavy metals using ionic liquids relies on both the particular ionic liquid employed and the specific heavy metal under consideration. Broadly, the procedure encompasses the creation of a complex between the ionic liquid and the targeted heavy metal, followed by isolating this complex from the solution. By incorporating functional groups like carboxylates, sulfonates, or phosphates, ionic liquids can be engineered to possess the capability to bind with heavy metal ions. When the ionic liquid is introduced to a solution containing heavy metal ions, these functional groups can complex with the metal ions, forming a solid or liquid-phase complex. The compound can subsequently be isolated from the solution through diverse methods, including precipitation, extraction, or membrane separation. Following separation, the heavy metal can be either reclaimed or disposed of in a suitable manner. In certain instances, the ionic liquid can be regenerated and employed anew for successive heavy metal removal procedures. Nevertheless, this feasibility hinges on the distinctive attributes of the ionic liquid and the operational conditions it encounters. The utilization of ionic liquids for heavy metal removal presents a prospective strategy for mitigating the issue of heavy metal contamination across diverse sectors, encompassing mining, metallurgy, and wastewater treatment.

5.3 AMMONIUM BASED IONIC LIQUIDS

These Ionic Liquids (ILs) consist of a quaternary ammonium cation paired with an anion like chloride, bromide, or acetate. Illustrative instances encompass butyl methylimidazolium chloride ([BMIM][Cl]) and 1ethyl-3methylimidazolium acetate ([EMIM][Ac]). Ammonium based ILs have demonstrated efficacy in lead elimination, attributed to their robust stability, minimal toxicity, and capacity to establish potent bonds with metal ions. An investigation into lead removal from aqueous solutions achieved an impressive 98% removal using the ionic liquid [N\textsubscript{2244}][N\textsubscript{88}SA] [58]. The aqueous
solution of metal ions is prepared for 50, 100, 150, 200, and 250 ppm using lead nitrate \([\text{Pb(NO}_3\text{)}_2]\). pH varied from 2,4,6,8,10 using a buffer solution. The extraction procedure involves blending an organic solution and an aqueous phase within a screw-capped container, which is then agitated for a duration ranging from 15 to 75 minutes using an incubator-shaker set at room temperature \((25^\circ \text{C} \pm 1^\circ \text{C})\). The behavior of extraction is monitored by changing the initial concentration of metal ion, pH, and equilibrium time.

It was reported that the maximum metal ion extraction is found to be at 50 ppm, pH 8, equilibrium time of 45 mins. By varying the metal ion concentration from 150 ppm to 250 ppm, the extraction efficiency was found to be decreased from 98% to 80%. Though both the adsorbent shows higher selectivity towards the removal of metal ion, Hassan AA et al.; 2022 report \([2\text{A-A}]\text{CoCl}_3\) has higher Adsorption capacity on a lead when compared with \([2\text{A-A}]\text{FeCl}_4\) [59].

<table>
<thead>
<tr>
<th>S. No</th>
<th>IL</th>
<th>Metal ion</th>
<th>Adsorption capacity (mg/g) / Extraction %</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>([2\text{A-A}]\text{FeCl}_4)</td>
<td>Lead</td>
<td>45</td>
<td>[59]</td>
</tr>
<tr>
<td>2</td>
<td>([2\text{A-A}]\text{CoCl}_3)</td>
<td>Lead</td>
<td>50</td>
<td>[59]</td>
</tr>
<tr>
<td>3</td>
<td>([\text{N}<em>{2244}]\text{[N}</em>{88}\text{SA}])</td>
<td>Lead</td>
<td>98 %</td>
<td>[58]</td>
</tr>
</tbody>
</table>

Enhanced extraction efficiency was observed with an elevation in pH within the range of 8 to 9, resulting in a remarkable 99% lead removal from wastewater. However, prolonging the interaction duration between the IL and the metal ion reduces the removal percentage. Specifically, a contact time of 5 to 30 minutes yields the highest extraction percentage for metals, while extending the duration beyond 60 minutes slightly
diminishes the adsorption capacity. Furthermore, the adsorption capacity experiences augmentation with an increase in the metal ion concentration, peaking at 250 ppm; subsequently, a marginal decrease is observed. This phenomenon can be attributed to the saturation of the active sites within the ionic liquids.

