



Exploration and Review on Ion-Exchange Resins

Dr. Sumita Dabas

Assistant Professor

Applied Science

Maharaja Surajmal Institute of Technology

Abstract: Ion-exchange resins and polymers facilitate in ion exchange process. Organic polymer substrates are used to create insoluble matrices (or support structures), which typically take the shape of tiny (0.25-1.43 mm radius) white or yellow microbeads. Ion exchange refers to the trapping of certain ions and the release of other ions via porous beads. Ion-exchange resin comes in a wide variety of kinds. The commercial resin market is dominated by polystyrene sulfonate. Ion-exchange resins have several applications in the fields of separation, purification, and disinfection. Water softening and water purification are two of the most prevalent kinds of this. When using natural or synthetic zeolites for such procedures proved to be impractical, ion-exchange resins were often offered as an alternative. Additionally, ion-exchange resins perform well as biodiesel filters. This paper explores the Ion-exchange resins and polymers, Resin Structure, how Particle Size Distribution of Ion Exchange Resins.

Key Word: Ion-exchange, resins and polymers, Organic Synthesis

I. Introduction

Cross-linked polystyrene is the main component of most commercially available ion-exchange resins. After polymerization, the ion-exchanging sites are included. When styrene and a little amount of divinylbenzene are copolymerized to create polystyrene, crosslinking is added. Crosslinking reduces the resin's ion-exchange capacity and increases the time required to complete ion-exchange procedures, but it makes the resin more durable overall. Smaller particles have a bigger surface area, but they result in a higher head loss during column processing, which in turn affects the resin's other properties. Ion-exchange resins may be created both as beads and as membranes. Electrodialysis makes use of ion-exchange membranes manufactured from strongly cross-linked ion-exchange resins that permit the passage of ions but not water. The functional groups of the four most common ion-exchange resins are as follows:

- Strongly acidic, typically featuring sulfonic acid groups, e.g. sodium polystyrene sulfonate or polyAMPS,
- Strongly basic, typically featuring quaternary amino groups, for example, trimethylammonium groups, e.g., polylactic,
- Weakly acidic, typically featuring carboxylic acid groups,
- Weakly basic, typically featuring primary, secondary, and/or tertiary amino groups, e.g. polyethylene amine.

Chelating resins are another type of ion-exchange resin that is well-known. The two most common types of resins for the ion-exchange process are anion resins and cation resins. As their names imply, anion resins are drawn to electronegativity, while cation resins are drawn to cationic charges.

II. Literature Review

Huo & Lu (2022), To catalyse the ring-opening reaction of ethylene oxide with acrylic acid, chromium (III) supported by an ion exchange resin is used. Kinetic analysis reveals that the catalytic activity is mostly due to the presence of heterogeneous chromium species, rather than chromium leached from the support. Both the catalyst's activity and stability are significantly impacted by the resin's pore structure and functional groups. The activity and stability of chelate resin IRC748-supported Cr(III) are enhanced by a novel activation process, and a mechanism for this activation is provided. When looking at regeneration performance and productivity, the heterogeneous catalysis system with

IRC748@Cr (III) clearly outperforms the standard homogeneous system. Last but not least, a comprehensive chromium recycling method was created to help with the eco-friendly and effective synthesis of HEA.

Zhou et al. (2022), Epoxy (EP) thermosets have many potential uses because to their great mechanical strength and heat resistance in fields including energy, aerospace, electronics, and construction, but this also makes them more difficult to recover from in a controlled and efficient manner. Here, we provide a method for the rapid and efficient production of homogenous oligomers at 85 °C in about 4 hours by inducing the oxidative destruction of EP thermoset using acidic ion exchange resin. Free H⁺ from the ion exchange resin may activate the C-N bond, while the acid groups in the resin determine how deeply the C-N bond is oxidised. Complete degradation resulted in a constant molecular weight and polydispersity index over a wide range of degradation conditions. It was also a promising option for wastewater treatment in the fields of dye removal (CV adsorption capacity of 270 mg/g) and oil-water separation (water flux of 57,325 L m⁻² h⁻¹) due to its ease of preparation through water-induced phase separation and its high separation efficiency (99.9%). This study gets beyond the problems with conventional EP thermoset oxidative degradation systems, which include uncontrollable degradation and the resulting complexity of the products. Moreover, by making use of both waste EP and waste acidic ion exchange resins, it offers a fresh perspective on regulated recovery and value-added reutilization.

