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Review Article

Ion Exchange Resins and their Applications in Water Treatment and Pollutants Removal from Environment: A Review

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ABSTRACT

Ion exchange resin is a porous polymer with a high molecular weight. It has a few groups that can be exchanged into ions in the solution it comes into contact with. Ion exchange resins are available in different types and are widely employed in wastewater treatment. It removes unwanted ions from waste water, because it can exchange unwanted ions with its functional group. Until now, ions exchange mainly employed for the removal of different compounds from water, including dissolved organic matter and dissolved organic carbon, nitrate, copper, N-nitrosodimethylamine, fluoride, Nickel, boron, sulfamethazine, trihalomethanes (THMs) etc. In industry, various techniques are available for condensate water treatment, including flotation, membrane, sedimentation, coagulation, precipitation, chemical adsorption, filtration, catalytic oxidation, and electrochemical techniques. But existing techniques or processes are not feasible for water treatment in a confined place due to few advantages, including less efficiency in purification, being expensive, maintenance challenges, and high energy requirements. In contrast, ion exchange resins benefit from high separation selectivity, simple handling, and reusable resin. Few resins are too much costly, but being they are reusable, it makes them sustainable and cost-effective. Significant research is being conducted worldwide to uncover the potential effects of ion exchange resins. This review discussed their use in environmental cleanup, water treatment, and operational feasibility with multiple factors.

INTRODUCTION

Ion exchange resin is a type of macro molecular compound with a functional group mesh structure comprising three parts: an insoluble polymer with a three-dimensional mesh structure, multipurpose groups attached to the skeleton, and opposite charge transferable ions with functional groups [1]. The ion exchange technique involves exchanging ions between heavy metal ions and ion exchange resin to lower heavy metal concentrations in wastewater and cleanse it. Ion exchange is usually employed to extract or concentrate undesirable ions from the water. Ion exchange may be employed as a chemical feeder or a cleanup method because it is a critical process and ensures the predictable exchange of undesirable ions [2]. Specific ion exchange has several applications in industrial operations, including extracting ionic metals, separating desired from unwanted elements, and infusing drugs into a wound or incision following the surgery. The most prominent applications of ion exchange resins in the environment include hardness removal, deionization, distillation, and heavy metal removal from wastewater. Ion exchange is generally described as the reversible exchange of ions between a liquid and a solid in which the structure of the solid does not change considerably. In addition, ion exchange is a technique for softening water by exchanging calcium and magnesium ions for sodium ions. It's also used to remove metals from industrial effluents. Like ion exchange resins, polymeric adsorbents may be regenerated and reused, effectively removing dissolved organics. Humates and fulvates resins are strong base resins. These resins frequently remove organics as scavenger resins [3]. Ion exchange resins are mostly employed in biological applications such as water treatment and the purification of antibiotics, vitamins, and blood. Ion exchange resins are divided into two types: Anion exchangers interchange negatively charged exchangeable ions, whereas cation exchangers exchange positively charged mobile ions, as shown in Figure 1. The same basic organic polymers make anion and cation resins [4].

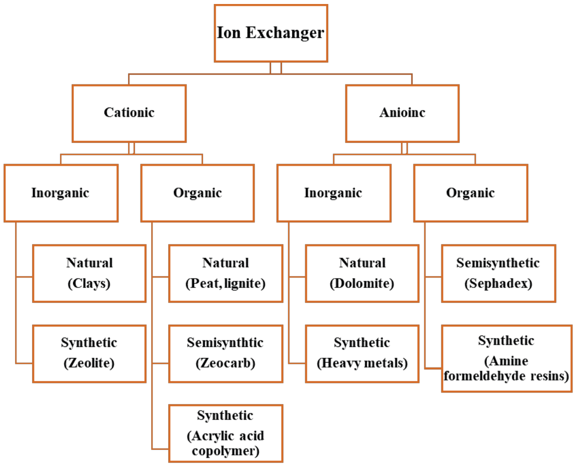

Figure 1: Ion exchange resin classification based on origin. Adapted[4].

