

Adsorption-based Separation and Recovery of Rare Earth Elements

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Introduction

This chapter briefly covers different technologies involved in the adsorption-based separation of rare earth elements (REE – the 15 lanthanide elements of the periodic table with atomic numbers $Z=51-71$, plus scandium $Z=21$, and yttrium $Z=39$). The separation technologies include a wide range of materials from ion exchange resins (IERS), metal (hydro)oxides adsorbents, and solvent impregnated resins (SIRs) that have the extractant impregnated into solid support to the recent technologies of surface-functionalized adsorbents with complexing ligand chemically anchored on to the solid support and ion-imprinted polymers with specific recognition sites for the desired REEs.

The adsorption sites in these adsorbents are various surface functional groups or ligands which can adsorb REEs through different mechanisms, i.e., physical adsorption, electrostatic interaction, and/or surface complexation. The adsorbent's behavior depends on the chemistry and chemical properties of these functional groups or ligands (discussed in section 2). Additionally, the interaction of the surface sites and the REEs is controlled by the chemical properties of REEs, such as charge, ionic radius, coordination number, aqueous speciation, and the ability to form complexes with the ligand.

REEs occurs dominantly in trivalent oxidation state, have variable coordination numbers (CN 8–12 (Cotton & Harrowfield, 2012)), and have similar ionic radii between adjacent REEs (which decreases with increasing atomic number among lanthanides) (Nash, 1993). They are considered hard acid cations and interact strongly with hard anions such as hydroxide, alkoxide, carbonates, and phosphates and have strong complexes with organic ligands containing carboxylates and phosphonates (Johannesson et al., 1995; Noack et al., 2016; Pearson, 1963; Xie et al., 2014). More stable REE-ligand complexes are obtained with multidentate ligands like amino-poly(carboxylic acids) due to the high coordination number of REEs (Noack et al., 2016; Xie et al., 2014). These characteristics of REEs affect the extent, kinetics, and mechanism of the adsorption. In aqueous solutions, the pH of the solution controls the REEs speciation. REEs are predominantly cationic REE(III) in aqueous solution at acidic pH and REEs hydroxides at alkaline pH (Callura, 2018; Ramasamy, Repo, et al., 2017). At high pH, the primary mechanism of REEs uptake can be the surface precipitation of REEs as hydroxides instead of adsorption (Dardenne et al., 2002; Farley et al., 1985; Iftekhhar, Ramasamy, et al., 2018; Piasecki & Sverjensky, 2008).

A measure of the adsorbent's effectiveness for separation and its performance can be obtained by conducting batch or column adsorption experiments. In batch adsorption, the frequently used characteristics are equi-

librium adsorption capacity (q_e) (eq. 1a), maximum adsorption capacity calculated using Langmuir isotherm (q_m) (eq. 1e), % adsorption (eq. 1b), solid-liquid distribution (partitioning) coefficient (K_d) (eq. 1c), and selectivity factor (SF) between element A and B (eq. 1d) in case of competitive adsorption or adsorption from a multi-element solution. These parameters are defined as follows:

$$q_e \left(\frac{\text{mg}}{\text{g}} \right) = (C_0 - C_e) * V/m \quad (1a)$$

$$\text{Adsorption (\%)} = \frac{C_0 - C_e}{C_0} * 100 \quad (1b)$$

$$K_d \text{ (ml/g)} = \frac{C_0 - C_e}{C_e} \frac{V}{m} \quad (1c)$$

$$\text{SF (A/B)} = \frac{K_{dA}}{K_{dB}} \quad (1d)$$

$$q_e \left(\frac{\text{mg}}{\text{g}} \right) = q_m \frac{K_L C_e}{1 + K_L C_e} \quad (1e)$$

where C_0 and C_e are initial and equilibrium concentrations of the adsorbate in the solution in batch adsorption (mg/L), m is the mass of the adsorbent used (g), V is the total volume of the solution (L), q is the adsorption (in mg/g), and K_L is Langmuir isotherm constant (L/mg).

Surface functional groups or ligands

The active components of an ion-exchange resin or adsorbent that interacts and binds the aqueous REEs species are the functional groups present on the surface. These functional groups can be active molecules of the polymeric ion exchange resins or ligands grafted on the solid support in functionalized adsorbents (shown in figure 1) or the existing functional groups of a naturally occurring surface, such as -O/-OH on the surface of a mineral oxide/hydroxide. They are involved in the uptake of REEs from solution through electrostatic interaction or surface complexation. The different functional groups can be classified based on the heteroatom bonded to the adsorbent surface (Yang et al., 2019). The common groups are O-containing-functional groups (e.g., -OH, -COOH, -C=O, and -C-O), S-containing functional groups (e.g., -SO₃H, C-S, C=S, and S=O), P-containing functional groups (e.g., -PO₂H₂, -PO(OH)₂), and N-containing functional groups (e.g., -NH₂, -NH, -C=N and -C-N) (Figure 1). Additionally, ligands containing multiple types of functional groups are common, especially in chelating resins and functionalized adsorbents (Figure 1), resulting in wide variations in REE sorption chemistry (Hérès et al., 2018; Page et al., 2017; Trochimczuk & Alexandratos, 1994). Polyfunctional ligands can provide additional affinities (Alexandratos & Smith, 2004a). Also, the same functional group can have a higher or lower affinity for REEs based on its side group (Martell & Hancock, 1996; Zhu & Alexandratos, 2015).

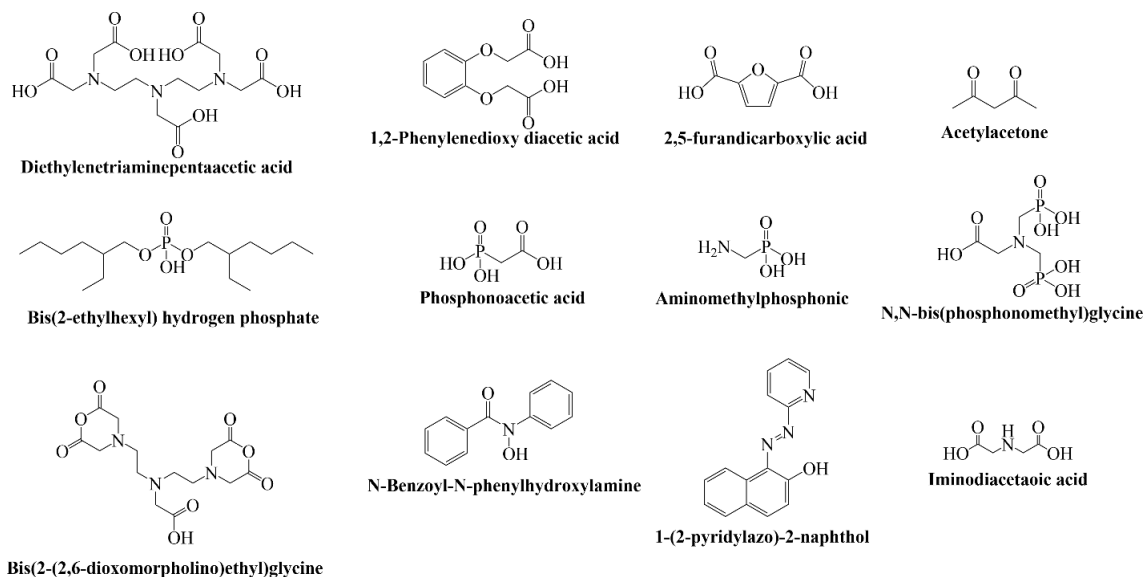


Figure 1: Different ligands used for REEs adsorption in chelating ion-exchange resins or grafted onto solid supports.

The most common functional groups used in ion-exchange and adsorption of REEs are carboxyl, found in both cation-exchangers (Bezzina et al., 2018; Shu et al., 2007; Xiong et al., 2011; Xiong, 2008) and various functionalized adsorbents (Figure 1) (Ahmed, Lee, et al., 2019; Callura et al., 2018; Noack et al., 2016; Polido Legaria, Rocha, et al., 2017; Ravi, Zhang, et al., 2018). The mechanism of REEs uptake by carboxyl-based adsorbents can be ion-exchange process in cation-exchangers or surface complexation in case of a chelating carboxyl-based surface ligand (e.g., complexation of REEs with diethylenetriaminepentaacetic acid (DTPA) functionalized adsorbent (Noack et al., 2016)). Many commercially available carboxyl-based cation exchange resins have been used for REEs extraction (Bezzina et al., 2018; Shu et al., 2007; Xiong et al., 2011; Xiong, 2008). Since carboxyl acid is a weak acid, its behavior is highly dependent on pH.

Sulfonic functional groups are the active component of the strongly acidic cation-exchange resins. The affinity of the counter-ion for the ion-exchanger depends on its charge and hydration radius (Harris & Lucy, 2015). REEs exist as triply charged positive ions in acidic aqueous solutions and hence have a high affinity to negatively charged sulfonic ions and can be separated from singly and doubly charged metal cations using interaction with sulfonic anion (Fritz & Garraida, 1963; Korkisch et al., 1967; Page et al., 2019; Strelow, 1960; Strelow et al., 1965). However, due to similar radii of adjacent Ln(III), selectivity for a particular Ln(III) is limited with sulfonic-acid cation-exchangers (Boyd, 1978; Strelow, 1960; Strelow et al., 1965; Strelow & Bothma, 1964). The sulfonic group is a strong acid; hence its behavior is mostly independent of pH.

Phosphorus-containing functional groups used for REEs sorption are organophosphoric acid, phosphonic acid ($-\text{PO}(\text{OH})_2$), and phosphonic ester $\text{PO}(\text{OR})_2$ based derivatives (Egawa et al., 1994; Ihara et al., 2001; Miklishanskii et al., 1968; Page et al., 2017). The ion-exchange resin containing phosphonic acid-based groups are considered weakly acidic cation-exchange resins similar to carboxyl-based ion-exchange resins and are dependent on pH. Additionally, P-based chelating ligands have been used as functional groups in different chelating resin (Callura et al., 2019; Hérès et al., 2018) and functionalized adsorbents (Figure 1) (Artiushenko, Kostenko, et al., 2020; Bertelsen et al., 2019; Callura et al., 2018; de Decker et al., 2016; Kavun et al., 2021; Noack et al., 2016; Ravi, Lee, et al., 2018; Z. . Wang et al., 2002; X. Zheng et al., 2020).

Most common among N-containing functional groups is amine-based compounds. The REE sorption mechanism for amino-based sorbent is anion-exchange process. These amino-based sorbents can be used to separate Th (IV) and U(IV), which form strong anionic compounds with nitrate and phosphate (Jackson,

1954). Among REEs, Ce(IV) can form anionic nitrates, which can be separated from other REEs using amino-based resins or adsorbents (Zhu & Chen, 2011). Moreover, N-based ligands are used for surface complexation of REEs in chelating resin (Niu et al., 2021; Page et al., 2019) and other adsorbents (Figure 1) (de Decker et al., 2016; Lee et al., 2019; Ramasamy, Puhakka, Repo, Ben Hammouda, et al., 2018; Ramasamy, Repo, et al., 2017).

In naturally occurring oxidic adsorbents such as ferric hydroxide or silica oxide, the surface OH groups undergo protonation-deprotonation and produce surface charges which lead to electrostatic attraction of cations and anions present in the solution. They can electrostatically attract REEs cations resulting in the adsorption of REEs.

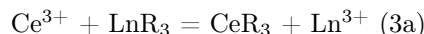
Ion-exchange resins

Ion-exchange in the context of solid-phase extraction involves a reversible interchange of ions between a solid phase (or ion-exchanger) and the solution through electrostatic sorption and desorption to and from the ion-exchange material. The ion-exchangers are classified as cation or anion-exchanger based on the mobile exchangeable ions (i.e., counter-ions). Acidic cation-exchangers, introduced in 1944 by cross-linking polystyrene with 6-8% divinylbenzene, have cations as counterions and attract and bind cations, while anion exchangers, introduced later in 1948, can attract and bind anions from solution. Based on the physical form of the ion-exchanger, ion-exchangers can be classified as membranes, fibers, hydrogels, or resins. Ion-exchange resins (IERS), which represent the major class of ion-exchangers, are insoluble polymers with active-ion groups, commercially available as spherical beads or particles, and have been used to separate REEs mainly in chromatographic setup (Ehrlich & Lisichkin, 2017).

Cation-exchange resins

Strongly acidic cation-exchange resins: Strongly acidic cation-exchange resins are formed by copolymerization of polystyrene and divinylbenzene and have sulfonic (SO_3^-) groups introduced to the benzene rings. There are many sulfonic (SO_3^-) group-based resins available under various trade names (e.g., Amberlite IR-120, Dowex 50WX), having different grain sizes, pore diameters, sorption capacities, degrees of cross-linking, and other characteristics (Ehrlich & Lisichkin, 2017). Sulfonic acid-based cation-exchangers have been used to separate REEs but are not very selective for a specific REE over the other.

In cation-exchange resins (CERs), the strength of cation binding depends on the charge and radius of the hydrated ion (Harris & Lucy, 2015). The electrochemical attraction increases with decreasing ionic radius for ions with the same charge. Within Ln(III), the ionic radius decreases with the increasing atomic number from La(III) (ionic radius: 103 pm) to Lu(III) (ionic radius: 86.1 pm), and thus the binding strength to cation-exchanger increases with atomic number. However, the use of strongly acidic cation-exchange resins for the separation of individual REEs in mineral acids, such as HCl, H_2SO_4 , and HNO_3 is not selective due to similar ionic radius of adjacent Ln(III) (Boyd, 1978; Strelow, 1960; Strelow et al., 1965; Strelow & Bothma, 1964). The similar ionic radius of adjacent Ln(III) results in similar electrostatic attraction as evident by similar equilibrium constants for an ion-exchange reaction involving a strongly acidic cation-exchanger (3a). The ratio of the ion-exchange equilibrium constants of adjacent Ln(III) for reaction similar to (3a) does not exceed 1.1 (Boyd, 1978).



This limits the use of strongly acidic cation-exchange resins in individual REE separation from a solution containing a mix of different REEs. Still, these resins can be used for the separation of Ln(III) from other cations of lower or higher ionic charge (Fritz & Garraalda, 1963; Korkisch et al., 1967; Page et al., 2019; Strelow, 1960; Strelow et al., 1965).

The separation of individual REEs increased with the use of complexing ligands as eluents for strongly acidic cation-exchanger (Boyd, 1978; B. Chen et al., 2017; Spedding et al., 1947, 1954; Strelow & Victor, 1990). The REE ions form complexes with the ligand. These REE-ligand complexes have less affinity for the exchanger than corresponding REE ions, which results in easier desorption of REE-ligand complex and a difference in relative REE desorption based on the stability of individual REE-ligand complex. With the same ligand, the relative concentration of different REE-ligand complexes depends on the ratio of their REE-ligand complex's stability constants. Since the ratio of stability constants of REE-ligand complexes (Karraker, 1961; Mackey et al., 1960; Schoeb, 1965; Suzuki et al., 1980; Wheelwright et al., 1953; Wood, 1993) of neighbor REEs is significantly higher than the ratio of ion-exchange constants (Boyd, 1978), better separation between REE is obtained during elution (Chen et al., 2017). The stability of REE-ligand complexes increases with the increasing atomic number for most complexing ligands, which leads to an order of elution from Lu(III) to Ln(III) with complexing ligand as eluent (Karraker, 1961; Mackey et al., 1960; Schoeb, 1965; Suzuki et al., 1980; Wheelwright et al., 1953; Wood, 1993). The different complexing ligands used as eluent for REEs chromatographic separation using strong acidic cation-exchangers are discussed later in the chapter (section 8.2).

The sulfonic cation-exchangers with complexing ligand eluents have been mainly used in the chromatographic separation of REEs (Ehrlich & Lisichkin, 2017). However, alternatively, in a batch adsorption process, Khawassek et al. (2019) used macroreticular sulfonic acid resin Dowex 50X8 to adsorb REEs from effluents solution collected from the hydrometallurgical process for El-Erediya mineralization. The maximum total REE uptake from leachate solution was 80 mg REEs/g. Similarly, strong acid resin Amberlite 200C Na and Amberlite 200C H showed high sorption efficiency (more than 99.8%) for La(III), Ce(III), and Nd(III) (Kołodzyńska et al., 2019). Page et al. (2019) used strong acidic cation exchange resin, Lewatit MonoPlus SP 112, for La(III), Sm(III), and Er(III) adsorption in sulfate and chloride medium in the presence of competitive ions, such as Fe(III) and Al(III), and reported maximum adsorption capacity of 42 mg/g for Sm(III). The equilibrium constants for the ion-exchange reactions and the REEs selectivities were higher in the chloride medium than the sulfate medium. The ion-exchange equilibrium constants for competitive ions, Fe(III) and Al(III), were significantly lower in both media. A macro-porous strongly acidic CER, SQS-6, adsorbed 97.6% La(III) and 90.36% Nd(III) in 4.0 M H₃PO₄ media with equilibrium capacities of 13.8 and 12.70 mg/g (in 8 M H₃PO₄), respectively (Abu Elgoud et al., 2019).

Carboxylic acid-based cation-exchange resins: Carboxylic acid-based cation-exchange resins can form complexes with REEs in addition to electrostatic interaction (Arnold & Hing, 1967; Kazantsev et al., 1974). The carboxylic functionalized cation-exchangers involve copolymerization of methacrylic acid or acrylic, or acrylonitrile, generally, with divinylbenzene. The type of carboxylic group on cation-exchanger affects the adsorption of REEs; for example, polyacrylic acid resin (Amberlite XE 89) showed lower selectivity for lanthanide than the polymethacrylic acid resin (Amberlite IRC 50) (Arnold & Hing, 1967).