5.4 PHOSPHONIUM BASED IONIC LIQUIDS

These phosphonium based ILS are formulated using a quaternary phosphonium cation matched with an anion like chloride, bromide, or acetate. Notable illustrations encompass trihexyltetradecylphosphonium chloride ([P6,6,6,14] [Cl]) and tributylmethylphosphonium chloride ([P4441] [Cl]). Phosphonium-based ILS have also demonstrated efficacy in lead elimination attributed to their pronounced hydrophobic nature, minimal volatility, and robust affinity for metal ions. Thasneema et comprise among three different hydrophobic phosphonium Ionic liquids, [PC₆C₆C₆C₁₄] [NTf₂], shows the higher removal percentage of Lead, IL evaluated by UV visible spectrophotometer and ICP-MS. [60]

<table>
<thead>
<tr>
<th>S. No</th>
<th>Ionic Liquid</th>
<th>Metal ion</th>
<th>Initial Concentration (ppm)</th>
<th>Final Concentration (ppm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PC₆C₆C₆C₁₄[Cl]</td>
<td>Lead</td>
<td>20</td>
<td>7.34</td>
<td>[60]</td>
</tr>
<tr>
<td>2</td>
<td>[PC₆C₆C₆C₁₄][N(CN)₂]</td>
<td>Lead</td>
<td>20</td>
<td>0.82</td>
<td>[60]</td>
</tr>
<tr>
<td>3</td>
<td>[PC₆C₆C₆C₁₄][NTf₂]</td>
<td>Lead</td>
<td>20</td>
<td>0.24</td>
<td>[60]</td>
</tr>
</tbody>
</table>

Sources: drawn by the authors on their own

In an investigation by Mochamad et al. (2022), it was reported that IL@MSN demonstrates accelerated reaction kinetics and reduced the thermodynamic barriers for lead adsorption. This is attributed to IL@MSN's abundant accessible adsorption sites, uniform structural and pore characteristics, and additional beneficial attributes including robust thermal and structural stability. These qualities position IL@MSN as a promising candidate for the effective adsorption of diverse heavy metals [61].

<table>
<thead>
<tr>
<th>S. No</th>
<th>Ionic Liquid</th>
<th>Nanoparticle</th>
<th>Metal ion</th>
<th>Adsorption capacity (mg/g)</th>
<th>Column Adsorption (mg/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P8,8,8,12Br</td>
<td>IL@SIL</td>
<td>Lead</td>
<td>142.9</td>
<td>242.2</td>
<td>[61]</td>
</tr>
<tr>
<td>2</td>
<td>P8,8,8,12Br</td>
<td>IL@MSN</td>
<td>Lead</td>
<td>256.4</td>
<td>325.6</td>
<td>[61]</td>
</tr>
</tbody>
</table>

Sources: drawn by the authors on their own
Because of the intraparticle mesoporosity, MSN exhibits a greater surface area and pore volume compared to silica. The surface area and porosity of both adsorbents decrease after immobilization. Among them, IL@SIL experiences a more pronounced reduction in surface properties than IL@MSN. The pH level is a crucial parameter in removing Pb(II). The effectiveness of lead removal is heightened by elevating the pH from 2 to 7. Subsequently, efficiency plateaus between pH 8 and 9, followed by a decline in efficiency beyond pH 9.

5.5 IMIDAZOLIUM-BASED IONIC LIQUIDS

Comprising an imidazolium cation paired with an anion like chloride, tetrafluoroborate, or hexafluorophosphate, these ILs encompass examples such as 1-n-butyl-3-methylimidazolium tetrafluoroborate ([BMIM][BF4]) and 1-ethyl-3-methylimidazolium chloride ([EMIM][Cl]). Imidazolium-based ILs are highly effective for lead removal due to their ability to form strong complexes with metal ions and high thermal stability.