Zeferino et al. (2022), Using heterogeneous catalysis with the ion exchange resin Lewatit GF 101, this study seeks to produce neryl acetate from the nerol esterification process with acetic anhydride. Gas chromatography was used to track the reaction, while mass spectrometry and nuclear magnetic resonance spectroscopy verified the neryl acetate's molecular make-up. From an experimental design analysis, we determined how many factors affected neryl acetate production. At 40 degrees Celsius, 7% by weight of catalyst, 1:4 nerol to acetic anhydride molar ratio, 250 revolutions per minute (rpm), and 3 mmol of nerol, the reaction showed the highest combined values for nerol conversion (98.11%) and neryl acetate selectivity (86.10%) after 30 minutes. In only 40 minutes, we were able to convert all of the nerol with a selectivity of 82.34 percent. Since an excessive amount of acetic anhydride was used, the pace of the reaction was determined solely by the nerol degradation. Additionally, the value for the primary reaction kinetic constant reported by the pseudo-homogeneous model was 6 times larger than the value discovered by the parallel reaction. Three cycles of catalyst reuse were studied, and the results showed a high conversion (96.68%) and selectivity (83.78%) with little loss of catalytic activity.

Antonio & Poço (2022), Using a continuous packed bed tubular reactor (PBR) and catalysts based on niobium and zirconium compounds, as well as modified ion exchange resins (resins CT275 and SGC650H superacidified), and using DMSO and DMSO aqueous solutions as solvents, the production of HMF from the fructose reaction was investigated. The catalysts based on zirconium compounds and the ones created using niobium compounds performed the worst, while the superacidified ion exchange resins performed the best. If the residence duration in the SGC650H is kept constant, sulfonating the acidic cationic will increase the conversion and production of HMF by at least 10%. The DMSO and fructose feeding method yielded the most promising outcomes. Mesoporous structures seem to hinder the effectiveness of supported zirconium materials as catalysts. It was shown that the conversion of fructose to HMF was significantly reduced when water was present in the solvent reactive promote. This was true for all catalysts tested.

Yaghmaeiyan et al. (2022), Montmorillonite is the name given to microscopic crystals of the soft phyllosilicate group of minerals that precipitated out of a water-based solution. Aluminosilicates in the rock are concentrated and altered by natural weathering in cave environments. When combined with water, montmorillonite expands to several times its original volume. The expansion rate is determined by the exchangeable cation species present in the sample. Because sodium is the most abundant exchangeable cation, the swelling is magnified many times over. Consequently, Na-MMT is the primary component of nonexplosive agents used to fracture rock in quarries dedicated to the extraction of natural stone. Montmorillonite's useful properties have led to its incorporation in a wide range of products, including those used in the oil drilling industry, as a soil additive, as foundry sand, as a desiccant to remove moisture from air and gases, as a catalyst, and in a number of pharmaceutical and medicinal products. This article provides a comprehensive overview of the different synthetic approaches for preparing MMT-based catalysts for organic syntheses and evaluating their catalytic activities.

Zeferino et al. (2021), The goal of this research is to use the ion exchange resin Lewatit GF-101 for a heterogeneous catalysis of the geraniol esterification process with acetic anhydride, leading to the synthesis of geranyl acetate. Gas chromatography was used to track the reaction, while mass spectrometry and nuclear magnetic resonance spectroscopy proved the chemical make-up of the resulting geranyl acetate. Sulfonic group responsible for catalysis was established by Fourier transform infrared spectroscopy. A molar ratio of 1:4 between geraniol and acetic anhydride and a temperature of 40 °C were found to be the ideal experimental conditions for geranyl acetate synthesis using a process called experimental design analysis. Maximum selectivity (96.48 percent) and geraniol conversion (98.28 percent) were both achieved in this reaction. In 70 minutes, we were able to convert 100% of the geraniol with a selectivity of 95.94%. The pseudo-homogeneous model yielded a value for the secondary reaction's kinetic constant that was 31 times less than the value obtained for the primary reaction's kinetic constant. In addition, because there was already an abundance

of acetic anhydride present, the pace of the reaction was determined solely by the degradation of the geraniol. It was shown that after three cycles of reuse, the catalyst lost just a little amount of its catalytic activity, keeping its high conversion (94.43 percent) and selectivity (97.19 percent) throughout.