Many macro-porous carboxylic cation-exchange resins such as D113, D155, D152, D151, and SQD-85 have been used for REEs adsorption in acetate medium. The macro-porous carboxylic acid resin D113 was used for adsorption of La (III) ($q_m = 273.3$ mg/g (Shu et al., 2007)), Dy(III) ($q_m = 292.7$ mg/g (Wang & Gao, 2007)), Nd(III) ($q_m = 232.56$ mg/g (Xiong et al., 2011)) and Er(III) ($q_m = 250$ mg/g (Xiong et al., 2009)). The separation coefficients for La (III) adsorption onto D113 were 2.29, 3.64, 4.27, and 0.627 against Ce(III), Gd(III), Er(III), and Y(III), respectively (Shu et al., 2007). With another carboxylic acid resin D152, the maximum adsorption capacities at pH 6.70 for different REEs were between 238 mg/g (for Er(III)) and 510 mg/g (for Sm (III)) (Xiong et al., 2008). Similarly, D155 was used for Ce(III) ($q_m = 294$ mg/g) and Gd(III) ($q_m = 283$ mg/g) (Xiong, 2008), SQD-85 for Yb(III) ($q_m = 347.6$ mg/g) (Xiong et al., 2011), D151 for Ce(III) ($q_m = 392$ mg/g) (Yao, 2010), and a gel-type weak acid resin (110) for Yb(III) ($q_m = 265.8$ mg/g) (Zheng & Xiong, 2011). Commercial resin Amberlite IRC86 (functional group: carboxylic acid) and Purolite S910 (functional group = amidoxime) were used in various buffer solutions (i.e., malic acid, formic acid, acetic acid, alanine, and lactic acid) for adsorption of REE in the presence of competitive Fe(III) and Al(III) ions (Bezzina et al., 2018). The use of a carboxylate buffered system allowed easy separation of REE from Fe(III) and Al(III) ions. The carboxylic resin IRC86 showed higher capacity for HREEs in acetic acid

media at pH 4.4, showing preference order of Y(III) > Er(III) > Sm(III) > La(III).

The limitation of using carboxylic cation-exchange resins is that these resins operate in the weak acidic pH range (pH>3.5), posing additional challenges due to hydrolysis of REE ions and occurrence of other competitive cations such as Fe(III) (Ehrlich & Lisichkin, 2017; Kazantsev et al., 1974; Wood, 1993).

P-containing cation-exchange resins: The phosphorus-based ligand containing resins are considered part of the family of the weakly acidic cation-exchangers. Among different phosphorus-containing functional groups, phosphinic showed higher selectivity than phosphonic, with both showing higher selectivity than their respective oxidized derivatives (Egawa et al., 1994). Their Ln(III) distribution coefficient increased with increasing atomic number in general but with a plateau from Sm(III) to Ho(III). Macroreticular methylenephosphonic acid resin showed affinity series of Fe(III) ~ U(VI) ~ Mo(VI) > Bi(III) > Al(III) > Gd(III) > La(III) ~ V(V) > Pb(II) > Cd(II) > Cu(II) [?] Ca(II) [?] Ba(II) [?] Zn(II) > Mg(II) [?] Co(II) [?] Ni(II) (Jyo et al., 1997); whereas macroreticular phosphonic acid resin had affinity series of Mo(VI) [?] Fe(III) [?] U(VI) > Bi(III) [?] Lu(III) > Al(III) [?] Gd(III) > La(III) > Cr(III) > Pb(II) > Mn(II) [?] Cd(II) [?] Cu(II) > Ca(II) [?] Co(II) [?] Zn(II) [?] Ba(II) [?] Sr(II) > Ni(II) [?] Mg(II) (Ihara et al., 2001).

Many different P-based cation-exchange resins used for REE adsorption involve different side-group with phosphorous. The P-based resin containing P(R)(O)OH (R = Et, Bu) and -P(O)(OR)OH (R = Et, Pr, Bu) were used for chromatographic separation of La, Pm, and Eu with increasing K_d values with increase in atomic number (Miklshanskii et al., 1968). Among different adsorbents with phosphorus-containing ligands, the strength of metal ion binding is affected by electron density on the oxygen atom, the spacer connecting the phosphorous-containing ligand to the polymer matrix, and the hydrophilicity of its environment (Spiro D. Alexandratos & Hussain, 1998; Spiro D. Alexandratos & Zhu, 2005, 2008, 2015; Andrzej W. Trochimczuk & Alexandratos, 1994; X. Zhu & Alexandratos, 2014, 2015). The affinity for REEs increased with the introduction of hydroxyl or polyol into the spacer due to their stronger interaction with REEs (Alexandratos & Zhu, 2008).

Adsorbents containing di- and polyfunctional groups in addition to P-based groups have been studied for REE separation (Alexandratos & Natesan, 1999; Alexandratos & Hussain, 1995; Alexandratos & Smith, 2004b; Shumilova et al., 2012; Trochimczuk, 2000). The addition of a second functional group can enhance the behavior of the adsorbent, as in phosphorylated adsorbents, where the introduction of highly hydrophilic sulfonic acid eliminated intra-ligand hydrogen bonding, which reduced intra-ligand cooperation, and increased the accessibility of P-containing groups (Alexandratos & Smith, 2004b). Additionally, the sulfonic acid itself has an affinity for REE, which can increase REE adsorption (Ehrlich & Lisichkin, 2017). Bonding sulfonic acid groups to the phosphinated polystyrene matrix increased the Eu(III) distribution coefficient from 61.8 to 220.5 in a 1 N HNO₃ solution (Alexandratos & Hussain, 1995). Hérès et al. (2018) used Monophos and Diphonix resin, which had sulfonic groups together with alkylphosphonic groups for adsorption of REEs. The extraction efficiency of Monophos and Diphonix resin increased with increasing ionic radius of REEs.

Anion-exchange resins

REE ions do not form anions with inorganic ligands thus are poorly adsorbed on the anion-exchange resins (Ehrlich & Lisichkin, 2017; Koodynska & Hubicki, 2012; J Minczewski et al., 1982). Still, Th(IV) and U(VI) can be separated from solution containing REEs using anion-exchange resins (AERs) as they form anion complexes with nitrate and phosphate (Ehrlich & Lisichkin, 2017; Koodynska & Hubicki, 2012). Among REEs, cerium(IV) can form negatively charged complexes with nitrate and can be adsorbed to the AERs, e.g., anion-exchanger containing N-methyl-imidazolium group (Zhu & Chen, 2011).

Anionic REE-ligand complexes can be formed by adding organic compounds (e.g., methanol (Faris & Warton, 1962), ethanol (Hubicki & Olszak, 1998), and propanol (Hubicki & Olszak, 2002)) to nitric acid. These anionic complexes can be separated using a strongly basic anion-exchange resin. Anionic REE-ligand complex

electrostatically binds to the positive anion-exchanger. Similarly, complexing ligands such as ethylenediaminetetraacetic acid (EDTA) and cyclohexane-1,2-diaminetetraacetic acid (CDTA) were used to form anionic REE-ligand complex for REEs separation using anion-exchange resins (Hubicka & Hubicki, 1986; Hubicka & Kołodyńska, 2004, 2008; Jerzy Minczewski & Dybczyński, 1962; Wódkiewicz & Dybczyński, 1968). Binary mixtures of Y-Nd, Sm-Tb, La-Nd, and Dy-Er were separated using frontal chromatography with EDTA as eluent using different Dowex anion-exchangers (Hubicka and Hubicki 1986). Strongly basic anion resin Dowex 1 and Dowex 2 were used to separate REE complex with N-hydroxyethylenediaminetriacetic acid (HEDTA) and with iminodiacetic acid (IDA) (Hubicka & Drobek, 1997, 1998, 1999). Similarly, REEs complexes with DCTA of the $\text{Ln}(\text{dcta})^-$ type were chromatographically separated using different polyacrylate anion-exchangers (Amberlite IRA 68, Amberlite IRA 458, and Amberlite IRA 958) and different polystyrene anion-exchangers (Lewatit MonoPlus M 500, Lewatit MonoPlus M 600, Lewatit MonoPlus MP 64, Lewatit MonoPlus MP 500, and Lewatit MP 62) (Hubicka & Kołodyńska, 2004, 2008).

Chelating ion-exchange resins

Chelating ion-exchange resins are equipped with ligands that form complexes with metal ions through their functional groups (Garg et al., 1999). Chelating ion-exchange resins used for REE separation contain iminodiacetate, aminomethylphosphonic, hydroxamine, and diamide (Ehrlich & Lisichkin, 2017; Koodynska & Hubicki, 2012). Many commercially available iminodiacetate based resins such as Amberlite IRC 718, Chelex 100, Dowex A-1 (Mathur & Khopkar, 1985; Schrobilgen & Lang, 1968), Duolite ES466, Lewatit TP 207 (Junior et al., 2021; Niu et al., 2021), and Purolite S930 Plus (Page et al., 2019) have been used for REE separation (Ehrlich & Lisichkin, 2017; Koodynska & Hubicki, 2012).

Iminodiacetic acid resins are also characterized by a very high selectivity for REE over the alkali and alkaline earth metals, often present in high concentrations in alternative REE resources (Ehrlich & Lisichkin, 2017; Koodynska & Hubicki, 2012; Page et al., 2017, 2019). An iminodiacetic acid resins, Purolite S930Plus, showed higher selectivity for REEs in the presence of high Na and Ca concentration than the sulfonic acid resin (SA), sulfonic-phosphonic resin (Purolite S957), and aminophosphonic resins (Purolite S950) (Page et al., 2017). However, the SA resin, Purolite S957, and Purolite S950 were tolerant towards REEs adsorption from acid solutions up to 0.5 M $[\text{H}^+]$, whereas iminodiacetic acid resins effectively adsorbed REE only at $[\text{H}^+] < 0.001$ M. For the sulfonic acid resin, the selectivity was $\text{REE} [?] \text{ Th} > \text{Fe} [?] \text{ Al}$ whereas for other resins it was $\text{Th} [?] \text{ Fe} [?] \text{ REE} [?] \text{ Al}$. In another study with Purolite S930Plus, the resin selectively adsorbed La(III) over Mg(II) with a selectivity factor of 3046 in 1 M MgCl_2 , but the selectivity factor decreased to 453 and 240 in 0.5 M $\text{MgCl}_2 + 0.5$ M MgSO_4 and 1 M MgSO_4 medium, respectively (Page et al., 2019). Another iminodiacetic acid-based resin, TP207, showed adsorption capacity order of $\text{La(III)} > \text{Eu(III)} > \text{Y(III)}$, with capacity of 0.73 mmol/g (or 101.5 mg/g) for La(III) at pH 4.0 (Niu et al., 2021).

The REEs extraction efficiency using different aminophosphonic resins (Tulsion CH-93, Purolite S940, Amberlite IRC-747, Lewatit TP-260) decreased with an increase in Z/IR (atomic number/ionic radius) from Sc up to a plateau of La, Nd, and Gd, with an increase and increased after that with Z/IR from Dy to Yb (Hérès et al., 2018). Concurrently, the extraction efficiency decreased with an increase in ionic radius (IR) in general, with a slight spike at Nd (III) and Pr(III). Another chelating ligand diglycolamic acid-containing polymeric adsorbent showed adsorption capacity (q_m) of 0.113 mmol Dy/g (or 18.3 mg/g) and selectively adsorbed REEs at low pH values (Shinozaki et al., 2018). Other chelating ligands ethylenetriaminepentaacetic dianhydride (DTPADA), phos-phonoacetic acid (PAA), and N,N-bis(phosphonomethyl)glycine (BPG) containing polymers had maximum adsorption capacities of 2.9, 5.0, 3.0 mg/g, and respectively for a mixture of three REEs (Nd(III), Gd(III), and Ho(III)) (Callura et al., 2019, 2021). N-based chelating resin, Dowex M 4195 with bis(2-pyridylmethyl) amine showed very low sorption (maximum 3.1%) for La(III), Ce(III), Nd(III) (Kołodyńska et al., 2019).

Inorganic adsorbents

Inorganic adsorbents used for REEs adsorption include mineral oxides and hydroxides, clay minerals, and nanomaterials. Mineral oxides and hydroxides are adsorbents with reactive sites containing oxygens (O^{2-}) or hydroxides ($-OH$) that interact with cations and anions. The mineral adsorbents used for REEs adsorption are silica, alumina, iron (hydro)oxides, Mn oxides, and TiO_2 .

Silica has been studied as an adsorbent for Gd(III), Y(III) (Kosmulski, 1997b), and Yb(III) (Marmier et al., 1999). These investigations focused on surface complexation modeling and % uptake and did not report maximum uptake in mg/g, distribution (partitioning) coefficient, or separation factor. Alumina was studied for adsorption of Gd(III), Y(III) (Kosmulski, 1997a), Yb(III) (Marmier et al., 1997), and Eu(III) (Wang et al., 2006). TiO_2 was studied for adsorption of Y(III) (Zhang et al., 2004), Nd(III) (Ridley et al., 2005; Zhang et al., 2004), and Eu(III) (Tan et al., 2009). The q_m for Eu(III) was 1.5 mg/g with TiO_2 and 2.7 mg/g in the presence of fulvic acid (Tan et al., 2009).

Other researches involving inorganic adsorbents are Yb(III) adsorption on hematite (Marmier et al., 1997), La(III) onto hematite (Nicolas Marmier & Fromage, 1999), REEs onto Mn oxide, Fe oxy-hydroxide (Davranche et al., 2004, 2005; Ohta & Kawabe, 2001), and REEs on amorphous ferric hydroxide (Quinn et al., 2006, 2007). In addition to oxides and hydroxides, other minerals have been used as adsorbents as well. Adsorption of Nd(III) onto kaolinite (Aja, 1998), Ln(III) onto kaolinite and smectite (Coppin et al., 2002), Eu(III) onto montmorillonite (Kowal-Fouchard et al., 2004), REEs on kaolin (XIAO et al., 2016), REEs adsorption onto Kaolinite (Feng et al., 2021), and Eu(III) on halloysite and kaolinite (Zhou et al., 2022) are such studies involving inorganic mineral adsorbents. Kaolin showed a saturated adsorption capacity of 1.731, 1.587, and 0.971 mg/g for La(III), Nd(III), and Y(III), respectively (XIAO et al., 2016). Mosai et al. (2019) used natural zeolite and bentonite to recover REEs from aqueous solution and reported q_m values of 0.09-0.24 mg/g and 1.07-2.87 mg/g for adsorption of different REEs onto zeolite and bentonite, respectively.

Most of the research mentioned above focuses on understanding the mechanism of REE adsorption onto the inorganic adsorbent and uses surface complexation models. The mechanism of adsorption is required for a better understanding of natural as well as engineered systems. However, since the adsorption capacity of these unmodified adsorbents is low (i.e., around 0.01-0.1 mmol/g) (Ehrlich & Lisichkin, 2017), it is impractical to employ these adsorbents for REE separation at an industrial scale.

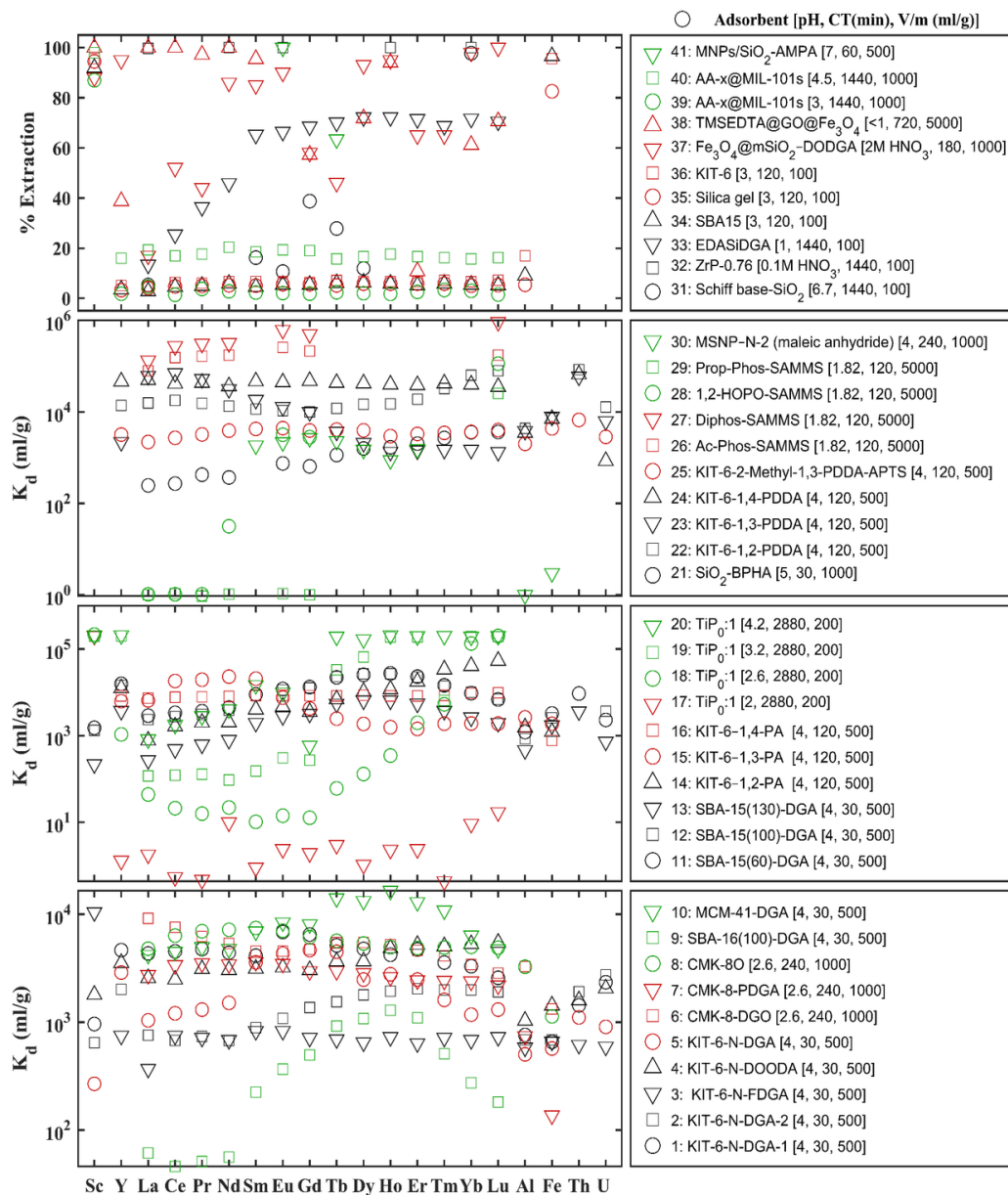


Figure 2: Distribution coefficient (K_d) for various adsorbents. The legends include adsorbent with the experimental condition (pH, contact time (CT), and V/m ratio (volume of solution/mass of adsorbent)) Source for data: Adsorbents 1-2 (Florek et al., 2014), 3-5 (Florek et al., 2015), 6-8 (Perreault et al., 2017), 9-13 (Juère et al., 2016), 14-16 (Hu et al., 2017), 17-20 (pH is equilibrium pH) (Zhang et al., 2018), 21 (Artiushenko, Ávila, et al., 2020), 22-25 (Hu et al., 2019), 26-29 (Yantasee et al., 2009), 30 (Zheng et al., 2015), 31 (Amarasekara et al., 2009), 32 (Veliscek-Carolan et al., 2014), 33 (Ogata et al., 2015b), 34-36 (Giret et al., 2018), 37 (Li et al., 2018), 38 (Barrak et al., 2019), 39-40 (Lou et al., 2019), 41 (Kostenko et al., 2019).