Applications

Because of its uncomplicatedness, efficacy, recovery, cheap cost, and selectivity, the ion exchange technique[5], is the most effective and appealing approach for decreasing hardness in water through a mechanism. Domestic progress of these technologies exemplifies this procedure's ability for the treatment of water to totally or partially remove magnesium and calcium levels. Ion exchange technology, which is currently in use, is thought to be a cost-effective and ecologically friendly way for eliminating hardness (calcium and magnesium) ions removal) [6]. According to the theory of ion exchange (electrochemical process), negative and positive ions in water are exchanged with hydroxide ions (OH$^-$)and hydronium (H+). A 1-mm size porous bed of insoluble polymers and numerous ion exchange sites is required for this process to perform. When water goes over the bed, positive metallic ions (calcium, aluminum, and sodium) are swapped with H+. In contrast, negative metallic ions (chloride, nitrate, and sulfate) are replaced by OH$^-$ [7, 55].

Removal of Copper and Nickel using ion exchange resins

Anthropogenic activities and natural processes affect surface and groundwater, limiting its value for drinking, industrial, recreational, agricultural purposes[8]. Different industries, including mining, steel, and electroplating, discharged heavy metals through aqueous discharge [9]. These industrial operations discharge untreated effluents with detrimental environmental effects [10]. These harmful heavy metals should be removed from wastewater for human health and a safe environment. Most toxic heavy metal effluent, such as copper and nickel, is produced primarily by the processing, mineral mining, metal smelting, dyeing, and printing industries[11]. Currently, ion exchange, electrochemical, biological techniques, and photocatalytic technologies are used for treating copper and nickel wastewater [12]. Besides, this ion exchange technique has a wide variety of applications in the treatment of wastewater containing metal because of its benefits of strong separation selectivity, its simplicity of operation, and reusability of resin [13]. Hubicki et al. 2015 described the process of removal of copper and nickel in their experiment. Two processes are mainly involved in it, namely static ion exchange experiment and dynamic ion exchange experiment[1, 14].

Removal of DOC and hardness using cation exchange and magnetic ion exchange

Water softening is the process of removing hardness ions from water. Magnesium and calcium salts such as sulphate, nitrates, chlorides, and phosphates do not precipitate upon boiling and produce permanent water hardness. Because of its selectivity, simplicity, cheap cost, efficacy, and recovery, the ion exchange technique is the most popular and appealing approach for decreasing hardness in water [15]. Miguel et al. 2016 employed a magnetically enhanced anion exchange resin and a typical cation exchange resin technique in a single thoroughly mixed tank to remove dissolved organic carbon (DOC) and hardness at the same time [16]. Depleted cation and anion exchange resin may regenerate using table salt (NaCl) in a single, thoroughly mixed tank. Sodium chloride regeneration solution 20 % (m/v), combined ion-exchange groundwater treatment can even remove 97 % of total hardness and 76 % dissolved organic carbon (DOC).

Using a multi-cycle ion-exchange nitrate selective resin to treat Nitrate-contaminated water

Nitrate pollution of surface and groundwater is becoming a worldwide concern [17, 18]. A high amount of nitrate in drinkable water can induce thyroid gland enlargement and might be a human carcinogen[19, 20]. Furthermore, nitrate can be converted to nitrite, which then combines with the ferrous ions of hemoglobin in the blood to generate methemoglobin, which is lethal to newborns [21]. Because groundwater is frequently utilized for agricultural and industrial purposes, it is essential to remove nitrates from untreated water [22]. Several conventional nitrate treatment methods have recently been proposed, including membrane separation, biological denitrification, chemical reduction, sorption, and ion exchange [19, 23, 24]. Because of its simplicity and cheap cost, ion exchange is an effective method for eliminating inorganic anions like nitrate from aqueous solutions [25]. On several strong basic anion exchange resins that are commercially available, nitrate can be significantly adsorbed [26, 27]. Meng *et al*., 2014 described, tritylamine strong base anion exchange resin bio regeneration approach, as well as multi-cycle loading and bioregeneration cycles. Following each round of exhaustion, the resins' biological regeneration will occur for 48 hours using a salt-resistant, nitrate-perchlorate-lowering culture [28]. Direct contact between the resin and the culture should be prevented by enclosing the resins with a membrane. Now this culture can renew the resin and allow it to be reused. The nitrate concentration in a samples can reach its maximum level within approximately half an hour after addition of resins. This is because desorption rate of nitrate from resin is 0.099±0.003 hr^{-1}. Within these 21 hours, microorganisms in the aqueous phase will begin to deteriorate the nitrate, and the nitrate concentration will be non-detectable after 10 hours. Comparing multiple studies reveals that, till now, this method has had high efficacy in very low budget [29].