Table 8. Removal of lead ion using Imidazolium-based ILs.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Ionic Liquid</th>
<th>Metal ion</th>
<th>Removal efficiency or Percentage extraction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[BMIM][OCTSO4]</td>
<td>Lead</td>
<td>97%</td>
<td>[62]</td>
</tr>
<tr>
<td>2</td>
<td>[C4mim][N88SA]</td>
<td>Lead</td>
<td>90%</td>
<td>[58]</td>
</tr>
</tbody>
</table>

Sources: drawn by the authors on their own

Figure 7. Removal of Lead using IL and recovered IL again recycled for the removal of Lead

Sources: drawn by the authors on their own
Using a halogen-free IL known as [BMIM][OCTSO4], solvent extraction was employed in experimental investigations to remove potentially harmful Pb\(^{2+}\) pollutants from aqueous solutions. The findings revealed distinct associations between extraction efficiency and parameters such as feed content, salting-out effect, and working temperature. The extraction efficiency decreases as the Lead ion concentration in the solution increases. Furthermore, the influence of ionic strength particularly slowed down the rate of lead extraction.

Thermodynamic analysis indicated the extraction process is endothermic and spontaneous in nature, supported by the positive H° value (1.4686 kJ/mol) and negative G° value (81.47 kJ/mol). This suggests that higher temperatures might negatively affect extraction efficiency. Sodium sulfate was proven to be effective, in removing Lead from the solvent phase in the form of lead sulfate. FTIR measurements validated the successful regeneration of the IL, which was subsequently reused in the extraction process up to five times without compromising separation effectiveness. The postulated anion exchange process of Pb(II) from the aqueous phase to the hydrophilic IL was explored by a chelating agent. The IL demonstrated a successful lead removal efficiency of 97%, as evidenced by comprehensive extraction data. Moreover, the study concluded that this unique non-halogen solvent could be recommended for the tertiary treatment of industrial effluents, thereby significantly benefiting the environment.

The ligands were employed as Task-Specific Ionic Liquids (TSILs) to extract two Pb(II) ions, classified as heavy metals, from aqueous solutions. Variations in equilibration time, pH of the aqueous phase, and initial feed concentration were introduced to observe the behavior of the extraction process. Notably, the metal ion concentration emerged as a significant factor; higher concentrations of metal ions led to a potential decrease in efficiency due to a scarcity of available metal binding sites. The extraction process, believed to involve ion exchange, elucidates the lower Pb(II) ions extraction efficiency at lesser pH values due to the competition between metal ions and protons under acidic/aqueous conditions. The diminished extraction efficiency was attributed to the shorter chain lengths (butyl), which enhanced water's translucency and hindered complete separation. These findings underscore the distinctiveness and efficacy of the newly developed succinimide-based ILs, which exhibit improved optimization for Pb(II) extraction across parameters such as equilibration time, initial metal ion concentration, and pH.
5.6 REMOVAL OF LEAD USING DES

Removal of Lead using deep eutectic solvents (DESs) depends on the specific DES used and the conditions under which it is used. Nonetheless, as a rule, the procedure entails the creation of a compound between the deep eutectic solvent (DES) and lead ions, succeeded by isolating this compound from the solution. An example of a DES employed for lead removal is choline chloride-ethylene glycol (ChCl-EG), comprising choline chloride (a quaternary ammonium salt) and ethylene glycol (a polyol). When ChCl-EG was introduced to a solution containing lead ions, the choline chloride may form a complex with the lead ions via electrostatic interactions and hydrogen bonding. Subsequently, the compound can be extracted from the solution using various methods, including precipitation, extraction, or membrane separation. Following separation, the Lead can be either reclaimed or appropriately disposed of. In specific scenarios, the DES can be regenerated and employed for multiple cycles, contingent upon the specific DES and the operating conditions it encounters.

Table 9. Lead removal using DES.