Nonetheless, there are some recent studies involving novel inorganic adsorbents that show promising results. Multiple Zirconium organophosphonate (ZrP) with different Zr:P ratios were prepared using low-temperature hydrothermal reactions of zirconium propoxide with amino tris(methylene phosphonic acid) (ATMP). The

adsorbents showed selectivity for lanthanide elements over mono- and divalent metal ions. The sorption capacities of 37, 56, and 60 mg Eu/g were reported for ZrP-0.65, ZrP-0.71, and ZrP-0.76 (legend 32, Figure 2), respectively (Velisek-Carolan et al., 2014). In another study, Attallah et al. (2016) synthesized a number of aluminum silicotitanates (ATS 1-31) and obtained 99% La (III) and Eu (III) adsorption. Inorganic titanium phosphate showed Sc(III) uptake capacities of 26.1, 8.25, and 3.3 mg/g for amorphous, α -, and γ -TiP, respectively. In chromatographic separation using amorphous TiP, almost all Sc(III) were eluted using a mixed acid comprising of nitric and phosphoric acid, with Sc(III)/Fe(II) and Sc(III)/Al(III) enrichment factor of 9 and 265, respectively (Zhang, Koivula, et al., 2017). Titanium phosphate prepared from acidic wastewater of titanium dioxide achieved maximum Ce(III) adsorption capacity (q_m) of 158.0 mg/g and was selective for Ce in presence of Na, K, Ca, and Mg ions (Zhaowang Liu et al., 2021). Another inorganic adsorbent, layered titanium (IV) butyl phosphate (TiP), showed Dy(III) uptake of more than 25 mg/g and a maximum separation factor of 2065 for Dy(III)-Nd(III), 11.5 for Dy(III)-Tb(III), and around 25 for La(III)-Ce(III) in respective binary element solutions (Zhang et al. 2018). Adsorptions conducted at different pH resulted in selectivity for different Ln(III) with the highest distribution coefficient (K_d) of around 10^5 ml/g (legend 17-20, Figure 2). The adsorbent TiP showed selectivity for Yb(III) and Lu(III) at pH 2.6. The distribution coefficient (K_d) of different REEs measures the selectivity of the adsorbent for a particular REE in competitive adsorption (Figure 2).

With another inorganic adsorbent amorphous zirconium phosphate (am-ZrP), maximum adsorption of 27.5 mg/g and 38.3 mg/g for Nd and Dy were obtained (Xu et al., 2018). The SF for Dy(III)/Co(II), Nd(III)/Co(II), Dy(III)/Nd(III) were 1811, 958, and 1.9, respectively (Xu et al., 2018). A microporous titanate, ETS 10, had adsorption capacities (q_m) of 48.8, 68.1, 99.0, 124.7, and 122.7 mg/g, respectively for Y(III), Nd(III), Eu(III), Tb(III), and Dy(III) (Thakkar et al., 2019). Magnetic hydroxyapatite composite (CaHAP/NF) derived from calcium hydroxyapatite $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$, and nickel ferrite $[\text{NiFe}_2\text{O}_4]$ was synthesized by a coprecipitation method had capacities of 137.35 and 130.43 mg/g for Eu(III) and Tb(III) (Attia et al., 2019). Adsorbent synthesized through modification of titanium oxide modified with arsenate (4As-TiO₂) and further doping with Nd (Nd/4As-TiO₂) reached maximum capacities of 65 and 37 mg/g for Y(III) at pH 9, respectively with the possible mechanism of Y(III) surface precipitation in alkaline medium and Y(III) surface complexation in neutral medium (Vasylyeva et al., 2021).

Many metal-oxides based nanoparticles have been tested for REE adsorption. Fe(III)-Ti(IV) mixed oxide nanoparticles showed capacities of 229, 181, and 126 mg/g for Ce(III), Nd(III), and Gd(III), respectively (Metwally & Rizk, 2014). Nano maghemite showed Y(III) uptake capacity of 13.5 mg/g (Dubey & Grandhi, 2016). A magnetic nanoparticle (MNP) $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.2$) had adsorption capacity of 125 mg/g and 25 mg/g for La(III) and Ce(III) while $\text{Co}_x\text{Mn}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.8$) had adsorption capacity of 189 mg/g and 294 mg/g for La(III) and Ce(III) (Ghobadi et al., 2017). In another study, MNP MnFe_2O_4 prepared via co-precipitation and further modified with graphene oxide (MnFe_2O_4 -GO) showed high capacities for La(III) and Ce(III) adsorption (Ghobadi et al., 2018). The adsorption capacity of MnFe_2O_4 -GO for La(III) was 1001 mg/g and Ce(III) was 982 mg/g at pH 7, both higher than MnFe_2O_4 (La(III) = 785 and Ce(III) = 770 mg/g) (Table 1). Other Magnetic nano- MnFe_2O_4 composites with Al_2O_3 and SiO_2 -chitosan showed similar high adsorption capacities (Liu et al., 2021) (Table 1). Other high-capacity REEs adsorbents are listed in Table 1 (adsorbents are discussed in their respective sections).

Table 1. Some adsorbents with high adsorption capacity ($q_m > 350$ mg/g) for various REEs (III).

Adsorbent	Type of adsorbent	q_m (mg/g) for REE(III)
D152	Carboxyl acid-CER	La: 486, Pr: 373, Nd: 453, Sm: 510, Gd: 391, Dy: 413, Lu:
D151	Carboxyl acid-CER	Ce: 392
MnFe_2O_4	Inorganic adsorbent	La: 785, Ce: 770
MnFe_2O_4 -GO	Inorganic adsorbent/ GO based	La: 1001, Ce: 982
TMO-nanowire	Inorganic adsorbent	La: 1111, Ce: 1000
MnFe_2O_4 - Al_2O_3	Inorganic adsorbent	La: 885, Ce: 879
MnFe_2O_4 @ SiO_2 -CS	Composite adsorbent	La: 1030, Ce: 1020

Adsorbent	Type of adsorbent	q_m (mg/g) for REE(III)
SH-MCM-41	OMS based	La: 560.56, Gd: 467.60, Yb: 546.68
APHMSN	Functionalized mesoporous silica	Gd: 387.3
Fe ₃ O ₄ /MnO ₂ /rGO	GO based	La: 1016, Ce: 981
GO@TiP-Sponge	GO based	Dy: 576.17
CNT/GO hybrid hydrosol	CNT-GO based	Gd: 534.76
ZIF-8	MOF	Dy: 430.4
ZIF-8	MOF	La: 385
HKUST	MOF	Ce: 353
ZnGA	MOF	Y: 377.02
Mg-Fe-LDH-Cyanex272	Metal based	La: 480,8
CMC-g-PAC hydrogel	Composite adsorbent	La: 381.72

CER: Cation-exchange resin, TMO: Transition metal oxide, GO: Graphene oxide, OMS: ordered mesoporous silica, APHMSN: Amino-phosphonic functionalized hollow mesoporous silica nanoparticle, CNT: Carbon nanotube, MOF: Metal-organic framework, LDH: Layered double hydroxide, CMC-g-PAC: carboxymethyl-cellulose grafted polyacrylic acid.

Magnetic nanoparticle CuFe₂O₄ showed adsorption capacity of 51.02, 42.02, and 40.16 mg/g for Nd(III), La(III), and Ce(III), respectively (Tu & Johnston, 2018). Marwani et al. (2018) synthesized CeO₂-CdO nanomaterial and used it for adsorption of Y(III) from a solution containing Co(II), Cu(II), Cr(III), Cr(VI), Pb(II), W(VI), Y(III) and Zn(II). The distribution coefficient (K_d) for Y(III) reported was 17,743.90 ml/g with a capacity (q_m) of 84.67 mg/g. Other nano adsorbents, nano-thorium (IV) oxide, and nano-zirconium oxide showed adsorption capacities of 10.5 mg/g and 18.0 mg/g for Y (III), respectively (Dubey & Grandhi, 2019). High adsorption capacities of 1111 for La(III) and 1000 mg/g for Ce(III) were obtained at pH 5 with transition metal oxide (TMO) nanowires synthesized via hydrothermal processing of a metal mix (Co, Fe, Ni) followed by pyrolysis (Sarmadi et al., 2021).

Extractant immobilized materials

Extractants immobilized materials (EIMs) are a class of adsorbents in which the active component or extractant used to bind the target analyte separating it from its original medium is physically immobilized onto a solid support (Hidayah & Abidin, 2017). The active component or the extractant is a compound capable of ionic or complex interaction with the target metal ions. The active component is attached to the solid support's surface by physical adsorption, or it resides in a thin solvent layer covering the support surface, or it can be part of the bulk solvent filling the pores of the solid support. In literature, solvent impregnated resins (SIRs) is commonly used to identify adsorbent obtained when solvent extractant such as N,N-dimethylformamide (DMF), N,N,N',N'-Tetraoctyl diglycolamide (TODGA), and Cyanex-923 are infused onto solid support like silica or resin (Sun et al. 2009; Kabay et al. 2010; Zhu and Chen 2011). Another similar term, supported ionic liquid (SIL), describes adsorbents where ionic liquids are infused into the solid support (Bao et al., 2016; Zhu et al., 2012).

The separation processes involving EIMs have been termed as supported liquid extraction (SLE) or solid-supported liquid-liquid extraction (SLLE) (Florek et al., 2016; Hidayah & Abidin, 2017; Hu et al., 2018). Supported liquid extraction (SLE) is analogous to traditional liquid-liquid extraction (LLE), where target species are separated based on their relative solubilities in two different immiscible liquids, usually water and an organic solvent containing the extractant but instead of shaking the two immiscible phases together, the extractant is supported on a solid support and put in a column (or cartridge). The REEs containing solution is passed through, REEs ion gets adsorbed, and then eluent is used to desorb the adsorbed REEs species. In SLE, it is possible to achieve higher recovery due to the increase in surface area of interaction

between the extractant and the target cations and increasing the diffusion rate through control of the porous structure of the support material. Other advantages over traditional LLE are less use of organic compounds, waste reduction, and lack of third phase formation (Florek et al., 2016; Hidayah & Abidin, 2017; Kabay et al., 2010).

The synthesis of EIMs (SIRs and SILs) involves modification of already synthesized polymers or other solid supports like silica or activated carbon using dry or wet methods. In the dry method, the active component is impregnated into support in excess using a volatile solvent then the excess amount is evaporated by heating, thus leaving the active component physically adsorbed to the support surface. In the wet method, support is impregnated with a solution of active component in a non-polar or weakly polar solvent followed by repeated washing with water, leaving a layer of the non-polar solution of the active component (Bao et al., 2016; Ehrlich & Lisichkin, 2017). Based on the types of solid support used for preparing, these adsorbents can be broadly divided into organic polymer-based support and inorganic supports.

Organic polymer-based supports

Many researchers have used organic polymers as the solid support for solvent impregnated resins (SIRs) used for REEs uptake from solution. Relevant examples of polymer based SIRs include N,N,N',N' tetraoctyldiglycolamide (TODGA) and N,N,N',N' tetrakis-2-ethylhexyldiglycolamide (TEHDGA) impregnated Amberchrom CG-71 for REEs separation; tributyl phosphate infused Styrene-divinylbenzene to copolymer separate Am and Eu (Louis & Duyckaerts, 1984, 1985); 2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester (PC88A) infused Amberlite XAD-7 for separation of Gd and Y mixtures (WAKUI et al., 1988); 8-Quinolinol (oxine) and 2-(2-(5 chloropyridylazo)-5-dimethylamino)-phenol (5C1DMPAP) immobilized Amberlite XAD-4 and XAD-7 each for preconcentration of Ce, La, and Pr (Masi & Olsina, 1993); Amberlite XAD-7 impregnated with binary mix of cobalt dicarbollide and dibutyl-N,N-diethylcarbamoylmethyl phosphonate (DB-DECMP) for Eu sorption (Svoboda et al., 1997); bis(2,4,4-trimethyl pentyl) phosphinic acid (Cyanex 272) (Wang et al., 1998), 1-hexyl-4-ethyloctyl hydrogen isopropylphosphonic acid (HEOPA) (Wang et al., 2002), and bis(2,4,4-trimethylpentyl) monothiophosphinic acid (CL302, HL) (Jia et al., 2004) infused resin for HREEs separation.

Additional examples include PC88A infused styrene-divinyl benzene copolymer for Gd(III) and Tb(III) chromatographic separation (PARK et al., 2005), Octacarboxymethyl-C-methylcalix 4-resorcinarene impregnated Amberlite XAD-16 for La(III), Ce(III), and Y(III) preconcentration (Gok et al., 2007); XAD-4 infused with tri-n-octylmethylammonium chloride (Aliquat-336) in benzene for Ln(III) and Gd(III) (Elsofany, 2008); microporous polymer infused with phosphorus podands bearing two $\text{Ph}_2\text{P}(\text{O})\text{CH}_2\text{C}(\text{O})\text{NH}$ for REEs (Turano et al., 2008); Cyanex272- 2-ethylhexyl phosphoric acid-2-ethylhexyl ester (P507) impregnated resin for HREEs (Liao et al., 2010); TOPS-99 infused Amberlite XAD-4 to extracted Tb (Kumar et al., 2011), β -glycerophosphate impregnated Amberlite XAD 7 for La(III) (Gabor et al., 2016); di-(2-ethylhexyl)phosphinic acid (P227) impregnated XAD-7HP for HREEs (Yang et al., 2020); and HDEHP impregnated XAD-7 for REEs (Sert et al., 2021).

Lee et al. (2009) used trialkylphosphine-based (Cyanex 923), PC88A, and HDEHP for selective separation of La from Ce, Pr, Nd, and Sm, as well as from other concomitant metals in chloride medium. HDEHP provided the best separation with separation factors of 2.57, 3.63, 4.72, and 32.06 for Ce, Pr, Nd, and Sm over La (Lee et al., 2009, 2010b). The same adsorbent was used, followed by anion exchange and oxalate precipitation to obtain La_2O_3 of more than 99.9998% purity (Lee et al., 2010a). Amberlite XAD-7 coated with β -glycerophosphate had q_m of 33.8 mg/g for La (Gabor et al., 2016). Mondal et al. (2019) used N, N,N',N'-tetrakis-2-ethylhexyldiglycolamide (TEHDGA) impregnated XAD-7 resin to selectively adsorb REEs from coal fly ash solution containing Fe, Ca, Al, Mg, and Si with K_d of 200-520 ml/g for REEs and 0.2-2.9 ml/g for impurities. Cyanex 272 impregnated Amberlite XAD-7 resin showed distribution coefficient in order of $\text{Gd} > \text{Eu} > \text{Sm} > \text{Nd} > \text{Pr} > \text{La}$ with K_d value for Gd and Eu as 208.1 and 156.4 ml/g (İnan et al., 2018). The SIR P227 infused XAD-7HP showed selectivity series of $\text{Fe} > \text{Lu} > \text{Tm} > \text{Zn} > \text{Mg} > \text{Ca} > \text{Ho} > \text{Co} > \text{Ni} > \text{Cu} > \text{Al}$ (B. Yang et al., 2020). Another adsorbent, HDEHP-XAD-7 showed selectivity

series Gd > Eu > Sm > Nd > Pr > La with separation factors achieved Gd/La separation factors of >140 (Sert et al., 2021).