Ramírez et al. (2021), It has been investigated in a discontinuous reactor at 80120 °C and 2.0 MPa over 8 sulfonic polystyrene-DVB ion exchange resins as catalysts (catalyst loading 0.85-3.4%), how fructose is converted into butyl levulinate in aqueous 1-butanol (initial molar ratio 1-butanol/fructose 79, and butanol/water 1. The reaction itself occurs mostly in the swelling gel-phase of the resin that has been exposed to the reaction media. By analysing ISEC data, we can define the voids that form in the gel phase as a result of swelling of resins in water in terms of zones of varying polymer density. Ester formation is correlated with the shape of swelling resins. However, butyl levulinate is most abundant in low-density, swollen resins. Due to its ability to expand into more spacious regions of the gel phase, Dowex 50Wx2 proved to be the most useful. Thus, the processes involved in the transport of protons are more comfortably accommodated.

Badia et al. (2021), Following an experimentally designed study, the optimum conditions for synthesizing sec-butyl levulinate (SBL) through the proposed reaction pathway were determined for the liquid-phase esterification of levulinic acid (LA) with 1-butene (1B) over ion-exchange resins. The experiments were conducted at temperatures ranging from 313 to 383 K, with LA to 1B molar ratios ($R^{\circ}LA/1B$) in the range of 0.4 to 3. At 373 K and $R^{\circ}LA/1B = 0.5$, ideal experimental conditions, the 1B and LA yields to SBL are 48.1% and 76.8%, respectively. Using the empirical equations obtained between the conditions and the yields, we performed a response surface methodology analysis followed by multiobjective optimization to determine the conditions that would result in the highest yields for both reactants to SBL simultaneously. These conditions include a high initial concentration of 1B and a temperature range of 360-370 K. Results from preliminary tests suggest that SBL formation is promoted by a very dense polymer network. When compared to the other catalysts we evaluated, AmberlystTM15 stood out as the most promising since it achieved the maximum conversion with little side reaction extension. To determine whether or not the proposed chemical route was sustainable and to make a comparison to previously reported studies for the SBL synthesis, a green metrics analysis was carried out. When compared to the other possible outcomes, the chemical approach being offered is the most environmentally friendly choice.

Hu et al. (2021), The prodrug isosteviol was previously obtained from steviol using the Wagner-Meerwein rearrangement, a process that resulted in a low yield and a lengthy reaction time. Isomerization coupling reaction is presented herein as a method for producing isosteviol from the natural sweetener stevioside. The 92.98% pure isosteviol was obtained directly from a packed bed reactor with a stevioside conversion of 97.23% using only in-situ water-washing. Acidic ion-exchange resins provided greater product specificity towards isosteviol compared to the inorganic acid, organic acid, and acidic ionic liquids that were tested. The product also showed time- and dose-dependent inhibition of proliferation of the tested human cancer cells by inducing cell phase arrest, similar to but more potent than that seen with 5-Fluorouracil. Cell cycle arrest occurred in G1 in the SGC-7901, HCT-8, and HCT-116 cells, S in the HepG2, Huh-7, and HepG3B cells, and G2 in the MGC-803 cells.

Peláez et al. (2021), The acetalization of methanol to dimethoxymethane utilising the acidic ion exchange resin Amberlyst 15 as a catalyst led to a comprehensive evaluation of the utilisation of trioxane and depolymerized paraformaldehyde as formaldehyde precursors. All of the tests were conducted in isothermal batch and continuous fixed-bed reactors. Reaction rate and product selectivity were studied in relation to three primary operating parameters: temperature (80-120 °C); space time (2.7-6.2 kg h m³); and feed concentration (12-22 wt% of trioxane/formaldehyde, 2.5 wt.% of water on methanol). With over 90% selectivity, dimethoxymethane is produced as the primary reaction product when trioxane is used as the reactant. Over the course of more than 30 hours of continuous experimentation, the catalyst proved consistently reliable. However, the presence of water had a temporary inhibiting influence on the reaction rate, which may be explained by a competitive adsorption model. The experimental data were used to verify a hypothesised mechanistic kinetic model. Decomposition of trioxane to formaldehyde was determined to be the rate-limiting step of the reaction mechanism (activation energy 73.1 kJ mol⁻¹). This was shown in follow-up tests in which depolymerized formaldehyde was used in lieu of trioxane. The pace at which reactions occurred rose dramatically under these conditions. * 2021 The Authors. Society for Industrial Chemistry and John Wiley & Sons, Ltd., Biofuels, Bioproducts, and Biorefining.