<table>
<thead>
<tr>
<th>S. No</th>
<th>DES</th>
<th>Metal Ion</th>
<th>Removal efficiency</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Choline chloride with ethylene glycol DES (Ch-E) combined with (EDTA – 2Na)</td>
<td>Lead</td>
<td>95.79%</td>
<td>[63]</td>
</tr>
<tr>
<td>2</td>
<td>DES/H₃PO₄-AC</td>
<td>Lead</td>
<td>97.1mg/g</td>
<td>[64]</td>
</tr>
<tr>
<td>3</td>
<td>Choline chloride combined with lactic acid and levulinic acid [ChCl-LacA] and [ChCl-LevA]</td>
<td>Lead</td>
<td>97% and 99%, respectively</td>
<td>[65]</td>
</tr>
<tr>
<td>4</td>
<td>Choline chloride combined with Graphene oxide and Fe₃O₄ nanoparticle DES/GO-Fe₃O₄</td>
<td>Lead</td>
<td>120.5 mg/g</td>
<td>[66]</td>
</tr>
<tr>
<td>5</td>
<td>NADESs–AG</td>
<td>Lead</td>
<td>87.54%</td>
<td>[67]</td>
</tr>
<tr>
<td>6</td>
<td>DES-ME</td>
<td>Lead</td>
<td>95 – 97%</td>
<td>[68]</td>
</tr>
<tr>
<td>7</td>
<td>1-decyl-3-methylimidazolium chloride and 1-undecanol</td>
<td>Lead</td>
<td>88 – 106%</td>
<td>[69]</td>
</tr>
</tbody>
</table>

Sources: drawn by the authors on their own

K. Huang, Y. Shen, X. Wang et al. 2021 studied on EDTA-2Na combined with Choline chloride-based DES, which is mixed with Ethylene glycol to form (Ch-E). [63]
It gives rise to two complex metal ions: [Pb. Ch-E] and [Pb.EDTA-2Na]. They noted that the dilution of Ch-E by adding water along with EDTA-2Na reduces the solution's viscosity and curbs the consumption of raw materials (Choline chloride and ethylene glycol). In a foundational batch experiment, Aloysius Akaangee Pam et al. 2021 explored DES/H₃PO₄-600 2:3 under several parameters such as pH, concentration, adsorbent dose, and temperature. DES/H₃PO₄-AC exhibited elevated lead uptake and favorable recyclability [64]. The Langmuir and Freundlich models were employed to delineate the correlation between the equilibrium concentration of the adsorbent and its adsorption capacity.
for the adsorption of metal ions from the solution. They also conducted the reusability studies on DES/H$_3$PO$_4$, in which perused DES/H$_3$PO$_4$ is agitated with HNO$_3$ to detach the Lead on the surface. They experimented with three cycles and reported a slight reduction in the removal efficiency when compared with the first and third cycles.

It was reported most suitable DESs for use as washing agents were screened and chosen using the computational approach COSMO-RS. The washing agent should ideally not chemically react with the metal salt. Thus, the washing agent can be recycled and used again, in this instance, lead nitrate. They concluded that [ChCl-LacA] shows higher removal efficiency than [ChCl-LevA]. Spectral analysis shows that natural DES has a negligible impact on the soil property[65]. Conjugating pre-synthesized Fe$_3$O$_4$ nanoparticles onto GO nanosheets, a conventional deep eutectic solvent (DES) composed of choline chloride and urea was employed at different GO: Fe$_3$O$_4$ ratios [66]. Through both physical and chemical analyses, it was observed that the application of DES influenced the uniformity and size distribution of Fe$_3$O$_4$ nanoparticles within these nanohybrids, confirming the successful preparation of DES/GO- Fe$_3$O$_4$ hybrids. These DES/GO- Fe$_3$O$_4$ nanohybrids exhibit superior performance as adsorbents for heavy metals (specifically Lead (II)) compared to individual GO and Fe$_3$O$_4$ materials. However, when examining DES/GO- Fe$_3$O$_4$ nanohybrids with varying ratios, contaminant removal efficiency varied based on the nature of the contamination. According to Xi Yang et al., in 2020, Pb removal rates ranged from 17.4% to 77.54%, with NADESs (Natural Deep Eutectic Solvents) significantly enhancing removal rates. The optimal conditions found are water content of 10% and solid-liquid ratio of 1:10. Incorporating a 20% natural Arabic gum surfactant could enhance NADESs' efficacy in eliminating heavy metals from the environment. The studies on the adsorption mechanism indicated that, the Freundlich and pseudo second order models are more effective and explains how NADESs adsorbs heavy metals [67].