The examples SILs with organic polymer include 1-octyl-3-methylimidazolium hexafluorophosphate (C8mim⁺PF₆⁻) containing Cyanex923 immobilized on XAD-7 for REE extraction (Sun et al., 2008), trialkylmethylammonium sec-nonylphenoxyacetate ([A336][CA-100]) impregnated on Amberlite XAD-7 (Sun et al., 2009), Trihexyl(tetradecyl) phosphonium mono-(2-ethylhexyl) 2-ethylhexyl phosphonate ([P₆₆₆₁₄][EHEHP]) and trioctylmethylammonium bis(2,4,4-trimethylpentyl) phosphonate ([N₁₈₈₈][BTMPP]) impregnated Amberlite XAD-7 (Zhao et al., 2016), betainium sulfonyl(trifluoromethanesulfonylimide) poly(styrene-co-divinylbenzene) [Hbet-STFSI-PS-DVB] impregnated Amberlite XAD-16 (Avdibegović et al., 2017), 1-butyl-3-methylimidazoliumbis(trifluoromethylsulfonyl)imide ([Bmim][NTf₂]) combined with N,N-dioctyldiglycolamic acid (DODGAA) and impregnated into Amberlite XAD7HP (Friend et al., 2020), and trihexyl (tetradecyl) phosphine bis (2,4, 4-trimethyl-amy)-phosphonate (Cyphos IL 104) impregnated polymer membrane (Wang et al., 2020).

Inorganic supports

Inorganic supports mostly include silica-based polymers. In some cases, ordered mesoporous silica and carbon nanotubes have been used. Extractant bis(2-ethylhexyl) hydrogen phosphate (HDEHP) coated C18-hydrophobized silica was used for chromatographic separation of lanthanides (Sivaraman et al., 2002); 2-ethylhexylphosphonic acid mono-2-ethylhexyl ester impregnated silica-based urea-formaldehyde (SiO₂/UF) for Eu(III) and Nd(III) (Naser et al., 2015); HDEHP impregnated Polyethersulfone (PES) embedded with polyvinyl alcohol (PVA) and multiwalled carbon nanotubes (MWCNT) for Y(III) sorption (Yadav et al., 2015); and tetraoctyldiglycolamide impregnated Carbon inverse opals (C-IOP) for REEs (Turanov et al., 2015).

Cyanex 272 impregnated mesoporous silica MCM 41 was used for the extraction of lanthanides. The selectivity between light lanthanide (La(III)), medium lanthanide (Eu(III)), and heavy lanthanide (Lu(III)) followed the order of Lu(III) > Eu(III) > La(III) with separation factor of 61, 61 and 3504 for Lu(III)/Eu(III), Eu(III)/La(III) and Lu(III)/La(III), respectively (Mohammedi et al., 2019). Silica gel modified with 1-(-2-pyridylazo) naphthol (PAN) and acetylacetone (Acac) through solvent evaporation process was selective for Sc(III) against Fe(III) with selectivity factors of 5.79 and 8.95, respectively at pH 6 (Ramasamy, Puhakka, Repo, & Sillanpää, 2018). Magnetite nanoparticle was used as a support for coating di(2-ethylhexyl)phosphonate (HDEHP), bis(2,4,4-trimethylpentyl)phosphinic acid (CYANEX 272), and bis(2,4,4-trimethylpentyl)dithiophosphinic acid (CYANEX 301) (Molina et al., 2019). These coated magnetite nanoparticles had q_m of 6.6-8.3 mg/g for La(III), 7.7-8.7 mg/g for Pr(III), and 4.8-8.9 mg/g for Nd(III). The same extractant, HDEHP was infused into styrene-divinylbenzene copolymer immobilized silica particles (HDEHP-SiO₂-P) for REEs adsorption (Shu et al., 2017, 2018; Zhang et al., 2019). The adsorption capacity (q_m) of HDEHP-SiO₂-P was 38.95 mg/g for Ce(III) and 52.84 mg/g for Gd(III) (Shu et al., 2017). In a different study, the HDEHP-SiO₂-P had q_m of 14.1 mg/g for Sc(III) with Sc(III) selectivity factor of >50 over other REEs (Zhang et al., 2019).

Inorganic solid supports infused with ionic liquids are mesoporous silica doped with binary IL mixtures (C8mim+PF₆-/Cyphos IL 104 or C4mim+PF₆-/Cyphos IL 104) (Liu et al., 2009), silica gel impregnated with N-PhenacylPyrNTf₂ ionic liquid (Marwani & Alsafrani, 2013), silica doped with bifunctional ionic liquid trioctylmethylammonium 1-phenyl-3-methyl-4-benzoylpyrazol-5-onate ([A336]+[L]-) (Turanov et al., 2016), and MCM-41 silica impregnated with [Hbet-STFSI-PS-DVB] (Avdibegović et al., 2017). Among the SILs, trihexyl(tetradecyl)phosphonium bis(2,4,4-trimethylpentyl)phosphinate (Cyphos) entrapped in silica reached maximum adsorption capacities of 14.7 mg/g for Nd(III) and 19.8 mg/g at pH 4.0 (Mohamed et al., 2017). Ionic liquid (IL), 1-butyl-3-methylimidazolium bromide ([C4mim]⁺[Br]⁻) impregnated metal-organic framework (MOF) UiO-66 had a maximum Gd(III) adsorption capacity of 65 mg/g at pH 6 with Gd(III) selectivity in the presence of other metal ions (Na(I), Ca(II), Ma(II), Al(III), and Fe(III)) (Ahmed, Adhikary, et al., 2019).

The main limitation of SLEs is the gradual washout of the active component during operation (Bao et al., 2016). Possible solutions include the selection of highly hydrophobic and low soluble active components (Muraviev et al., 1998; Sparfel & Cote, 2004) and/or thorough washing of weakly adsorbed active components after their application onto the solid surface (Muraviev, 1998; Muraviev et al., 1998). Another method to prevent the leaking of the extractant from adsorbent grain is to coat a layer of polymer on the adsorbent, which acts as a semipermeable membrane or protective barrier for extractant while allowing the metal ion diffusion (Bao et al., 2016; Muraviev et al., 1998; Nishihama et al., 2013; Trochimczuk et al., 2004).

A protective barrier around the SIR was formed using polysulfone in dimethylformamide (DMF); however, loss of the adsorbed extractant [bis(2-ethylhexyl) hydrogen phosphate, bis- (2-ethylhexyl) hydrogen dithiophosphate, or bis(3- propylphenyl) dithiophosphate] still occurred (Muraviev et al., 1998). Better results were obtained with the coating of water-soluble polymer poly(vinyl alcohol) (PVA) precipitate onto SIR (Trochimczuk et al., 2004). The stability of the coating layer can be increased by cross-linking PVA with vinyl sulfone (Trochimczuk et al. 2004), boric acid (Yuan et al., 2010), and glutaraldehyde (Nishihama et al., 2013).

In general, EIMs (SIRs and SILs) can improve the performance of extractants by avoiding drawbacks of LLE, such as poor contact between the organic and aqueous phase, requirement of a large amount of extractant, emulsion formation, and formation of the third phase. The issue with SLEs is the stability of the active layer, which can wash out during operation. Moreover, the extractant layer may also be not uniform throughout the support surface, e.g., capillary forces may accumulate the extractant in narrow pores, a process enhanced in contact with an aqueous solution (Shenxu Bao et al., 2016). In addition, the complex nature of real-life REEs sources such as very acidic solutions can put extra pressure on these adsorbents, which can limit their industrial applications.

The adsorbents obtained through ligand functionalization to the surface of solid support using coupling agents provide an alternative to EIMs. The surface-functionalized adsorbents can be an alternative with better control of ligand distribution on the surface and better ligand and surface bonding and thus better stability, but however, they can be more resource intensive to produce.

Surface-functionalized adsorbents

In this class of adsorbents, the active component or the extractant is chemically immobilized onto the surface of the solid support through chemical bonds. The active component is usually a complexing ligand containing specific functional groups that can selectively bind to the target REE. These adsorbents have been used for solid-phase extraction (SPE) of various elements. Solid-phase extraction (SPE) is similar in the process as the solid-liquid extraction (SLE); however, the extractant or the ligand is chemically immobilized onto the surface in SPE as opposed to physical immobilization in the case of SLEs (Florek et al., 2016; Hidayah & Abidin, 2017; Hu et al., 2018).

A typical ligand functionalized adsorbent involves solid support (e.g., silica, polymer beads, or carbon nano-materials), coupling agent (e.g., silane), ligand containing a specific functional group (i.e., binding unit), and spacer between the coupling agent and the ligand (Pallavicini et al., 2014). Since the ligand is chemically bound to the surface, it is more robust than EIMs, provides better control of surface ligand distribution, and can work under extreme solution conditions. The surface-functionalized adsorbents used for REEs adsorption can be classified based on the type of solid support. Silica-based and carbon-based supports have been the primary focus for solid-phase extraction (SPE) of REEs; however, magnetic nanomaterials, metal-organic frameworks (MOFs), and other composite supports are gaining attention due to their various advantages.

Silica-based supports

Silica-based supports are popular for functionalized adsorbents used in SPE as they fulfill the requirements of good solid support: 1) They can have a large specific surface area (silica gel: usually 100-750 m²/g (Bhatnagar & Sillanpää, 2010), mesoporous silica >1000 m²/g (Meynen et al., 2009)), 2) are robust and reusable, 3) are easy to modify with functional groups, 4) have the possibility of shape control for various uses, and 5) show negligible swelling (Florek et al., 2016; Hu et al., 2018). Limiting factors affecting the use of silica as solid support are its tendency to lose the integrity of its porous structure under strong acidic conditions (El Mourabit et al., 2012; Florek et al., 2016) and its high dissolution rate in alkaline solution (Croissant et al., 2017; Crundwell, 2017).

Silica gel is a commonly used silica-based support. The other type of silica support is nano-porous silica material, further classified as macroporous (pore size >50 nm), mesoporous (pore size 2-50 nm), microporous (pore size < 2 nm), and hierarchically porous materials, which contain multiple levels of above porosities (Sun et al., 2016; Wan & Zhao, 2007). Mesoporous silica nanoparticles are gaining widespread attention in various fields due to uniform and tunable pore size, presence of internal and external pores, controlled morphology, and easy functionalization (Hu et al., 2018; Mehmood et al., 2017; Narayan et al., 2018).

Silica gel

Silica gel is the porous amorphous form of silicon dioxide (SiO₂), composed of interconnected networks of microscopic pores. It can have a pore size of 2-25 nm. The surface silanol groups present in silica gel are used for attaching organofunctional alkoxysilane through the silanization process. The organofunctional alkoxysilane is used for attaching functional groups in a process known as grafting. The most commonly used silane are amino-propyl alkoxy silanes (3-aminopropyl triethoxysilane (APTES) and 3-aminopropyl trimethoxysilane (APTMS)) as they allow easy attachment of amino-poly(carboxylic acid) and other functional groups (Noack et al., 2016; Ramasamy, Khan, et al., 2017). Both the silica gel and silica gel with attached organo-silanes (e.g., 3-aminopropyl silica gel) are available commercially under various brands and have been functionalized further for adsorption of REEs (Asadollahzadeh et al., 2020; Callura et al., 2018; Noack et al., 2016; Ogata et al., 2014, 2015a; Ramasamy, Khan, et al., 2017; Ramasamy, Puhakka, et al., 2017).

Instead of surface modification of already prepared silica gel or 3-aminopropyl silica gel, co-condensation of tetra-alkoxy silane Si(OR)₄ (generally, R = Me or Et) with silane coupling agent (RO)₃Si(CH₂)₃X (where R = Me or Et, X = complexing ligand group) have been used to obtain the required adsorbent (El-Nahhal & El-Ashgar, 2007).

Functional ligands grafted on the silica gel for REEs adsorption are 4-acylpyrazolone Schiff base (Amarasekara et al., 2009), diglycolamic acid (Ogata et al., 2014, 2015a, 2015b, 2016), 1-(-2-pyridylazo) naphthol (PAN) (Ramasamy, Puhakka, Repo, et al., 2018; Ramasamy, Repo, et al., 2017), acetylacetone (Ramasamy, Repo, et al., 2017), phosphonoacetic acid (PAA), N, N-bis(phosphonomethyl) glycine (BPG), diethylenetriaminepentaacetic dianhydride (DTPADA) (Callura et al., 2018; Noack et al., 2016), diethylenetriaminepentaacetic acid (DTPA) (Noack et al., 2016), diglycolamide (Zhe Liu et al., 2019) N-Benzoyl-N-phenylhydroxylamine (BPHA) (Artiushenko, Ávila, et al., 2020), amino-di(methylene-phosphonic) acid (Artiushenko, Kostenko, et al., 2020), N, N-dioctyldiglycolic acid (DODGA) (Li et al., 2020), polyhexamethylene guanidine and Arsenazo I or Arsenazo III (Losev et al., 2020), and bis(ethylhexyl)amido diethylenetriaminepentaacetic acid (Hovey et al., 2021).

The diglycolamic Acid -functionalized silica gel showed selectivity for HREEs with the highest adsorption capacity of 0.148 mmol/g (or 24.4 mg/g) for Ho(III) (Ogata et al., 2015a). Another adsorbent PAN-functionalized silica gel showed capacities of 82.72, 75.5, and 62.92 mg/g for La(III), Sc(III), and Y(III), respectively (Ramasamy, Puhakka, Repo, et al., 2018; Ramasamy, Repo, et al., 2017). The BPHA functionalized SiO₂ with adsorption capacities (q_m) of 6.7 and 8.3 mg/g for Eu(III) and Tb(III), respectively, was selective for HREEs with K_d values of 3500 ml/g for Lu(III) and Yb(III) each (legend 21, Figure 2) (Artiushenko, Ávila, et al., 2020).

Ordered mesoporous silicas

Ordered mesoporous materials have pore sizes of 2-50 nm with ordered arrangements of pores. Common ordered mesoporous silica materials are available as groups, defined as MCM (Mobil Composition of Matter) (e.g., MCM-41 (2d hexagonal, p6m), MCM-48 (cubic Ia3d), MCM-50 (lamellar)) (Beck et al., 1992; Florek et al., 2016; D. Kumar et al., 2001), SBA (Santa Barbara Amorphous), KIT (Korean Advanced Institute of Science and Technology), and COK (Centre for Research Chemistry and Catalysis). Within each mentioned group, there are different types of OMS with different pore symmetry, pore sizes, and pore volume (Beck et al., 1992; Florek et al., 2016; Hu et al., 2018; Huo et al., 1996; Trewyn et al., 2007).

Similar to surface functionalization of silica gel, the silica mesoporous can be functionalized through the reaction of organo-silanes with surface silanol group (grafting) or by co-condensation with tetra-alkoxy silane $\text{Si}(\text{OR})_4$ (generally, $\text{R} = \text{Me}$ or Et) and tri-alkoxyorganosilanes $(\text{R}'\text{O})_3\text{SiRX}$ ($\text{X} = \text{ligand}$) in the presence of a surfactant template (one-pot synthesis) (Florek et al., 2016; Hoffmann et al., 2006; Hu et al., 2018).

The abundance of silanol groups on the surface of silica (1-2 Si-OH per nm^2 on average (Ide et al., 2013)) allows for facile and efficient functionalization through grafting. The limitation of grafting manifests in the case of small pore size or narrow entrance of support and/or with a bulky size of the functional group. In such cases, the entrance may have a higher number of functional groups, or some smaller pores may lack functional groups due to pore blocking, resulting in an overall non-homogenous distribution (Hoffmann et al., 2006). The limitation of pore-blocking is not faced in co-condensation synthesis, and organic units are more homogeneously distributed than the grafting process (Hoffmann et al., 2006). However, in co-condensation, the concentration of ligands in the pore-wall tends to be lesser than the starting $(\text{R}'\text{O})_3\text{SiRX}$ in the reaction mixture. Additionally, the degree of mesoscopic order of the OMS decreases in co-condensation with increasing concentration of $(\text{R}'\text{O})_3\text{SiRX}$ in the reaction mixture, which leads to disordered products (Hoffmann et al., 2006). The increasing concentration of $(\text{R}'\text{O})_3\text{SiRX}$ in the reaction mix favors homocondensation over co-condensation, thus reducing the homogeneity and mesoscopic order of the OMS. Another challenge with one-pot syntheses of OMS is removing the surfactant template after co-condensation without destroying the surface ligands (Hoffmann et al., 2006).

Mesoporous KIT-6 has been functionalized with ethylenediaminetetraacetic acid (EDTA) (Ravi, Zhang, et al., 2018), phenylenedioxy diamide (PDDA) (Hu et al., 2019), bidentate phthaloyl diamide (PA) (Hu et al., 2017), diglycolamide-based (Florek et al., 2014, 2015, 2020), furan-2,4-diamido-propyltriethoxysilane (Florek et al., 2015, 2020), and 3,6-dioxaoctanedioic acid (Florek et al., 2015, 2020) for REEs adsorption. Similarly, MCM-41 has been functionalized with titanium(IV) alkylphosphate (Wenzhong Zhang, Avdibegović, et al., 2017), diglycolylamide (Juère et al., 2016), and iminodiacetamide (Fryxell et al., 2011) and SBA15 has been functionalized with diglycolamide (DGA) (Juère et al., 2016), benzene-1,3,5-triamido-tetraphosphonic acid (BTATPA) (Ravi, Lee, et al., 2018), phosphoric acid (Zheng et al., 2020), and 1,4-phthaloyl diamido-propyltriethoxysilane (Ryu et al., 2021) for REEs adsorption. In case of unmodified SBA-15 and KIT-6, uptake of Sc(III) (KIT-6: $q_m = 1.0 \text{ mg/g}$ (legend 36, Figure 2), SBA-15: $q_m = 1.1 \text{ mg/g}$ (legend 34, Figure 2)) was achieved through adsorption to accessible surface silanols (Giret et al., 2018).