Biswas et al. (2020), One of the most crucial parts of organic synthesis is heterogeneous catalysis. Polymer-supported catalysts have been used effectively in a number of catalytic organic reactions, thanks to the many advances made in the field over the last several decades. Among the many examples of heterogeneous polymer-supported catalysts, ion-exchange resins and polypeptides stand out as particularly useful for their accessibility, stability, recoverability, and reusability. Highly insoluble materials like cross-linked ion-exchange resins and polypeptides are preferable because they may be easily isolated from the reaction mixture and reused. The present review article summarises the various ion exchange resins as polymer-supported catalysts, including amberlite resin, polystyrene resin, polyionic gel-based systems, ion-exchange resins and prolineimmobilized species, PEG-bound poly (amino acid), amino acid anchored with

Merrifield resin, amphiphilic block polypeptides, etc. Their stability, mechanistic overview, appropriateness, etc. have all been discussed in detail, along with their production, characterizations, and catalytic applications in various organic transformations.

Vil et al. (2020), Despite the possibility of peroxide decomposition under heterogeneous conditions, bridged 1,2,4,5-tetraoxanes were successfully prepared using readily available acidic ion exchange resin with high yields. In vitro testing showed that the bridging tetraoxanes were very toxic to HeLa cancer cells, with cytotoxicities that rivalled or exceeded those of cisplatin, artesunate, and dihydroartemisinin.

Salvador et al. (2020), Biomass turpentine's hydration and isomerization with Purolite CT175 have been investigated. Hydrogenation activity was 97%, and selectivity for the production of terpenic alcohols was 57% when using heating and stirring with the ion exchange resin catalyst. In a high intensity ultrasound (HIU) condition, turpentine was isomerized using the Purolite CT175 catalyst, resulting in a 90% conversion and 30% selectivity for camphene after 30 minutes. We tested the reusability of the ion exchange resin in two different reactions and found that its performance remained stable after four cycles of use.

Cho et al. (2020), One of the most eco-friendly ways of turning CO₂ into useful chemicals is by the synthesis of cyclic carbonate from CO₂ and alkylene oxide. Synthesis of a [ZnX₂Cl₂]₂immobilized ion exchange resin (ZnX₂/IER) utilising four different zinc precursors, ZnX₂ (X = Cl, Br, OAc, and NO₃), and a chloride-anion exchange resin was performed (IER). Propylene carbonate was produced by a cycloaddition process involving carbon dioxide and propylene oxide (PO) using the created ZnX₂/IER (PC). ZnBr₂/IER was the most active of the produced catalysts, with PC yields of 76.7% after 2 hours at 80 °C and 99.1% after 8 hours. Five uses did not diminish the catalyst's effectiveness. The morphology and zinc content of both new and recycled ZnBr₂/IER were studied by FT-IR, SEM-EDS, and ICP-OES, and no significant differences were found. The synthesised catalyst was shown to be suitable for use in commercial PC synthesis procedures by undergoing a 96-h continuous reaction in a fixed-bed setup.

Hu et al. (2020), Using a unique technique including ion exchange and in situ solvothermal procedures, the metal-organic framework (MOF)-supported macroscale resin catalysts IRA900(xOH)-MIL-101(Al)-NH₂ (x denotes the concentration of NaOH) were effectively produced. Organic processes benefit greatly from the as-prepared catalysts' hierarchical pore architecture, which facilitates mass transfer and interactions with catalytic active centres. Therefore, the eco-friendly IRA900(0.2OH)-MIL-101(Al)-NH₂ catalyst system achieves around 99% yield after 5 hours of operation at 110 degrees Celsius, demonstrating exceptional superior activity and stability in the one-pot deacetalization-Knoevenagel condensation process. The as-prepared catalysts may be recycled without any further processing beyond natural sedimentation because to their millimetre-sized resin carrier and strong spherical form. This study combines the benefits of ion-exchange resins with functionalized MOF materials to propose an efficient technique for constructing non-toxic acid-base catalysts.