Time-lapse Ion Exchange Resin Sachets (TIERS) for detecting illegal pollutant disposal in mixed Agricultural and Industrial areas.

The farmlands have been threatened by illegal wastewater discharges containing high concentrations of metals from surrounding factories, resulting in severe loss in food safety, agricultural production, and human health [30]. Water quality data is generally obtained on a regular basis by field sampling and subsequent physicochemical studies of the samples in a laboratory-based setting. Multiple different approaches for water treatment are also being employed in industries including classical analysis tools (i.e., inductively coupled plasma mass spectrometry), traditional analysis techniques, inductively coupled plasma atomic emission spectrometry, atomic fluorescence spectrometry, inductively coupled plasma optical emission spectrometry, and atomic absorption spectrometry, but these all are costly and time-consuming. Nowadays, fast-screening technology uses portable X-ray fluorescence (XRF) spectroscopy and ion exchange resins to determine the source of pollutants in agricultural and industrial settings [31]. The time-lapse ion exchange resin sachet (TIERS) composition is a nonwoven bag packed with about 20g of resins, as shown in Figure 2-b deployed in irrigation canals to continually absorb trace elements and metal in water. The nonwoven fabric is the wrapping material because it has strong cation exchange permeability without any materials that can alter experiment results; secondly, a plastic shell is employed to protect the resin sachet from being pricked by sharp objects in rapid water flow. During the monitoring phase, the resin sachets should be deployed as time-lapse ion exchange sachets (TIERS) for seven days to collect trace elements and metal in the streams at the selected sites [32, 33]. It is important to note that the number of metals and trace elements identified by the XRF correlates to the quantity of metals and trace elements found in the resin. It cannot provide the mean water concentration during the observation period or accurately represent the quantity of metals and other elements in water at any specific point in time. Time-Lapse Ion Exchange Resin Sachet as shown in Figure 2-a, they may be brought to the laboratory for XRF detection after observation [32, 33]. The plastic shell might be reused until it can no longer be utilized for the subsequent field sampling. Leftover resins and unrecycled plastic shells as shown in Figure 2-c, will be discarded as recycled plastic rubbish.

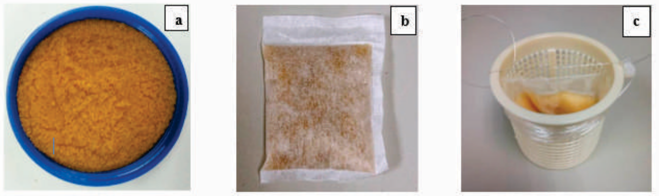

Figure 2: Different forms of resins including (a) Resins, (b) Resin Sachet and (c) Resin Sachet in a plastic

Use of ion exchange resins to remove N-nitrosodimethylamine and Trihalomethanes precursors in each treatment.

In developing countries, contamination of effluent discharge and sewage lines affects the drinking water supply lines, and in this way water sources contaminated by wastewater effluent are increasingly being used in drinking water systems [34]. During the oxidation /disinfection of these fluids during the treatment of water, several disinfection byproducts, comprising the possible human carcinogen (NDMA) and the regulated (THMs), may be generated [35]. Beita-sandi and Karanfil 2017 describe ion exchange resins' ability to reduce trihalomethanes (THMs) and N-nitrosodimethylamine (NDMA) precursors in each treatment. A cation exchange resin (Plus) may target nitrosodimethylamine precursors, whereas an anion exchange resin (MIEX) was previously used to manage THM precursors [36]. Beita-sandi and Karanfil, 2017 in their experiment, treated wastewater effluent and surface water samples. Both resins were used to extract THMs (39–65 %) and NDMA (43–85 %) precursors simultaneously

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[36]. With low initiating NDMA FP (14 ng/L), no NDMA precursor elimination was seen in surface water. With Plus and MIEX resins applied alone, the elimination of NDMA FP and THMs FP was (49-90%) and (41-69%), respectively. These findings indicate no interaction between the resins, implying that regulating NDMA and THM precursors simultaneously is possible. A 50 % reduction in the elimination of NDMA precursors will be there when the calcium content increases[36].