Diglycolylamide (DGA) was used as a common ligand for three different OMS solid supports, SBA-15, MCM-41, and SBA-16, to investigate the effect of silica support pore network structure (2D vs. 3D), pore shape (cylindrical vs. cage-like), and pore size on the adsorption of REE from synthetic samples of REEs and REEs with Al, Fe, Th and U ions (shown as legend 9-13, Figure 2) (Juère et al., 2016). The 2D hexagonal structure (SBA-15) has the advantage over the 3D cage-like structure of SBA-16 since the cage-like pore structure and narrow connectivity made SBA-16 more prone to pore blocking. The pore size of SBA-15 was tuned by varying aging temperatures during synthesis. The highest capacity of extraction was observed for SBA-15(80)-DGA (pore size, 5.2 nm), which was attributed to the presence of certain confinement of the targeted ions by SBA-15 material with a smaller pore (5-8 nm) (Juère et al., 2016). Functionalization of DGA onto MCM-41 (3.2 nm, 2D pore) resulted in the obstruction of the entrance of pore during grafting due to smaller pore size hence had lower extraction capacity (Juère et al., 2016).

The ligand immobilization on the surface of solid support can lead to reduced flexibility, which results in a more stable bite angle (angle formed by chelate ligands) and yields enhanced selectivity towards particular REE cations (Hu et al., 2018). The ligand DGA was functionalized onto KIT-6 by anchoring on both ends (KIT-6-N-DGA-1) or single-end (KIT-6-N-DGA-2) (Florek et al., 2014). KIT-6-N-DGA-1 had a higher extraction capacity for REEs (especially MREEs) than KIT-6-N-DGA-2 (ligand 1-4, Figure 2). The higher extraction capacity of KIT-6-N-DGA-1 was attributed to increased rigidity in the DGA ligand anchored on the surface at both ends, which increased the size-specific cavity (Hu et al., 2018). The presence of competitive ions did not affect K_d values (ligand 3-4, Figure 2). The separation factor between Eu (III) and Th(IV) was 6.3, and between Eu(III) and U(IV) was 3.4 for KIT-6-N-DGA-1 (Florek et al., 2014).

The effect of different bite angles of ligands on the selectivity of REEs was studied using DGA, 3,6-dioxaoctanediamidopropyl (DOODA), and furan-2,4-diamidopropyl (FDGA) functionalized KIT-6 (Florek et al., 2015, 2020). The DOODA ligand has a smaller bite angle than DGA (Figure 3); hence showed a preference for smaller Ln(III) (Ho-Lu, legend 4-5, Figure 2) (Florek et al., 2015; Hu et al., 2018). Hu et al. (2017a) grafted phthaloyl diamide (PA) bearing different bite angles onto KIT-6 by varying the position (ortho, meta, and para) of the amide groups. The KIT-6-1,2-PA (ortho-position) with a smaller bite angle showed higher affinity for heavy Ln(III), which have smaller ionic radii (legend 14, Figure 2), whereas the KIT-6-1,3-PA showed selectivity for middle-size Ln(III) due to its larger bite angle (legend 15, Figure 2). KIT-6-1,4-PA did not show selectivity for a particular lanthanide (legend 16, Figure 2) due to the absence of any synergist action of the moieties (Hu et al., 2017, 2018). In another study, the bite angle of phenylenedioxy diamide (PDDA) functionalized modified KIT-6 was varied by using PDDA with amide at different positions (Hu et al., 2019). Results analogous to KIT-6-PA systems were obtained as adsorbent KIT-6-1,2-PDDA having the smallest bite angle (Figure 3) showed high affinity for heavy lanthanides (Tm(III), Yb(III), and Lu(III)) with smallest ionic radii (legend 22, Figure 2), adsorbent KIT-6-1,3-PDDA with larger bite angle showed higher selectivity for light lanthanides (La(III), Ce(III), and Pr(III)) with larger ionic radii (legend 23, Figure 2). KIT-6-1,4 PDDA did not show selectivity (legend 24, Figure 2) and behaved similarly to KIT-6-1,4-PA.

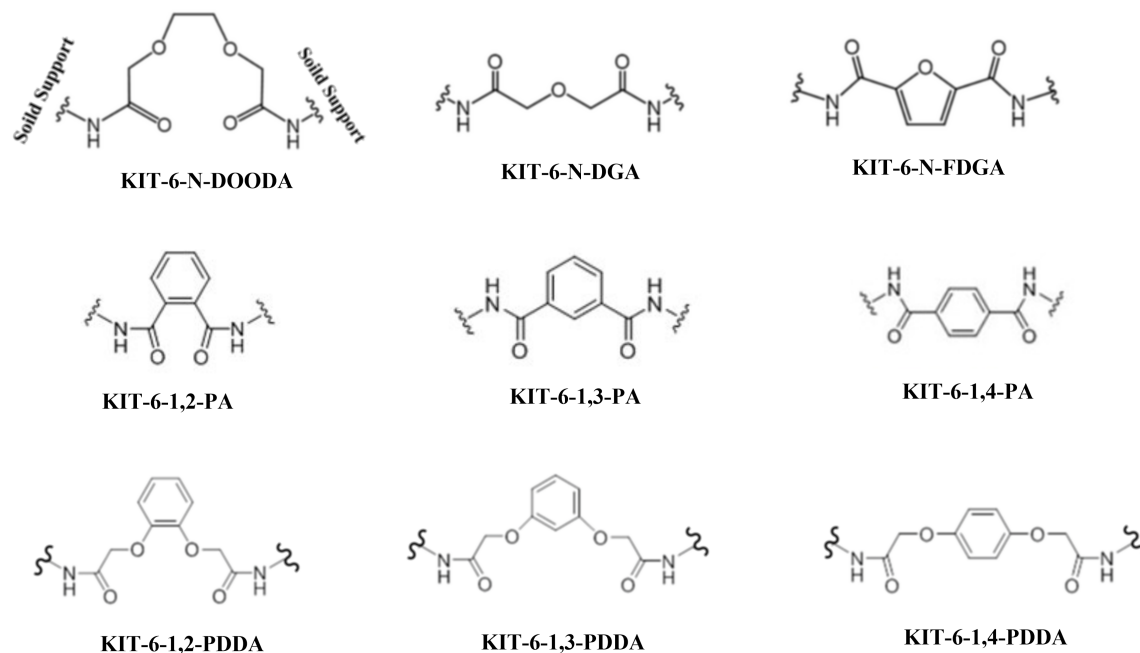


Figure 3: Different bite angles of the ligands grafted onto KIT-6 (modified after (Florek et al., 2015; Hu et al., 2017, 2019)). DOODA: 3,6-dioxaoctanediamidopropyl, DGA: diglycolylamide FDGA: furan-2,4-

diamidopropyl (Florek et al., 2015, 2020), PA: phthaloyl diamide (Hu et al., 2017, 2018) PDDA: phenylene-dioxy diamide (Hu et al., 2019).

In other examples of functionalized ordered mesoporous silica used for REEs uptake, Dy(III) was selectively adsorbed from a solution of Cu(II), Dy(III), Fe(III), Nd(III), and Zn(II) using amino and carboxylic functionalized mesoporous silica having different pore sizes (3, 5, 12, and 22 nm) (Kaneko et al., 2018) and using amino, carboxylic, and diglycolic anhydride functionalized mesoporous silica with a sheet and spherical morphologies as well as non-porous stöber silica (Kaneko et al., 2019). Zhang and their colleagues (Zhang, Avdibegović, et al., 2017) used titanium(IV) alkylphosphate grafted MCM41 for adsorption in the binary equimolar solutions of Sc-La and Nd-Dy. Ravi et al. (2018) functionalized KIT-6 and KCC-1 with EDTA and employed them for Nd(III) adsorption from single-element solution (Ravi, Zhang, et al., 2018). The same team, in a different study, used benzene-1,3,5-triamido-tetraphosphonic acid (BTATPA) modified SBA-15 for adsorption of Nd(III), Y(III), La(III), and Ce(III) from single element solution and reported K_d (ml/g) values of $\sim 10^4$, $\sim 10^4$, $\sim 1.5 \times 10^5$, and $\sim 1.04 \times 10^5$ respectively (Ravi, Lee, et al., 2018). In other studies, SBA-15 functionalized with phosphorus acid achieved a maximum Gd(II) adsorption capacity of 204.4 mg/g (Gao et al., 2017), and sulfhydryl MCM-41 (SH-MCM-41) showed maximum adsorption capacities of 560.56, 467.60, and 540.68 mg/g for La(III), Gd(III), and Yb(III), respectively (Li et al., 2019).

Mesoporous silica foam (MSF) and fibrous nano-silica KCC-1 were grafted with poly(amidoamine) dendrimers (PAMAM) using 3-aminopropyltriethoxysilane (APTES) and glutaraldehyde (GTA) as a cross-linking spacer (Lee et al., 2019). The adsorption capacity of MSF based adsorbent PAMAM@GTA-NH₂-MSF was higher than KCC-1 based adsorbent PAMAM@GTA-NH₂-KCC-1 with values of 86, 104, 110, and 132 mg/g for La(III), Ce(III), Nd(III), and Gd(III) respectively for MSF based adsorbent. Both adsorbents showed selectivity for Gd(III) from a solution containing Na(I), Ca(II), Mg(II), Al(III), and Fe(III) with the recovery of 75.8% with PAMAM@GTA-NH₂-MSF and 67.2% with PAMAM@GTA-NH₂-KCC-1. The recovery of Gd(III) increased to 86% with further functionalization of PAMAM@GTA-NH₂-MSF with N-(phosphonomethyl) iminodiacetic (PMIDA) (Lee et al., 2019). N-methyl-N-phenyl-1,10-phenanthroline-2-carboxamide (MePhPTA) functionalized mesoporous silica adsorbed Eu(III) and Sm(III) with maximum adsorption capacities of 125.63 and 124.38 mg/g, respectively at pH 4 (Awual et al., 2013). Ordered mesoporous silica functionalized with 4-tert-Octyl-4-((phenyl)diazanyl)phenol (TOPP) reached maximum Yb(III) adsorption of 139.19 mg/g at pH 5 and was selective against Na(I), K(I), Ca(II), Mg(II), Zn(II), and Al(III) (Rahman et al., 2020). Hollow mesoporous silica nanosphere (HMSNs) functionalized with amino-phosphonic acid had an adsorption capacity of 387.3 mg/g for Gd(III) at pH 5 (Yin et al., 2020).

Carbon-based supports

Carbon-based adsorbents and supports have various forms, such as mesoporous carbon, activated carbon, graphene oxide, and carbon nanotubes. Carbon-based support can be an alternative to silica supports to overcome the low stability of silica-based support in acidic conditions (Hu et al., 2018). However, the surface functionalization of carbon-based supports can be more challenging than silica-based supports (Hu et al., 2018).

Ordered mesoporous carbons

Ordered mesoporous carbons (OMCs) can work as better solid support under acidic conditions because of higher chemical resistance than mesoporous silica while possessing comparable porosity and surface area (Hu et al., 2018). However, the synthesis and functionalization of OMCs are more challenging than OMS. Ordered mesoporous carbon synthesis can be done by hard or soft template methods.

In the hard template method, an ordered mesoporous solid (mostly ordered mesoporous silica) is used as a mold, and its pores are impregnated with a selected carbon precursor (e.g., Sucrose), which is then polymerized and carbonized (Eftekhari & Fan, 2017). In the end, the template is dissolved and removed

using strong acid (e.g., HF) or base (e.g., NaOH) (Chuenchom et al., 2012). The porosity and structure of OMC can be tuned by selecting an appropriate hard template.

On the other hand, in the soft template method, OMC is directly synthesized by self-assembling a block of copolymer surfactant and a carbon precursor. In this method, the template is removed by a thermal process. The pH, temperature, and gel composition can be varied to control the porosity and morphology of the mesoporous carbon (Ma et al., 2013). In comparison with the hard template method, OMCs synthesized through soft templates have a continuous framework with thick pore walls, hence have more stability against thermal and oxidation treatment during functionalization (Eftekhari & Fan, 2017).

In adsorption studies involving OMCs, Parsons-Moss et al. (2014) investigated Eu(III) adsorption using a carbon-silica nanocomposite (C-CS) type OMC functionalized with -COOH and reported adsorption capacity (q_m) of 138 mg/g at pH 4.0. Perreault et al. (2017) functionalized CMK-8, a 3D cubic ordered mesoporous carbon, with different DGA-based ligands. Among these CMK-8 based adsorbents, the K_d value for different Ln(III) in the presence of Al(III) and Fe(III) were highest for diglycolylester grafted CMK-8 (CMK-8-DGO) followed by oxidized CMK-8 (CMK-8-O) and chloropropyl diglycolylamide grafted CMK-8 (CMK-8-PGA) (legend 6-8, Figure 2). Bertelsen et al. (2019) modified two OMC materials, MC-*l*-MSN, and CMK-3 type OMC, with bis-(2-ethylhexyl) phosphoric acid (HDEHP) and investigated batch adsorption of Eu(III) as well as column separation of Nd(III) and Eu(III) using HDEHP-OMC-*l*-MSN. The HDEHP-OMC showed q_m of 0.35 mmol (or 53.2 mg) Eu(III)/g. Mesoporous carbon was functionalized with a single stranded oligo consisting of 100 thymine units, and it achieved adsorption of 9.57, 38.27, and 52.15 mg/g, for Lu(III), Dy(III), and La(III), respectively. The adsorbed amounts of REEs increased with an increase in the metallic radius from Lu to La (Gismondi et al., 2022; Unsworth et al., 2020).

Activated carbon /Graphene oxide /Carbon nanotube

Activated carbon. Activated carbon (AC) is an environmentally friendly and low-cost adsorbent with a high surface area but has little affinity for REE(III) in native form; thus, functionalization with ligands that have affinity for REEs is required for its application in REEs adsorption (Asadollahzadeh et al., 2020). The ligands used for AC functionalization are Schiff's base derived from 3 diethylenetriamine and 3,4-dihydroxybenzaldehyde (AC-DETADHBA) (Marwani et al., 2017), Carboxylic acid (Kilian et al., 2017; Marwani et al., 2017), and EDTA (Babu et al., 2018). The EDTA functionalization of AC (AC-EDTA) increased adsorption capacity to 71.4 Nd(III) mg/g from 19.1 Nd(III) mg/g at pH 5 (Babu et al., 2018). The adsorbent AC-EDTA showed higher selectivity towards HREEs. Carboxyl functionalized AC (AC-COOH) showed an adsorption capacity of 89.50 mg/g for La(III) at pH 6.0, whereas AC-DETADHBA showed a higher adsorption capacity of 144.80 mg/g for La(III) at the same pH (Marwani et al., 2017). In a different study, AC-COOH showed very low adsorption of 2.1 mg/g for Sc(III) at pH 2.0 (Kilian et al., 2017), suggesting that the pH plays a vital role in AC-COOH adsorbents, likely due to the weakly acidic nature of -COOH group.

Graphene oxide. Graphene oxide (GO) contains hydroxyl, epoxide, carbonyl, and carboxyl groups, essential sites for functionalization with ligands. Moreover, due to the presence of these groups, GO can adsorb REEs without functionalization. A colloidal graphene oxide suspension had Gd(III) adsorption capacity of 286.86 mg/g at pH 5.9 (Chen et al., 2014). Graphene oxide nanosheets (GONS) obtained maximum adsorption of 175.44 mg/g for Eu(III) at pH 6 (Sun et al., 2012). The maximum Eu(III) adsorption decreased slightly to 167.16 mg/g at pH 2 (Sun et al., 2012). In another study with GO nanosheet, the maximum adsorption capacities were in the order of Gd(III)>Nd(III)>Y(III)>La(III) with values 225.5, 188.6, 135.7, and 85.7 mg/g at pH 6, respectively (Ashour et al., 2017). Unmodified Graphene oxide showed an adsorption capacity of 39.7 mg/g for Sc(III) at pH 4, which was better than -COOH functionalized AC and chelating resin Chelex 100 (contains iminodiacetic acid) but lower than -COOH modified MWCNT (Kilian et al., 2017). Higher adsorption of 89.7 mg/g and 70.2 mg/g for Eu(III) using GO and magnetic GO (by modifying with Fe₃O₄) was achieved at pH 7 (Li et al., 2015).

GO was used to produce amine-functionalized mesoporous graphene (AMG) followed by functionalization

with carbamoyl phosphine oxide moiety (CMPO, triethylphosphonoacetate) and it reached an adsorption capacity of 26.9 mg/g for La(III) (Kim et al., 2019). Fe_3O_4 and MnO_2 modified GO nanocomposites, $\text{Fe}_3\text{O}_4/\text{MnO}_2/\text{rGO}$ (FMG), provided high maximum adsorption capacities of 1016 and 981 mg/g for La(III) and Ce(III), respectively, at pH 7 (Liu et al., 2020) and is among the adsorbents with the highest capacity for REE(III) (Table 1). Another adsorbent, polyaniline functionalized GO, achieved 250.74 mg/g Eu(III) adsorption (Sun et al., 2013). Polyurethane sponge was used as a support polymer for titanium phosphate with graphene oxide (GO@TiP-Sponge) and showed a maximum capacity of 576.17 mg/g for Dy(III) (Peng et al., 2020). In comparison, GO@TiP had a maximum Dy(III) adsorption capacity of 316.75 mg/g (Peng et al., 2020). GO- tris(4-aminophenyl)amine composite had a Langmuir adsorption capacity of 46.35 mg/g for Yb(III) at pH 6 (Zhao et al., 2021). Another GO-based adsorbent, graphene oxide/poly (N-isopropyl acrylamide-maleic acid) [GO/P(NIPAM-MA)] cryogel, adsorb La(III) with equilibrium adsorption capacity of 33.1 mg/g at pH 5 with separation factors of 2.86, 7.57, 8.00, 6.69, and 1.45 for La over Cu, Co, Ni, Nd, and Yb, respectively (Yang et al., 2020). GO functionalized with 3-[2-(2-aminoethylamino) ethylamino] propyl-trimethoxysilane (GO-APTS) showed adsorption capacities of 110.0, 93.4, 103.2, 83.7, 97.2, 48.3, and 92.8 mg/g for Ho(III), Er(III), Eu(III), Lu(III), Tm(III), Y(III), and Yb(III), respectively (Bao et al., 2022). The adsorbent was selective for Ho(III) over alkali or alkaline-earth metal ions with SFs of above 600. A further modified adsorbent combining GO-ATPS with Fe_3O_4 resulted in lower capacities of 72.1, 67.1, 65.2, 65.0, 73.2, 36.3, and 68.7 mg/g for Ho(III), Er(III), Eu(III), Lu(III), Tm(III), Y(III), and Yb(III), respectively, due to lower APTS fraction in the composite (Bao et al., 2022).