III. Anion resins

Strongly basic anion resins are also possible. In contrast to weakly basic anion resins, which are neutralised at higher pH levels, strongly basic anion resins retain their negative charge over a broad pH range. Due to deprotonation at high pH, weakly basic resins lose their charge. Still, they provide superior mechanical and chemical stability. Since they have a high ion exchange rate and are not strongly basic, weakly base anion resins are ideal for these organic salts.

Anion resins are regenerated by being subjected to a very basic solution, such sodium hydroxide in water. By flushing out the trapped negative ions with the regenerant chemical, the resin's exchange capacity is renewed throughout the regeneration process.

3.1 Types of Ion Exchange Resins

In the case of ion exchange resins, the charged functional groups are typically salts of sulfonic or carboxylic acids, or quaternary ammonium salts. Ion exchange materials can be broken down into two broad categories, based on their respective charges: cation exchange resin and anion exchange resin.

3.2 Cation Exchange Resins

Cation exchange resins (CERs) have functional groups with negative charges, which attract cations (positively charged ions) in solution. It can be used to purify water by filtering out the positive ions that have accumulated in it.

There are two additional categories for Cation Exchange Resins:

- **Strong acid cation (SAC) resins:** They are made of polystyrene with a sulfonate functional group (SO_3^-) that is either charged with hydrogen ions (H^+) or sodium ions (Na^+).
- **Weak acid cation (WAC) resins:** They are composed of acrylic polymer with carboxylic acid groups as functional groups and have a high affinity for hydrogen ions. These are commonly used to remove alkalinity-associated cations.

3.3 Anion Exchange Resins

Positively charged functional groups found in anion exchange resins are attracted to the dissolved anions. Among the functional groups included in their matrices is amine. These are also used to clean water by filtering out the impurities that have a negative charge. Anion resins may be broken down into two groups:

Strong base anion (SBA) resins: The polystyrene matrix in these resins has been chloromethylated and then aminated with dimethylamine. Depending on the nature of the ions being exchanged, chloride ions or hydroxide ions will be produced.

Weak base anion (WBA) resins: The polystyrene matrix also serves as the basis for their construction. The solution's pH controls how ionised they become. They can also remove ions from concentrated mineral acids by acting as acid absorbers due to their lack of exchangeable ions.

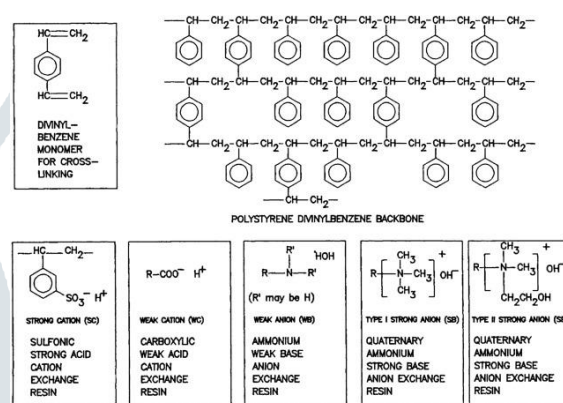


Figure: A schematic diagram of polystyrene structure and different types of Ion Exchange Resins.

In addition to cation and anion exchange resins, chelating resins are also available. In virtually all cases, they interact with cations and are made composed of polystyrene bearing a variety of functional groups such as amino phosphonic, triethylammonium, and thiol. These resins are used for the selective removal of metals and other substances from mixes.

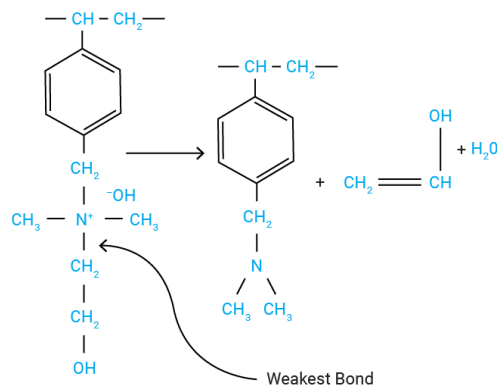
Desalination of seawater, softening of hard water, recovery of metal ions, and product and water purification are only few of the many uses for ion exchange membranes (IEMs) [1, 2]. Although anion exchange membranes are becoming important for applications such as the retention of multivalent ions and the recovery of precious metals from the effluent of the metal plating industry, they have received less attention in the literature than their cation exchange counterparts. Cross-linked polystyrene anion exchangers are typically made by chloromethylating a styrene/divinylbenzene copolymer with an alkylating reagent like chloromethyl methyl ether or bis chloromethyl ether. The polymer's ion-exchange properties are added thereafter by a treatment with amines. Both alkylating chemicals, however, have been linked to considerable health risks, and their usage was severely limited in 1967 when it was discovered that they posed a significant cancer risk. In addition, the chloromethylation process causes further cross-linking that impairs the performance of the resins [7]. It is believed that the ion-exchange resin's capacity is impacted and its fragility is increased due to the secondary cross-linking that happens through methylene group bridging.