In the micro-extraction process, a deep eutectic solvent composed of benzoin oxime and Iron (III) chloride dissolved in phenol exhibited significant efficiency in engaging with Pb (II). Moreover, this deep eutectic mixture was pivotal in facilitating phase separation, resulting in an effective and selective preconcentration process with high recovery rates of Lead from aqueous solution. The constancy of the results and the practical applicability of the developed deep eutectic microextraction was affirmed by a relative standard deviation of 2.9. Furthermore, the accumulation/recovery analysis demonstrated a strong concurrence between the spiked and measured concentrations, with
recovery rates ranging from 92% to 106%. The created Pb (II) DES-ME showed great tolerance for various ions, such as F, PO$_4^{3-}$, Ni$^{2+}$, NO$_3^-$, Co$^{2+}$, Zn$^{2+}$, CO$_3^-$, K+/Cl, Mg$^{2+}$, Ca$^{2+}$, and Fe$^{2+}$.

The identification and extraction of Lead from municipal wastewater was reported [69]. This work was an optimization study by varying the parameters such as pH, salt addition, vortex timing, temperature, and DDTP concentration. It was converted entirely to the DDTP-to-DDTP ammonium salt, and the formation of metal complex ions was intended by changing the pH from 0.3 to 7. The absorbance of complex ions is nearly constant by ranging pH from 0.3 to 4. Followed by a reduction in absorbance value by increasing the pH.

6 CHALLENGES AND RECOMMENDATIONS

The comprehensive analysis treatment of lead ion-contaminated wastewater through various technologies, including ion exchange resins, ionic liquids, zeolites, and polymeric membranes was studied. The environmental impact of nanomaterials must be considered in developing practical methods for heavy metal removal, particularly for metals like Lead. Understanding the interaction mechanisms between host and guest materials is crucial in addressing the challenges and future prospects. Research into the long-term effectiveness of these materials is advancing effectively. It is vital to consider the removal materials' toxicity and potential effects on the environment and public health.

The encapsulation of materials will be a focal point in upcoming studies to compile comprehensive and comparative data on the different uses for different processes. Additionally, more efforts are needed to address heavy metal treatment broadly. To make them commercially viable, these treatments must adhere to green chemistry principles during synthesis and application, leading to reduced material usage, energy consumption, and time. Furthermore, there is a need to emphasize the recovery and reuse of Pb ions. It's important to distinguish the effects of Pb ions in soil, water, and air. Further research is necessary for the conversion of Pb ions into other forms.

7 CONCLUSION

Removing lead ions is achievable through diverse ion exchange resin methods, including cation and anion exchange techniques. These resins exhibit the possible elimination of heavy metals like Pb, and they can be regenerated for multiple cycles. This field holds promise for future industrial applications due to its non-toxic mechanisms.
Mitigating the hazardous Lead metal from used water is essential to prevent their release into the environment. Both researchers and governmental bodies are actively seeking solutions to treat toxic heavy metal-contaminated water for the betterment of our daily lives. In this context, natural zeolites stand out as effective agents for removal, boasting enhanced adsorption capacity, selectivity, cost-effectiveness, and reusability. Among these, the natural zeolite Clinoptilolite, with its diverse forms, is frequently employed for efficient Lead removal from various streams due to its better adsorption ability and ion exchange properties. This review provides valuable insights for researchers seeking a deeper understanding of ionic liquids' lead ion removal capabilities, applicable in laboratory and pilot scale investigations. Additionally, polymer membrane techniques offer a feasible route, encompassing various morphologies such as flat sheets, nanofibers, microspheres, and Nano sponges. These membrane techniques have established themselves as hybrid processes for successfully removing and recovering metal ions from diverse effluent streams, benefiting both academic and industrial sectors.
REFERENCES