Carbon nanotubes. Carbon nanotubes (CNTs) are tubes of graphite sheets and can be divided into two types: Single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) with a set of concentric nanotubes. The examples of CNTs based adsorbent studied for REEs separation include oxidized MWCNTs (Alguacil et al., 2020; Behdani et al., 2013; Fan et al., 2009; Koochaki-Mohammadpour et al., 2014; K. Li et al., 2015), CNT modified with -COOH (Kilian et al., 2017), MWCNT modified with tannic acid (Tong et al., 2011), and MWCNT/ Fe_3O_4 composites (Chen et al., 2009; Fan et al., 2009). The CNT modified with -COOH showed higher adsorption (37.9 mg/g) for Sc(III) than AC-COOH (2.1 mg/g) at pH 2.0 (Kilian et al., 2017). The adsorption of Sc(III) onto CNT-COOH increased to 42.5 mg/g at pH of 4.0. Oxidized MWCNTs showed good adsorption (80-100%) for target REE(III) in the presence of competitive ions, and the adsorption increases with pH since at higher pH, the surface is negatively charged, leading to higher sorption of positively charged REE(III) cations (Cardoso et al., 2019). A CNTs/GO hybrid hydrosols had Gd(III) adsorption capacity of 534.76 mg/g at pH 5.9 (Lanyu Guo et al., 2018). CNT modified with furfuryl amine and further functionalized with poly(acrylic acid) reached a maximum equilibrium Eu(III) adsorption capacity of 130.8 mg/g as opposed to 46.67 mg/g for pristine CNT at pH 7 (Linru Guo et al., 2020).

Other supports/adsorbents

Magnetic nanomaterials

Researchers have explored adsorbents obtained after coating Fe_3O_4 nanoparticles with SiO_2 or TiO_2 shell and then the functionalization of the surface of the coated layer. The advantage of magnetic nano-adsorbent is the convenient collection/separation of adsorbents by using magnets after adsorption, avoiding the issue involved with the isolation of nanoparticles, which tends to form stable sols in batch reactors. The coating with SiO_2 or TiO_2 provides higher surface -OH density, which results in higher surface ligand density and easier functionalization. The coating also protects the Fe_3O_4 nanoparticle from oxidation.

Polido Legaria et al. (2017) used EDTA, DTPA, and triethylenetetraminehexaacetic acid (TTHA) functionalized SiO_2 nano-adsorbents, both magnetic and nonmagnetic, and reported uptake up to 300 mg REE(III)/g. REE uptake order was Dy(III) > Nd(III) > La(III) for EDTA-functionalized, Nd(III) > La(III) > Dy(III) for DTPA-functionalized, and La(III) > Nd(III) > Dy(III) for TTHA-functionalized adsorbent. Kostenko et al. (2019) synthesized Fe_3O_4 magnetic nanoparticles (MNPs) with and without a coating of silica and functionalized them with aminomethylenephosphonic (MNPs/ SiO_2 -AMPA and MNPs/AMPA). The adsorption

capacities for Eu(III) were 69 and 77 mg/g for MNPs/SiO₂-AMPA and MNPs/AMPA at pH 7.0, respectively. Magnetic Fe₂O₃ coated with silica and functionalized with APTMS, (γ -Fe₂O₃-NH₄OH@SiO₂(APTMS)) achieved maximum Dy(III) adsorption of 23.3 mg at pH 7 (Kegl et al., 2019). Magnetic nanoparticle functionalized with poly(aminoethylene N-methyl 1-formic acid, 1-phosphonic acid) (PAEMFP) reached 25 mg/g Nd(III) adsorption capacity at PH 6 (Miraoui et al., 2016). Other research involving coated magnetic nano-adsorbents for REEs adsorption include silica-coated magnetic particle grafted with 2-ethylhexyl phosphonic acid mono-2-ethylhexyl (P507) using 3-chloropropyltryethosylsilane as silane-coupling agent (Wu et al., 2013) and magnetic Fe₃O₄ coated with SiO₂ and TiO₂ and modified with N-[(3-trimethoxysilyl) propyl] EDTA (TMS-EDTA) (Dupont et al., 2014).

Some studies have directly functionalized the magnetic nano-particles (Chen et al., 2012; Gaete et al., 2021; Ngomsik et al., 2012; Yang et al., 2012). Citric acid-functionalized maghemite nanoparticles had q_m of 74.4 mg/g and 71 mg/g for Eu(III) and La(III), respectively (Ngomsik et al., 2012). Magnetic nano-particles Fe₃O₄ with humic acid coating (Fe₃O₄@ HA MNPs) synthesized through chemical coprecipitation was able to remove 99% of Eu(III) at pH 8.5 (Yang et al., 2012). In another study, bentonite was used as a support to prepare di (2-thylhexyl) phosphoric acid-immobilized magnetic GMZ bentonite and was used to adsorb Eu(III) (capacity of 48.02 mg/g at pH 3.05) (Chen et al., 2012). Another adsorbent, phosphonic acid-functionalized magnetite nanoparticle (PA-MNP), showed a capacity of 18.4, 17.6, and 23.9 mg/g for La(III), Pr(III), and Sm(III), respectively at pH 4 (Gaete et al., 2021).

Metal-organic frameworks

Metal-organic frameworks (MOFs) have ordered crystalline porous structures composed of a three-dimensional network of metal or metal oxide clusters held together by multidentate organic ligands (i.e., linker), e.g., aromatic polycarboxylates. MOFs have received considerable attention as support for grafting various REEs selective ligands. The desirability of MOFs as support lies in their high surface area, high porosity, adjustable pore size, and tunable surface functionality (Baumann et al., 2019).

The MOF, HKUST-1, showed an adsorption capacity of 353 mg/g for Ce(III) at pH 6 (Zhao et al., 2019). MOF ZIF-8 showed higher adsorption capacity (385 mg/g) for La(III) than another MOF ZIF-90 ($q_m = 168$ mg/g for La(III)) that had a different linker (Jiang et al., 2016). MOF Zeolitic imidazolate frameworks-8 nanoparticle (ZIF-8 NP) has adsorption capacities of 28.8 mg/g, 281.1 mg/g, and 430.4 mg/g for La(III), Sm(III), and Dy(III), respectively at pH 7 (Abdel-Magied et al., 2019). MOF ZIF-8 functionalized with -COOH showed an adsorption capacity of 175 mg/g for Nd(III), significantly higher than unfunctionalized ZIF-8 (57 mg Nd(III)/g) (Ahmed et al., 2021). Another MOFs UiO-66-(COOH)₂ functionalized with polyacrylonitrile had maximum adsorption capacities of 214.1 mg/g and 191.9 mg/g for Tb(III) and Eu(III), respectively at pH 6 (Hua et al., 2019). Similar MOF UiO-66 dual functionalized with -COOH and -NH₂ obtained equilibrium adsorption capacity of 79 mg/g for Gd(III), significantly higher than pristine UiO-66 with 16 mg Gd(III)/g (Ahmed, Lee, et al., 2019). A MOF, ZnGA, synthesized by the reaction of zinc acetate and glutaric and then functionalized with polymer-based on p-chlorocresol and piperazine had Y(III) adsorption capacity of 377.02 mg/g at pH 6 (Mahmoud et al., 2019).

In several different studies, MIL-101 was functionalized with different functional groups and used for REEs adsorption (de Decker et al., 2016; Kavun et al., 2021; Y.-R. Lee et al., 2018; Lou et al., 2019; Ryu et al., 2021). Among MIL-101 functionalized with -NH₂, ethylenediamine (ED), diethylenetriamine (DETA), and N-(phosphonomethyl)iminodiacetic acid (PMIDA), the REE adsorption capacity increased in the order of MIL-101 < MIL-101-NH₂ < MIL-101-ED < MIL-101-DETA < MIL-101-PMIDA with the highest being 90.0 mg Gd(III)/g onto MIL-101-PMIDA at pH 4.5 (Lee et al., 2018). Acrylic acid-functionalized MIL-101 had adsorption capacities of 90.21, 104.59, 58.29, and 74.94 mg/g for Sc(III), Nd(III), Gd(III), and Er(III), respectively, at pH 5.5, and was selective for Sc(III) in the presence of other REEs and competitive cations (Lou et al., 2019). In a different study involving MIL-101 functionalization with tributyl phosphate (TBP), HDEHP, and bis(2,4,4-trimethylpentyl) phosphinic acid (Cyanex 272), the adsorption capacity increased in the order of MIL-101-TBP < MIL-101-Cyanex 272 < MIL-HDEHP with a maximum adsorption capacity

of 57.47 mg/g at pH 5.5 for HDEHP functionalized adsorbent (Kavun et al., 2021). The MIL-101-HDEHP showed selectivity factors of 22.8 and 7.7 for Er(III) over Nd(III) and Gd(III) in Er(III)-Nd(III)-Gd(III) mix solution with all three adsorbent showing high selectivity (>90%) for Er(III) over Co(II), Ni(II), Cu(II), and Zn(II).

Metal-based supports

A metal-based support Mesoporous Zirconium Titanate (ZrTi-0.33) was functionalized with methylphosphonic acid (MeP), amino trismethylenephosphonic acid (ATMP), phosphono-imido-dicarboxylic acid (PIDC), 4-amino,1-hydroxy,1,1-bis-phosphonic acid butane (HABDP), and 1-hydroxyethylene-1,1-bis-phosphonic acid (HEDP) bis-phosphonic acids, 1,4-diphosphonic acid butane (BuDP) and 1,4-diphosphonic acid benzene(BenDP) and used for $^{153}\text{Gd(III)}$ adsorption (Griffith et al., 2010). ATMP based adsorbent achieved the highest K_d (>10000 in 10^{-3} M and 10^{-5} M HNO_3).

Similar support, mesoporous TiO_2 particle, was functionalized with dimethylphosphato-ethyltriethoxysilane and reached Ce(III) adsorption capacity of 92.6 mg/g while completely separating Ce(III) from Sr(II) and Cs(I) (Moloney et al., 2014). Mg-Fe hydrotalcite modified with Cyanex 272 (bis (2,4,4-trimethylpentyl) phosphinic acid) showed separation factor (SF) >6.3 for La(III)/Nd(III) (Gasser & Aly, 2013) and >3.6 for Ce(III)/Eu(III) (Gasser et al., 2017).

Composite supports

A composite support of nano-silica (12 nm particle size) and AC (0.8 mm pellets) was modified with 1-(2-Pyridylazo) 2-naphthol (PAN) (Ramasamy, Puhakka, Repo, Ben Hammouda, et al., 2018). The adsorbent obtained adsorption capacities of 103.5, 112.7, and 84.1 mg/g for La(III), Sc(III), and Y(III), respectively. Another composite support consisting of nano-silica grafted carbon nanotubes (both SWCNT and MWCNT) functionalized with 1-(2-pyridylazo)-2-naphthol (PAN) were selective for Sc(III) in mixed REE solution (Ramasamy et al., 2019). However, the adsorption capacities for Sc(III) were lower than La(III) and Y(III) in mono-element solution with adsorption capacities of 12.68, 80.68, and 48.34 mg/g for Sc(III), La(III), and Y(III), respectively, in the SWCNT and 103.2, 32.92, and 68.78 mg/g, respectively with the MWCNT (Ramasamy et al., 2020). MWCNT embedded with Fe_3O_4 nanoparticles were functionalized with carbon disulfide and achieved 23.23 mg/g La(III) adsorption (Huang et al., 2021). A nano porous graphene and zinc-trimesic acid (Zn-BTC) MOF composite showed selectivity for Ce(III) with SFs 12,081.04, 20.05, and 328.80 for Ce(III) over Lu(III), La(III), and Pr (III), respectively (Wu et al., 2021). The SFs between adjacent lanthanide Nd/Pr, Sm/Eu, Gd/Tb, and Tb/Dy reached 9.80, 3.11, 2.20, and 1.68. The maximum capacity of the adsorbent was about 300 mg REEs/g. Another composite consisting of nano porous graphene oxide and zinc- terephthalic acid (Zn-BDC) MOF reached a maximum capacity of 344.48 mg REEs/g with high SFs for Sc, i.e., Sc/Tm [?] 529.57, Sc/Er [?] 461.91, and Sc/Y [?] 445.70 (Chen et al., 2022). It was also selective for Tm and Er with SFs for Tm/Eu [?] 4.55, Tm/Pr [?] 4.20, Tm/Nd [?] 3.96, and Er/Eu [?] 3.9. A composite obtained via the introduction of a MOF MIL-101 shell over a magnetite (Fe_3O_4) core and functionalized with $-\text{SO}_3$ and diethylenetriamine (DETA) extracted REEs from aqueous and brine solution with efficiency up to 99.99% (Elsaidi et al., 2018).

A silica/polymer (SiO_2 -P) composite support synthesized by immobilizing styrene-divinylbenzene copolymer (SDB) in porous silica (SiO_2) was functionalized with 2,6-bis(5,6,7,8-tetrahydro-5,8,9,9-tetramethyl-5,8-methano-1,2,4-benzotriazin-3-yl)pyridine ($\text{Me}_2\text{-CA-BTP}$) and was used for Ln(III) adsorption. Similar SiO_2 -P supports were functionalized with a mixed trialkyl phosphine oxide (TRPO) (where R_1 , R_2 , and R_3 are different alkyl groups) (Yu et al., 2018) and functionalized with HDEHP for REEs(III) adsorption (Zhang et al., 2019).

An organic-inorganic hybrid hydrogel, polyethylenimine–acrylamide/ SiO_2 , showed selectivity factors of 105-450 for REEs over other metals (Wang et al., 2017). A porous carboxymethyl cellulose hydrogel containing polyacrylic acid had a monolayer adsorption capacity (q_m) of 381.72 mg/g for La(III) at pH 5.58 and 320.47 mg/g for Ce(III) at pH 5.83 (Roosen et al., 2016; Zhu et al., 2016). Chitosan containing acrylic

acid-co-styrene sulfonate/smectite clay hybrid granular hydrogel (CTS-g-(AA-co-SS)/ISC) had adsorption capacities of 232.97 mg/g for Gd(III) and 185.47 mg/g for Ce(III) at pH 5 (WANG et al., 2017). A magnetic $\text{MnFe}_2\text{O}_4@\text{SiO}_2$ -chitosan composite achieved one of the highest adsorption capacities of 1030 mg/g and 1020 mg/g for La(III) and Ce(III), respectively, (Table 1) (Liu et al., 2021).

Similar to chitosan containing hydrogel, many composite supports are based on composites of biological materials with inorganic materials or polymers (Iftekhar, Ramasamy, et al., 2018). REEs adsorption has been studied with silica-chitosan hybrid beads functionalized with EDTA, DTPA (Roosen et al., 2014), PAN, and acetylacetone (Ramasamy, Puhakka, Iftekhar, et al., 2018), Zn/Al Layered double hydroxide (LDH) intercalated cellulose (CL) (Iftekhar et al., 2017b), cellulose-silica nanocomposite (Iftekhar et al., 2017a), and Gum Arabic (GA)-polyacrylamide-silica nanocomposite (Iftekhar, Srivastava, et al., 2018). Among these adsorbents, silica-chitosan-PAN showed the highest adsorption capacities of 199.8, 198.8, and 123.4 mg/g for La(III), Sc(III), and Y(III), respectively, at pH 5. The LDH-CL adsorbent had q_m values of 102.25, 92.51, and 96.25 mg/g for Y(III), La(III), and Ce(III), respectively at pH 7 (Iftekhar et al., 2017b). The cellulose-silica nanocomposite and the GA-polyacrylamide-silica nanocomposite reached q_m of 29.48 mg/g and 7.90 mg/g for La(III), respectively and 23.76 mg/g and 11.05 mg/g for Sc(III), respectively at pH 6 (Iftekhar et al., 2017a; Iftekhar, Srivastava, et al., 2018). The EDTA and PDTA functionalized silica-chitosan had adsorption capacity (q_m) of 0.27 mmol/g (or 38.9 mg/g) for Nd(III) at pH 6 (Roosen et al., 2014), and equilibrium capacity of 6.74 mg/g and 8.99 mg/g for Sc(III) at pH 2.

Molecular/Ion-imprinted polymers

Molecular/ion-imprinted polymers (MIPs/IIPs) are sorbents with specific recognition sites for a desired molecule or ion (Chen et al., 2016; Ensing & De Boer, 1999; Fu et al., 2015; Wackerlig & Schirhagl, 2016). This is achieved by copolymerizing functional monomers and cross-linkers in the presence of the target molecule/ion that acts as a template molecule. Then the template ion/molecule is removed chemically, leaving behind a binding site-specific to the template (Chen et al., 2016; Fu et al., 2015).