Over the last two decades, polymer chemistry has made significant strides. Since the byproduct of many synthetic organic chemical reactions—polymers—can be difficult to extract from the intended result, this branch of chemistry has gained notoriety. However, if a polymeric reagent is employed instead during the organic synthesis, the by-product will stay bound to the insoluble polymer and may be easily filtered out. It is common practise to use non-recyclable catalysts, including metal chlorides or mineral acids, in electrophilic aromatic replacements. When cation exchange resins are used instead, product recovery is streamlined and the amount of waste produced is cut down significantly. The prospective employment of low-cost, easy-to-obtain catalysts is of particular interest to us. Because of their improved reactivity, increased reaction rate, increased selectivity, and minimal post-reaction work-up requirements, organic reactions on solid phase have attracted a lot of attention in organic synthesis in recent years. Here, we detail the use of cation exchange resins in the Pechmann condensation for the synthesis of coumarin derivatives.

IV. Resin Structure

Most ion exchange resins used in the processing of corn sweetener are copolymers of styrene and divinylbenzene that have been activated with sulfuric acid or one of a number of amine compounds to create cation resins and anion resins, respectively.

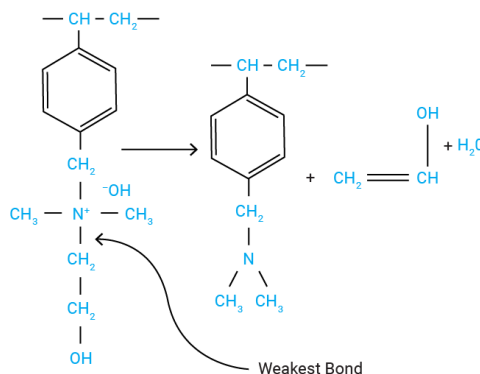
Styrene-Divinylbenzene Cation and Anion Resin Structure



Since the insoluble resin matrix and bonded functional groups can exchange ions or adsorb molecules from a solution, they can alter the ionic or molecular concentrations in the syrup. Due to their characteristics, ion exchange resins have become indispensable in the HFCS refining process.

When the resin's temperature is too high during service or regeneration, degradation reactions that lead to the loss of functional groups speed up significantly. While the operating temperature of cation resins is capped by product degradation rather than resin degradation, strong base anion resins begin to degrade significantly before syrup. It has been found that the Type II strong base anion resin in the polishing mixed beds is the least thermally stable of the four resin types used. In a Type II strong base anion resin, the bond between the alcohol group and the nitrogen atom is the most thermally unstable.

4.1 Hoffman Degradation of Strong-Base Resins (Type II Strong Base Anion)



4.2 Particle Size Distribution of Ion Exchange Resins

By passing a representative sample through a series of standard sieves, the particle-size distribution of ion exchange resins may be calculated. The findings are typically reported as a percentage of the sample size that was retained by or passed through the sieves' respective pore sizes. Resins are most informative when they are completely swelled. The results of wet-screen studies are more reliable and widely used than those of dry-screen analyses. Since ion exchange resins may swell significantly, it is important to note whether the results were acquired wet or dry in any report of particle-size distribution from screen analysis. The effective size and uniformity coefficient are two measures of particle size and size distribution that may be derived from screen analysis. The effective size of a filter is measured in millimetres and is the aperture that allows just 10% of a resin sample through. To calculate the uniformity coefficient, divide the sieve aperture (in millimetres) that retains 40% of the sample by the opening that retains 90%.