Use of ion exchange resin for Removal of Ammonium from a synthetic water solution

One of the most hazardous elements is ammonium, and it can enter the aquatic environment directly through municipal effluent discharges[37] and animal excretion of nitrogenous wastes, as well as indirectly through nitrogen fixation, air deposition, and runoff from agricultural fields. In addition to that, industrial effluents (Table. 1), animal manure, and fertilizers are familiar sources of ammonium in water. As per previous studies, the quantity of ammonium in industrial effluents varies substantially depending on the type and size of the industry that realease it. Table 1 shows different industries wastewater containing ammonium concentration. Ammonium removal is primarily accomplished through biological treatment (nitrification) or air stripping[38]. On the other hand, these treatments are much more effective but have technical limitations due to the pH of the wastewater (pH adjustment is necessary to achieve an alkaline pH) and the susceptible microorganisms used in biological treatment. Nitrate formation will also occur that must be further removed [39].

Table 1: Concentration of ammonium in wastewater from different industries

Industrial wastewater	Concentration of ammonium	Reference
Wastewater from dairy farms	5.9-36.7	Tocchi et al., (2012)
Textile mill waste	54	Tchobanoglous et al.,(2003)
Wastewater from coal gasification of wastewater	134	Wang et al., (2014)
Opto-electronic wastewater	567	Daverey et al.., (2012)
Water from waste dumps	820	Farkas et al., (2005)

So, ion exchange can respond quickly to shock loads while providing strong chemical resistance and an effective working temperature range. Ammonium removal in ion exchange methods has been extensively studied due to its strong pH sensitivity [40]. It was reported that pH values for the removal of ammonium are 6-7 and below are best; in contrast, treatment efficiency rapidly decreases at pH 8-10 and above, so in this process, pH contribution matters a lot [41]. The process can be managed and ramped up if the mechanism of ammonium removal is well known. As sorbent, a commercially available cation exchange resin (C150H) is used nowadays. The thermodynamics can be estimated by using the Langmuir model. The shrinking core model can be employed to match the kinetic data linked to the ion exchange process in the analysis of the sorption process.

Use of strongly basic anion exchange resin for Removal of Nitrate

Nitrate pollution in groundwater and surface water is becoming a critical concern worldwide [42]. Nitrate in routine water use can cause thyroid gland enlargement and is a possible human carcinogen[20]. Furthermore, nitrate can be converted to nitrite and combined with the Fe^{+2} of hemoglobin in the blood to generate methemoglobin, which is deadly to newborns. Although nitrate concentration level in surface waters is typically below 5 mg/L, nitrate pollution of groundwater is a severe problem in developing countries. As a result, removing nitrates from wastewater is essential. Membrane separation, Biological denitrification, ion exchange, chemical reduction, and sorption methods for the removal of nitrate have all been used in many countries[43]. Because of its simplicity and low cost, ion exchange effectively eliminates inorganic anions like nitrate from aqueous solutions[44]. Nitrate can be effectively absorbed by several commercially available strong basic anion exchange resins as shown in Figure 3. However, groundwater typically contains large amounts of competing anions such as bicarbonate ions, sulphate and chloride, and nitrate [45]. Because sulphate is a divalent ion that conventional highly basic anion exchangers preferentially absorb due to electrostatic interaction, the resin sorption capacity for nitrate, a monovalent ion, is dramatically reduced [46]. Nitrate-specialty resins, including Imac HP555, Purolite A 520E (A520E), Amberlite IRA 996, and Indion NSSR have since been developed as strongly basic anion exchangers [47]. These nitrate-specialized resins are functionalized by reacting with triethylamine to generate quaternary ammonium exchange sites instead of the shorter chain trimethylamine used in ordinary resins.