The IIPs show high selectivity for the target REEs. Biju, Gladis, and Rao (2003) achieved high selectivity for Dy(III) over Y(III), Nd(III), Lu(III), and La(III) with selectivity factors (SFs) of around 66, 82, 175, and 116, respectively by using Dy(III) ion-imprinted polymer based on 5,7-dichloroquinoline-8-ol and 4-vinyl pyridine. Similarly, Er(III) (Kala et al., 2004, 2005; Rao et al., 2006) and Nd(III) (Guo et al., 2009) ion-imprinted polymers based on 5,7-dichloroquinoline-8-ol and 4-vinyl pyridine were prepared and tested for selectivity over different lanthanides. In all of these investigations, the selectivity of the imprinted ion was significantly increased (Guo et al., 2009; Kala et al., 2004, 2005; Rao et al., 2006). Similarly, several IIPs (Pr(III)-IIP, Nd(III)-IIP, Sm(III)-IIP, Eu(III)-IIP, and Gd(III)-IIPs) were synthesized with maximum sorption capacities of 125.3, 126.5, 127.6, 128.2, and 129.1 mg/g for Pr(III), Nd(III), Sm(III), Eu(III), and Gd(III), respectively (Yusoff et al., 2017). A phosphonic-based La(III)-ion imprinted polymer showed an adsorption capacity of 62.8 mg/g for La(III) and a selectivity factor of 54.57 for La(III) over Cu(II) (Ni et al., 2021).

Dolak et al. (2015) used Nd(III)-IIP to selectively extract Nd(III) in the presence of Ce(III), La(III), and Eu(III). The selectivity coefficient for Nd(III) over Ce(III), La(III), Eu(III) were 234.3, 129.6, and 248.4, respectively; however, the maximum adsorption capacity was only 15.03 mg/g. In different investigations, Gd(III) ion-imprinted polymers bearing N,N'-bisacetamidostyrene diethylenetriaminetriacetic acid (DTPA-bisamide) (Garcia et al., 1998; Vigneau et al., 2001) and N-acetamidostyrene ethylenetriaminetriacetic acid (EDTA-amide) (Vigneau et al., 2001) exhibited at least 3-fold increase in selectivity than analogous non-imprinted polymers. The authors noted that DTPA (nine-coordinate chelating agent) based Gd(III)-IIP showed higher Gd/La selectivity (maximum value of ~8.3) for Gd(III) in a binary solution of Gd(III) and La(III) than EDTA (five-coordinate chelating agent) based Gd(III)-IIP (around 3.0). The same DTPA-based Gd(III)-IIP was used to separate Gd(III) and other lanthanides and actinides (Vigneau et al., 2002). Other studies on imprinted polymer include La(III)-IIP (Mustapa et al., 2016), Ce(III)-IIP (Keçili et al., 2018;

Mustapa et al., 2016), Y(III)-IIPs (Zulfikar et al., 2017), Nd(III)-IIP (Moussa et al., 2017), ionic imprinted mesoporous bilayer films (IIBFs) for Dy(III) and Nd(III) adsorption (Zheng et al., 2018), Gd (III)-imprinted membranes (GIMs) (Cui et al., 2019), and Gd(III)-imprinted divinylbenzene and methacrylic acid copolymer (Bunina et al., 2021). The IIPs show a stronger affinity for the imprinted REE cation compared to other REEs.

Surface ion-imprinted polymers are derivative of IIP technology and include the formation of IIP on a surface. A surface-IIP was prepared for L(III) using MCM-41 as support and APTES as the functional monomer (Qin et al., 2022). The surface-IIP showed an adsorption capacity of 272.2 mg/g. Other examples of surface-IIP are Ce(III)-imprinted polymer with attapulgite support (Pan et al., 2010), Ce(III)-imprinted polymer functionalized potassium tetratitanate whisker (Zhang et al., 2010), Ce(III)-IIP functionalized on SBA-15 (Meng et al., 2014), and Gd(III) imprinted magnetic ordered mesoporous carbon (OMC) (Patra et al., 2017).

The limitation in the application of IIP stems from the large number of inaccessible adsorption sites since these sites are embedded inside the polymer (Canfarotta et al., 2016; Dong et al., 2021; Huang et al., 2019). Considering that IIP preparations are usually a sophisticated and chemically expensive process, presence of inaccessible sites is a big hindrance for widespread industrial application. Additional challenges arise due to low mass transfer rates (Aravind & Mathew, 2018; Dong et al., 2021; H. Xu & Guo, 2012). These limitations can be improved with surface ion-imprinted polymers (Dong et al., 2021), but more research effort is required in this direction.

Elution solutions

Mineral acids

In the adsorption-based separation process, the use of mineral acids for desorption of adsorbed ions and regeneration of the adsorbent is commonplace. However, in the case of REEs chromatographic separation using strongly acidic cation-exchange resin, the use of mineral acids such as HCl, H₂SO₄, HNO₃, and HBr as eluents results in very low separation among REEs (Korkisch et al., 1967; Nelson, 1965). However, these acids can be used to separate REEs from other monovalent and divalent ions using strongly acidic cation resin (Fritz & Garralda, 1963; Page et al., 2019; Strelow, 1960; Strelow et al., 1965). Between various strong mineral acids, the distribution coefficients (K_d) for different REE ions with strongly acidic cation-exchange resin are higher for HCl (Strelow, 1960) than H₂SO₄ and HNO₃ (Strelow et al., 1965) (i.e., in 0.5 M HCl, K_d = 2480, 2460, 1460 in 0.5 N H₂SO₄; K_d = 1860, 1800, 1380 and in 0.5 N HNO₃; K_d = 1870, 1840, 1020 for La(III), Ce(III), and Y(III), respectively).

In the case of weakly acidic cation-exchange resins, strong mineral acids can be used for desorption. At very low pH, the excess of hydrogen ions results in the desorption of REE ions from the resin surface through ion-exchange. Thus, strong mineral acids are used for the regeneration of resin in many cases. For example, HCl was used with various carboxyl based weakly acidic cation-exchanger D152 (0.5 M HCl) (Xiong et al., 2008), D155 (0.25 M HCl+0.5 M NaCl) (Xiong, 2008), D113 (4 M HCl) (Xiong et al., 2009), and D151 (0.5 M HCl) (Yao, 2010). In the case of strongly basic anion-exchangers, the elution of the adsorbed anionic REE-ligand complex is carried out with HNO₃, H₂SO₄, NH₄SCN, and CH₃COOH solutions (Faris & Warton, 1962; Hubicki & Olszak, 1998, 2002; Koodyńska & Hubicki, 2012).

Similarly, chelating resins can be regenerated using mineral acids. In a study with multiple chelating resins, Page et al. (2017) achieved high elution (>97%) for iminodiacetic (IDA) resins with 0.1-1 M HCl, the highest being 99.9% with 1 M HCl. For sulfonic/phosphonic (SP) and aminophosphonic (AP) resins, a higher strength of HCl (2-4 M) achieved 58-80% elution. In another study, 2 M HCl and 2 M HNO₃ were used for desorption of La(III), Ce(III), and Nd(III) ions from chelating resin Dowex M 4195; however, the highest desorption was only 43.9% for Ce(III) achieved with 2 M HNO₃ (Kołodźńska et al., 2019). Other examples of mineral acid as eluent for chelating resins are 2 M HCl for iminodiacetic acid resin (IDAAR) (Xiong et al., 2006); 1

M HCl, 6 M HCl, 1 M HNO₃, and 6 M HNO₃ for Tulsion CH-90 resin (Dutta et al., 2008).

Mineral acid, HNO₃, was used in the desorption step for REE adsorbed onto alumina and hematite (Kosmulski, 1997b; Marmier et al., 1997). The elution of REE from amorphous ZrP with 1 M mineral acids decreased in the order of H₂SO₄ > HNO₃ > HCl > H₃PO₄, with the highest being 85.1% and the lowest of 73.2% (Xu et al., 2018). In the case of inorganic TiP, 0.5 M HNO₃+0.5 M H₃PO₄ eluted 98.3% Sc(III) (Wenzhong Zhang, Koivula, et al., 2017). Other inorganic nanomaterials have been desorbed using 0.001 M HCl (Zhao et al., 2019), 0.3 M HCl (Marwani et al., 2018), 0.2 M HNO₃ (Ghobadi et al., 2017, 2018), and 0.05-0.8 M HNO₃ (Tu & Johnston, 2018). 0.2 M HNO₃ desorbed >80% REE from Co_{0.2}Mn_{0.8}Fe₂O₄ and Co_{0.8}Mn_{0.2}Fe₂O₄ (Ghobadi et al., 2017) and >90% REE from MnFe₂O₄ and MnFe₂O₄-GO (Ghobadi et al., 2018). With CuFe₂O₄ nanoparticles, 100% REE desorption was obtained with 0.05-0.8 M HNO₃ (Tu & Johnston, 2018).

Mineral acid HCl is very frequently used as an eluent in solvent-impregnated resins. The examples of the use of different concentrations of HCl as eluent for SIRs include the use of 0.15 M HCl (Lee et al., 2010a, 2010b), 0.2 M HCl (Park et al., 2005), 0.5 M HCl (Yin et al., 2020), 1 M HCl (Kumar et al., 2011), and 2 M HCl (Aardaneh et al., 2008). Kumar et al. (2011) used HCl, HNO₃, H₂SO₄, and (NH₄)₂CO₃, and reported 99.7%, 99.1%, 100%, and 74.6% elution at 1 M concentration. HCl with strength >0.1 M achieved almost complete desorption of La(III) from P227-impregnated XAD-7HP (Yang et al., 2020). Nitric acid solutions are also effective for elution from different SIRs (Helaly et al., 2012; Louis & Duyckaerts, 1984, 1985). İnan et al. (2018) used 0.01 M HNO₃ to desorb REEs from Cyanex impregnated Amberlite XAD-7. 0.1 M HNO₃ was used as a stripping agent for SIL obtained through ([A336] [CA-100]) impregnation into XAD-7 (Sun et al., 2009). Another SIL loaded with Sc(III) was stripped using 1 M HCl and 1 M HNO₃ with efficiencies >90% and 100% with 1 M H₂SO₄ (Avdibegović et al., 2017).

Similarly, for surface-functionalized adsorbents and ion-imprinted polymers, mineral acids are mostly used for the desorption of REEs. The strength of the acid solution used for desorption has varied from 0.1 M HCl to 2.0 M HCl (e.g., 0.1 M HCl (Ahmed, Lee, et al., 2019; Kostenko et al., 2019; Y.-R. Lee et al., 2018; Ryu et al., 2021), 0.25 M HCl (Hua et al., 2019), 0.3 M HCl (Lou et al., 2019), 0.5 M HCl (Chen et al., 2014; Ravi, Lee, et al., 2018), 1.0 M HCl (Babu et al., 2018; Gasser et al., 2017; Moussa et al., 2017), 2 M HCl (Li et al., 2019; Qin et al., 2022; Yusoff et al., 2017), and 1.0-2.0 M HCl (Ogata et al., 2015a)). Other mineral acids such as HNO₃ with the strength of 0.01-6.55 M (Ashour et al., 2017; Shuangyou Bao et al., 2022; Bertelsen et al., 2019; Callura et al., 2018; Chen et al., 2014; Noack et al., 2014; Rahman et al., 2020; Ravi, Zhang, et al., 2018; Zhao et al., 2021) and H₂SO₄ (e.g., 0.1 M - 1 M H₂SO₄ (Ogata et al., 2015a), 0.1 M H₂SO₄ (Gaete et al., 2021)) have been used as well. Mineral acids have usually provided desorption in the order of 90-100% for functionalized adsorbent and ion-imprinted polymers. The mechanism of desorption with mineral acid is the ion-exchange reaction between protons and the adsorbed ions (Ogata et al., 2015a).

Organic acids and complexing ligands

Along with mineral acids, various organic acids and complexing ligand solutions have been used for the desorption of REEs from different adsorbents. In the case of strongly acidic cation-exchange resins, the organic acid and complexing ligands play a vital part as eluent since they can increase the chromatographic separation between REEs in the elution step due to their difference in affinity for different REEs (Boyd, 1978; B. Chen et al., 2017; Spedding et al., 1947, 1954; Strelow & Victor, 1990). The examples of organic acids used as eluents in REEs separation include acetic, malonic, phthalic, and other carboxyl acids, hydroxy acids, phosphonic, and amino phosphonic acids (Kodynska & Hubicki, 2012).

However, the best results for REEs desorption and separation from strong acidic cation-exchange resins were obtained using complexing ligand as eluent, primarily eluents based on polyamino-polycarboxylic acid such as ethylenediaminetetraacetic acid (EDTA) (Smith & Hoffman, 1956; Spedding et al., 1954a; Spedding & Powell, 1954); Diethylenetriaminepentaacetic acid (DTPA) (Chuveleva et al., 1974, 1995; Hale & Hammer, 1972; Kharitonov et al., 2009b; Kogan & Ratner, 1971), nitrilotriacetic (Kharitonov et al., 2009a; Martynenko

et al., 1968, 1972; Wheelwright, 1969), hydroxy-ethylethylenediaminetriacetic (Hagiwara, 1969; James et al., 1961; Strelow & Victor, 1990), cyclohexane-1,2-diaminetetraacetic (Gschneidner & Eyring, 1982), and iminodiacetic acids (Martynenko et al., 1972).

The advantage of using polyamino-polycarboxylic acid as eluent is that they form strong complexes with REE, reducing the consumption of ligand and resulting in concentrated elutes. Also, the stability constant of different REEs with these complexes differs more than their ion-exchange constants, which results in a higher degree of separation (Chen et al., 2017; Ehrlich & Lisichkin, 2017; Koodynska & Hubicki, 2012). The most widely used polyamino polycarboxylic is ethylenediaminetetraacetic acid (EDTA). EDTA is readily available, inexpensive, and easy to regenerate. Additionally, due to the multidentate nature of EDTA, the REEs form 1:1 complexes with EDTA, which reduces metal zone tailing.

EDTA has been used as a stripping agent for SLEs and functionalized adsorbents (Gupta & Sengupta, 2017; Li et al., 2018; Liu et al., 2009; Zhao et al., 2016). EDTA and oxalic acid were used for desorption with amide functionalized multiwalled carbon nanotubes (Gupta & Sengupta, 2017). Other organic compounds used for desorption of REEs include acetonitrile (Abdel-Magied et al., 2019; Jiang et al., 2016; Zheng et al., 2015), methanol (Abdel-Magied et al., 2019), and ammonium oxalate (Florek et al., 2014, 2015; Giret et al., 2018; Hu et al., 2017, 2019; Juère et al., 2016; Perreault et al., 2017).

Application to real samples

Examples of using solid-liquid separation at an industrial level are scarce. Diphonix was used to extract REE from the nitric acid solution from apatite processing on a pilot scale at Akron public corporation (Ehrlich & Lisichkin, 2017). However, there are lab studies in literature where various adsorbents have been used to separate REEs from various natural samples such as bauxite mud (Hu et al., 2019; Ochsenkühn-Petropulu et al., 1995; Roosen et al., 2016; ZHOU et al., 2008); Silicate & niobium mining deposits (Hu et al., 2017); apatite, orthite, and slag (Kostenko et al., 2019; Ogata et al., 2016); bastnäsite (Dolak et al., 2015), acidic mine drainage (Hermassi et al., 2021; Ramasamy et al., 2019; Ramasamy, Puhakka, Iftekhhar, et al., 2018; Ramasamy, Puhakka, Repo, Ben Hammouda, et al., 2018); spiked seawater (Callura et al., 2018; Noack et al., 2016); spiked river/groundwater and sewage water (Marwani et al., 2018; Yantasee et al., 2009); geothermal brines (Liu et al., 2021), acidic streams, dialysate (Yantasee et al., 2009); REE mineral leachate (Giret et al., 2018); industrial wastewater (Li et al., 2013); leached solution of spent Ni-MH cells (Gasser & Aly, 2013; Kołodyńska et al., 2019), thin-film phosphors leached solution (Schaeffer et al., 2017), phosphoric acid plant effluent (Al-Thyabat & Zhang, 2015), zinc mine ore (Fonseka et al., 2021), and coal fly ash (Brown & Balkus, 2021; Hovey et al., 2021; Mondal et al., 2019).

These adsorbents showed varying degrees of success for REEs extraction (Figure 4). REEs extraction from red mud used ion-exchanger Dowex 50W-X8 in combination with the solvent extraction method (Ochsenkühn-Petropulu et al., 1995). The whole separation process resulted in an average 93% recovery of Sc(III). High La(III) and Nd(III) recovery (98%) from spent Ni-MH cells were achieved using layered double hydroxide (or hydrotalcite) functionalized with Cyanex-272 (Fe-Mg-LDH-Cyanex-272) (Gasser & Aly, 2013). In another study, 95% of REE were separated at pH 4.2 from the waste sulfate solutions of uranium leaching solution using carboxyl adsorbent CYBBER LX 280, after an initial step involving Fe(OH)₃ precipitation (Lokshin et al., 2013). Bidentate phthaloyl diamide (PA) functionalized KIT-6 showed high selectivity for Lu(III) from a leached solution of silicate and niobium mining deposit samples (legend 6-11, Figure 4) (Hu et al., 2017). The adsorbent tetradentate phenylenedioxy diamide (PDDA) functionalized KIT-6 showed a higher affinity for HREEs in the case of KIT-6-1,2-PDDA (legend 14 Figure 4) and LREEs with KIT-6-1,3-PDDA (legend 15 Figure 4) while extracting REEs from red bauxite residue (Hu et al., 2019). Silica gel functionalized with phosphonoacetic acid (PAA), N, N-bis(phosphonomethyl) glycine (BPG), diethylenetriaminepentaacetic acid (DTPA), and diethylenetriaminepentaacetic dianhydride (DTPADA) were able to adsorb REEs from spiked brine samples with high efficiency (legend 16-26, Figure 4) (Callura et al., 2018; Noack et al., 2016). Nd(III)-ion imprinted polymer extracted 100% Nd(III) from bastnäsite leachate solution (Dolak et al., 2015).