References

1. Huo, F., & Lu, Y. (2022). Green and high-efficiency synthesis of 2-hydroxyethyl acrylate with ion exchange resins as Cr (III) support and collector. *Chemical Engineering Journal*, 137130.
2. Zhou, X., An, W., Xia, X., Long, Y., Liu, X., Xu, S., & Wang, Y. Z. (2022). Recovery and Reutilization of Epoxy Thermoset via Acidic Ion Exchange Resin-Induced Controllable Oxidative Degradation and Subsequent Micro spheroidization. *ACS Sustainable Chemistry & Engineering*, 10(17), 5582-5589.
3. Zeferino, R. C. F., Piaia, V. A. A., Orso, V. T., Pinheiro, V. M., Zanetti, M., Colpani, G. L., ... & Riella, H. G. (2022). Neryl acetate synthesis from nerol esterification with acetic anhydride by heterogeneous catalysis using ion exchange resin. *Journal of Industrial and Engineering Chemistry*, 105, 121-131.

4. Antonio, I. L., & Poço, J. G. R.(2022). Comparison of niobium and zirconium oxides-based catalysts and super acidified ion exchange resins as efficient catalysts for dehydration of fructose to HMF. *International Journal of Development Research*, 12(05), 55877-55888.
5. Yaghmaeiyan, N., Mirzaei, M., & Delghavi, R. (2022). Montmorillonite clay: Introduction and evaluation of its applications in different organic syntheses as catalyst: a review. *Results in Chemistry*, 100549.
6. Zeferino, R. C. F., Piaia, V. A. A., Orso, V. T., Pinheiro, V. M., Zanetti, M., Colpani, G. L., ... & Riella, H. G. (2021). Synthesis of geranyl acetate by esterification of geraniol with acetic anhydride through heterogeneous catalysis using ion exchange resin. *Chemical Engineering Research and Design*, 168, 156-168.
7. Ramírez, E., Bringue, R., Fite, C., Iborra, M., Tejero, J., & Cunill, F. (2021). Assessment of ion exchange resins as catalysts for the direct transformation of fructose into butyl levulinate. *Applied Catalysis A: General*, 612, 117988.
8. Badia, J. H., Ramírez, E., Soto, R., Bringue, R., Tejero, J., & Cunill, F. (2021). Optimization and green metrics analysis of the liquid-phase synthesis of sec-butyl levulinate by esterification of levulinic acid with 1-butene over ion-exchange resins. *Fuel Processing Technology*, 220, 106893.
9. Hu, X., Zhou, Z., Zhang, Z., Wang, X., Sui, X., Chen, J., ... & Lin, J. (2021). Reaction coupling separation for isosteviol production from stevioside catalyzed by acidic ion-exchange resin. *Bioprocess and biosystems engineering*, 44(1), 151-159.
10. Peláez, R., Marín, P., & Ordóñez, S. (2021). Effect of formaldehyde precursor and water inhibition in dimethoxymethane synthesis from methanol over acidic ion exchange resins: mechanism and kinetics. *Biofuels, Bioproducts and Biorefining*, 15(6), 1696-1708.
11. Biswas, K., Ghosh, S., & Basu, B. (2020). Ion-exchange resins and polypeptide supported catalysts: A critical review. *Current Green Chemistry*, 7(1), 40-52.
12. Vil, V. A., Yaremenko, I. A., Fomenkov, D. I., Levitsky, D. O., Fleury, F., & Terent'ev, A. O. (2020). Ion exchange resin-catalyzed synthesis of bridged tetraoxanes possessing in vitro cytotoxicity against HeLa cancer cells. *Chemistry of Heterocyclic Compounds*, 56(6), 722-726.
13. Salvador, V. T., Silva, E. S., Gonçalves, P. G., & Cella, R. (2020). Biomass transformation: hydration and isomerization reactions of turpentine oil using ion exchange resins as catalyst. *Sustainable Chemistry and Pharmacy*, 15, 100214.
14. Cho, S. H., Dahnum, D., Cheong, S. H., Lee, H. W., Lee, U., Ha, J. M., & Lee, H. (2020). Facile one-pot synthesis of ZnBr₂ immobilized ion exchange resin for the coupling reaction of CO₂ with propylene oxide. *Journal of CO₂ Utilization*, 42, 101324.
15. Hu, Y., Zhang, J., Wang, Z., Huo, H., Jiang, Y., Xu, X., & Lin, K. (2020). Ion-exchange fabrication of hierarchical Al-MOF-based resin catalysts for the tandem reaction. *ACS applied materials & interfaces*, 12(32), 36159-36167.