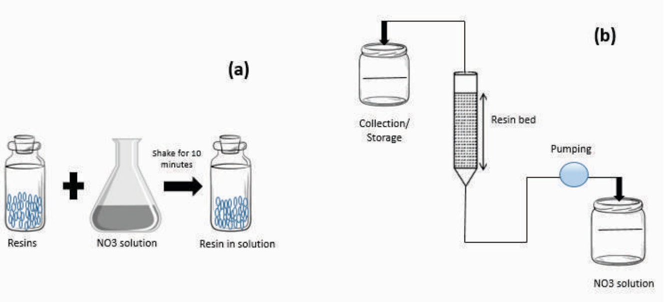

Figure 3: Removal of Nitrate from wastewater using ion exchange resins(a)sample prepration(b)process of separation

This way, nitrate selectivity improves, but its sorption kinetics and capacity suffer. To address this limitation, in a recent study, macroporous chloromethylatedstyrene–divinylbenzene copolymer allowed to react with N-dimethyloctylamine. As a consequence of converting one of the methyl groups of trimethylamine to an octyl group as the amination reagent, the new strongly basic anion exchange resin SE-1 is produced. Generally, the selectivity is improved by the long-carbon side chain, while the short chain improves the resin's kinetics and capacity for nitrate. Then, further physical properties of this resin were studied, and nitrate sorption ability was investigated. Broadly used 520E resin as a comparator resin to evaluate its efficacy because it is currently used for groundwater treatment [27].

Removal of Perfluorooctanoate (PFOA) using magnetic ion exchange resin

PFCs (Perfluorinated compounds) have been developed and utilized worldwide for their unique properties [48]. Perfluorinated carboxylates were a significant class of PFCs widely employed in various sectors, including food packaging, fabric protection, and fluoropolymer production[49]. Perfluorooctanoate(PFOA)was classified as a reduction strategy by the United States Environmental Protection Agency in 2006 because of its bioaccumulation, persistence, extensive dispersion, and toxicity in aquatic settings [50]. Perfluorooctanoate was also used in the semiconductor sector and as an emulsifier in the manufacturing of fluoropolymers [51]. The level of PFOA measured by the photolithography technique was 1000 mg L^{-1}. Furthermore, PFOA concentrations in surface water around industrial zones have reached 19.2 μg L^{-1} [52]. As a result of the above conditions, creating innovative low-cost methods with strong sorption ability to remove PFOA from contaminated water has been a challenge. A recent study discovered an excellent adsorbent for the Removal of (PFOA) in the aqueous phase using magnetic ion exchange (MIEX) resin [53]. A batch experiment was used to assess the PFOA adsorption performance. Some of the critical factors that affect the absorption of Perfluorooctanoate, including natural organic matter, initial concentration, bed volume, temperature, initial solution pH, stirring intensity, adsorption period, coexisting anions, adsorbent dose, and ion strength, were all investigated. In addition, the response surface method was employed to determine the critical elements influencing the effectiveness of Perfluorooctanoate removal. The Langmuir and pseudo-second-order models may describe the sorption equilibrium and kinetic data well.

CONCLUSIONS

This review emphasizes that ion exchange resins have benefits such as excellent separation selectivity, implicity of handling, and reusability. Although there are various methods for treating water, they might have disadvantages such as ineffective filtration, high costs, difficult maintenance issues, and high energy needs. Ion exchange resins, however, provide an affordable and long-lasting solution. The review also discusses particular uses for ion exchange resins. For instance, their selectivity and ease of use make them effective against copper and nickel removal from industrial effluents. In the case of water treatment or softening, ion exchange resins have the ability to remove ions that contribute to hardness, such as calcium and magnesium. It was also concluded that, combining cation exchange and magnetic ion exchange resins can remove hardness and dissolved organic carbon (DOC). This study additionally addresses the application of ion exchange resins for pollution monitoring and detection in industrial and agricultural regions. Overall, the review's emphasis on ion exchange resins' numerous uses and benefits in environmental contexts highlights both their potential and practical viability in different sectors.

Authors Contribution

Conceptualization: AA
Formal analysis: AA, MA, ZUA
Writing, review and editing: AA, MSM, MZA, MU, ZUA

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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