In fly ash leachate solution, bis(ethylhexyl)amido diethylenetriaminepentaacetic acid-functionalized silica showed selectivity for REEs over Fe and Al that were present in much higher concentrations than REEs (~700- to 90,000-fold excess) (Hovey et al., 2021). Eu(III) was selectively recovered (88% Eu(III) recovery, <10% recovery of competitive ions) from zinc mine ore leachate solution adjusted to pH 5.5 using PMIDA functionalized MOF (Cr-MIL-PMIDA) (Fonseka et al., 2021). The single-element Eu(III) adsorption at pH 5.5 was 90-91%; thus, the presence of a high concentration of competing ions did not affect the Eu(III) adsorption. The Langmuir maximum capacity (q_m) for Eu(III) on Cr-MIL-PMIDA was 69.14 mg/g.

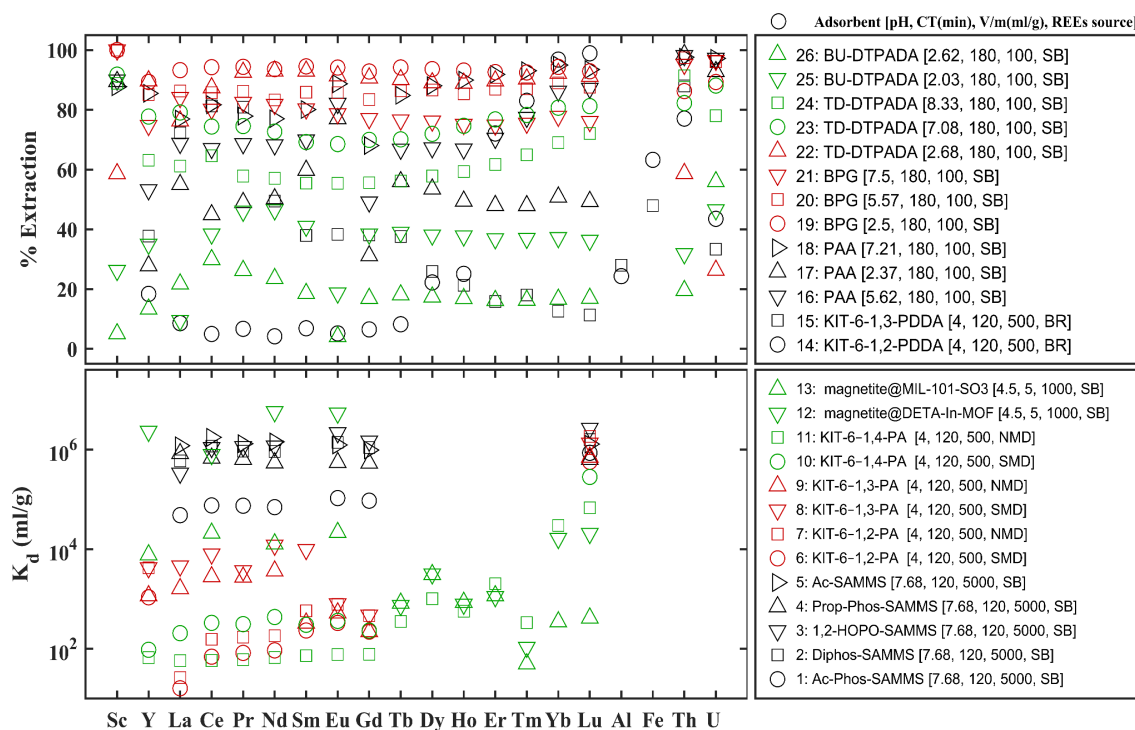


Figure 4: Distribution coefficient (K_d) for various adsorbents in actual REE solution. The legends include adsorbents with the experimental condition (pH, contact time (CT), V/m ratio (volume of solution/mass of adsorbent and source of the REE solution)). Sources of REEs: SRW: spiked river water, SB: spiked brine, SMD: Silicate mining deposit, NMD: Niobium mining deposit, BR: Bauxite residue Source for data: Adsorbent 1-5 (Yantasee et al., 2009), 6-11 (Hu et al., 2017), 12-13 (Elsaidi et al., 2018), 14-15 (Hu et al., 2019), 16-26 (reported pH is equilibrium pH) (Callura et al., 2018).

Difficulties with adsorption data present in literature:

Adsorption studies often involve isotherms and report maximum adsorption capacity (q_m). However, in many cases, the adsorption experiments only include a mono-element solution, making it difficult to predict the behavior of these adsorbents in a multielement solution or an actual field REEs solution (e.g., acid mine drainage, bauxite leachate). The presence of competitive ions can reduce the adsorption capacity of adsorbents for target ions by varying degrees. It is necessary for an adsorbent to retain its adsorption capacity in multielement solutions and be selective for the efficient separation of target elements. While many adsorption studies do include multi-element adsorptions, the type and concentration of competitive ions differ in different studies, making it difficult to compare the mechanism and performance of these adsorbents with each other. Even so, it should be a general practice to test the adsorbent in a multielement solution with competitive ions and actual field solutions.

Summary and outlook

The adsorption-based REEs separation has been explored for a long time, and the technology has evolved. For separating REEs from other cations with a different charge, cation exchangers may be recommended. However, for the selective separation of specific REEs, ligand-functionalized adsorbents promoting complexation are more suitable.

There remain strikingly large gaps in two directions with adsorption-based REE separation: 1) lack of industrial-level applications and setups, and 2) lack of fundamental level modeling and understanding of surface ligand behavior with the REE. Although there have been many REE separation studies at laboratory scale, there is a lack of examples of conversion to industrial level applications.

The challenges in SPE with functionalized adsorbents are the selection of selective ligands and predicting the behavior of these ligands once they are grafted onto a specific solid surface. No quantitative relationship has been developed between free-solution thermodynamics data and surface complexation constants for the functionalized adsorbents. Future research can employ quantum chemistry calculations to select ligands and predict the behavior after grafting. Understanding and modeling the ligand grafted on the solid surface and recognizing the difference in metal-ligand interaction on the surface against the metal-ligand interaction in the free solution can help better develop functionalized adsorbents.

Appendix A. Abbreviations

AC Activated carbon

AER Anion exchange resin

APTS 3-[2-(2-aminoethylamino) ethylamino] propyl-trimethoxysilane

APTES 3-aminopropyl triethoxysilane

APTMS 3-aminopropyl trimethoxysilane

ATMP Amino tris(methylene phosphonic acid)

ATS Aluminum silicotitanates

BHPA N-Benzoyl-N-phenylhydroxylamine

BPG Bis(phosphonomethyl) glycine

CER Cation exchange resin

CN Coordination number

CNT Carbon nanotube

COK Centre for Research Chemistry and Catalysis

Cyanex 272 Bis(2,4,4-trimethylpentyl)-phosphinic acid

DETA Diethylenetriamine

DGA Diglycolamide

DMF N,N-dimethylformamide

DOODA 3,6-dioxaoctanediamidopropyl

DTPA Diethylenetriaminepentaacetic acid

DTPADA Diethylenetriaminepentaacetic dianhydride

EDTA Ethylenediaminetetraacetic acid

FDGA Furan-2,4-diamidopropyltriethoxysilane
 GO Graphene oxide
 GONS Graphene oxide nanosheet
 HDEHP Bis(2-ethylhexyl) hydrogen phosphate
 HREE Heavy rare earth element
 IER Ion exchange resin
 IIP Ion-imprinted polymer
 KIT Korean Advance Institute of Science and Technology
 LREE Light rare earth element
 MCM Mobil Composition of Matter
 MIP Molecular imprinted polymer
 MOF Metal-organic framework
 MSF Mesoporous silica foam
 MWCNT Multi-walled carbon nanotube
 OMC Ordered mesoporous carbon
 OMS Ordered mesoporous silica
 PA Phthaloyl diamide
 PAA Phosphonoacetic acid
 PAN 1-(2-pyridylazo)-2-naphthol
 PC88A 2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester
 PDDA Phenylenedioxy diamide
 PES Polyethersulfone
 PMIDA N-(phosphonomethyl)iminodiacetic acid
 PVA Polyvinyl alcohol
 REE Rare earth element
 SBA Santa Barbara Amorphous
 SIL Supported ionic liquid
 SIR Solvent impregnated resin
 SLE Supported liquid extraction
 SLLE Supported liquid-liquid extraction
 SPE Solid-phase extraction
 SWCNT Single-walled carbon nanotube
 TEHDGA N,N,N,N' tetrakis-2-ethylhexyldiglycolamide
 TMO Transition metal oxide

TODGA N,N,N',N'-Tetraoctyl diglycolamide

TTHA Triethylenetetraminehexaacetic acid

ZrP Zirconium organophosphonates

References

- Aardaneh, K., Saal, D., Swarts, G., & Dewindt, S. C. (2008). TBP and TBP impregnated Amberlite XAD-4 resin for radiochemical separation of ^{88}Y from Sr and Al. *Journal of Radioanalytical and Nuclear Chemistry* , 275 (3), 665–669. <https://doi.org/10.1007/s10967-007-7074-6>
- Abdel-Magied, A. F., Abdelhamid, H. N., Ashour, R. M., Zou, X., & Forsberg, K. (2019). Hierarchical porous zeolitic imidazolate frameworks nanoparticles for efficient adsorption of rare-earth elements. *Microporous and Mesoporous Materials* , 278 (September 2018), 175–184. <https://doi.org/10.1016/j.micromeso.2018.11.022>
- Abu Elgoud, E. M., Ismail, Z. H., Ahmad, M. I., El-Nadi, Y. A., Abdelwahab, S. M., & Aly, H. F. (2019). Sorption of Lanthanum(III) and Neodymium(III) from Concentrated Phosphoric Acid by Strongly Acidic Cation Exchange Resin (SQS-6). *Russian Journal of Applied Chemistry* , 92 (11), 1581–1592. <https://doi.org/10.1134/S1070427219110156>
- Ahmed, I., Adhikary, K. K., Lee, Y. R., Ho Row, K., Kang, K. K., & Ahn, W. S. (2019). Ionic liquid entrapped UiO-66: Efficient adsorbent for Gd^{3+} capture from water. *Chemical Engineering Journal* , 370 , 792–799. <https://doi.org/10.1016/j.cej.2019.03.265>
- Ahmed, I., Bhattacharjee, S., Lee, C. S., Kang, K. K., Ahn, J. W., & Ahn, W. S. (2021). Aqueous Nd^{3+} capture using a carboxyl-functionalized porous carbon derived from ZIF-8. *Journal of Colloid and Interface Science* , 594 , 702–712. <https://doi.org/10.1016/J.JCIS.2021.03.036>
- Ahmed, I., Lee, Y.-R., Yu, K., Bhattacharjee, S., & Ahn, W.-S. (2019). Gd^{3+} Adsorption over Carboxylic- and Amino-Group Dual-Functionalized UiO-66 [Research-article]. *Industrial & Engineering Chemistry Research* , 58 (6), 2324–2332. <https://doi.org/10.1021/acs.iecr.8b05220>
- Aja, S. U. (1998). Sorption of the rare earth element, Nd, onto kaolinite at 25 °C. *Clays and Clay Minerals* , 46 (1), 103–109. <https://doi.org/10.1346/CCMN.1998.0460112>
- Al-Thyabat, S., & Zhang, P. (2015). In-line extraction of REE from Dihydrate (DH) and HemiDihydrate (HDH) wet processes. *Hydrometallurgy* , 153 , 30–37. <https://doi.org/10.1016/j.hydromet.2015.01.010>
- Alexandratos, S. D., & Natesan, S. (1999). Ion-selective polymer-supported reagents: The principle of bi-functionality. *European Polymer Journal* , 35 (3), 431–436. [https://doi.org/10.1016/S0014-3057\(98\)00142-6](https://doi.org/10.1016/S0014-3057(98)00142-6)
- Alexandratos, Spiro D., & Hussain, L. A. (1995). Bifunctionality as a Means of Enhancing Complexation Kinetics in Selective Ion Exchange Resins. *Industrial and Engineering Chemistry Research* , 34 (1), 251–254. <https://doi.org/10.1021/ie00040a026>
- Alexandratos, Spiro D., & Hussain, L. A. (1998). Synthesis of α -, β -, and γ -ketophosphonate polymer-supported reagents: The role of intra-ligand cooperation in the complexation of metal ions. *Macromolecules* , 31 (10), 3235–3238. <https://doi.org/10.1021/ma971587d>
- Alexandratos, Spiro D., & Smith, S. D. (2004a). High stability solvent impregnated resins: Metal ion complexation as a function of time. *Solvent Extraction and Ion Exchange* , 22 (4), 713–720. <https://doi.org/10.1081/SEI-120038701>
- Alexandratos, Spiro D., & Smith, S. D. (2004b). Intraligand cooperation in metal-ion binding by immobilized ligands: The effect of bifunctionality. *Journal of Applied Polymer Science* , 91 (1), 463–468. <https://doi.org/10.1002/app.13131>

- Alexandratos, Spiro D., & Zhu, X. (2005). Bifunctional coordinating polymers: Auxiliary groups as a means of tuning the ionic affinity of immobilized phosphate ligands. *Macromolecules* , 38 (14), 5981–5986. <https://doi.org/10.1021/ma050057b>
- Alexandratos, Spiro D., & Zhu, X. (2008). Polyols as Scaffolds in the Development of Ion-Selective Polymer-Supported Reagents: The Effect of Auxiliary Groups on the Mechanism of Metal Ion Complexation. *Inorganic Chemistry* , 47 (7), 2831–2836. <https://doi.org/10.1021/ic702263x>
- Alexandratos, Spiro D., & Zhu, X. (2015). The role of polarizability in determining metal ion affinities in polymer-supported reagents: monoprotic phosphates and the effect of hydrogen bonding. *New Journal of Chemistry* , 39 (7), 5366–5373. <https://doi.org/10.1039/C5NJ00387C>
- Alguacil, F. J., García-Díaz, I., Escudero Baquero, E., Rodríguez Largo, O., & López, F. A. (2020). On the Adsorption of Cerium(III) Using Multiwalled Carbon Nanotubes. *Metals* , 10 (8), 1057. <https://doi.org/10.3390/met10081057>
- Amarasekara, A. S., Owereh, O. S., & Aghara, S. K. (2009). Synthesis of 4-acylpyrazolone Schiff base ligand grafted silica and selectivity in adsorption of lanthanides from aqueous solutions. *Journal of Rare Earths* , 27 (5), 870–874. [https://doi.org/10.1016/S1002-0721\(08\)60352-X](https://doi.org/10.1016/S1002-0721(08)60352-X)
- Aravind, A., & Mathew, B. (2018). Electrochemical sensor based on nanostructured ion imprinted polymer for the sensing and extraction of Cr(III) ions from industrial wastewater. *Polymer International* , 67 (12), 1595–1604. <https://doi.org/10.1002/PI.5683>
- Arnold, R., & Hing, L. B. S. (1967). Selectivity of carboxylic ion-exchange resin for lanthanide ions. *Journal of the Chemical Society A: Inorganic, Physical, Theoretical* , 2 , 306. <https://doi.org/10.1039/j19670000306>
- Artiushenko, O., Ávila, E. P., Nazarkovsky, M., & Zaitsev, V. (2020). Reusable hydroxamate immobilized silica adsorbent for dispersive solid phase extraction and separation of rare earth metal ions. *Separation and Purification Technology* , 231 (August 2019), 115934. <https://doi.org/10.1016/j.seppur.2019.115934>
- Artiushenko, O., Kostenko, L., & Zaitsev, V. (2020). Influence of competitive eluting agents on REEs recovery from silica gel adsorbent with immobilized aminodiphosphonic acid. *Journal of Environmental Chemical Engineering* , 8 (4), 103883. <https://doi.org/10.1016/j.jece.2020.103883>
- Asadollahzadeh, M., Torkaman, R., & Torab-Mostaedi, M. (2020). Extraction and Separation of Rare Earth Elements by Adsorption Approaches: Current Status and Future Trends. In *Separation and Purification Reviews* (pp. 1–28). Taylor and Francis Inc. <https://doi.org/10.1080/15422119.2020.1792930>
- Ashour, R. M., Abdelhamid, H. N., Abdel-Magied, A. F., Abdel-Khalek, A. A., Ali, M. M., Uheida, A., Muhammed, M., Zou, X., & Dutta, J. (2017). Rare Earth Ions Adsorption onto Graphene Oxide Nanosheets. *Solvent Extraction and Ion Exchange* , 35 (2), 91–103. <https://doi.org/10.1080/07366299.2017.1287509>
- Attallah, M. F., Elgazzar, A. H., Borai, E. H., & El-Tabl, A. S. (2016). Preparation and characterization of aluminum silicotitanate: ion exchange behavior for some lanthanides and iron. *Journal of Chemical Technology & Biotechnology* , 91 (8), 2243–2252. <https://doi.org/10.1002/jctb.4810>
- Attia, M. A., Moussa, S. I., Sheha, R. R., Someda, H. H., & Saad, E. A. (2019). Hydroxyapatite/NiFe 2 O 4 superparamagnetic composite: Facile synthesis and adsorption of rare elements. *Applied Radiation and Isotopes* , 145 (December 2018), 85–94. <https://doi.org/10.1016/j.apradiso.2018.12.003>
- Avdibegović, D., Regadio, M., & Binnemans, K. (2017). Recovery of scandium(Sc^{3+}) from diluted aqueous solutions by a supported ionic liquid phase (SILP). *RSC Adv.* , 7 (78), 49664–49674. <https://doi.org/10.1039/C7RA07957E>
- Awual, M. R., Kobayashi, T., Miyazaki, Y., Motokawa, R., Shiwaku, H., Suzuki, S., Okamoto, Y., & Yaita, T. (2013). Selective lanthanide sorption and mechanism using novel hybrid Lewis base (N-methyl-N-phenyl-

1,10-phenanthroline-2-carboxamide) ligand modified adsorbent. *Journal of Hazardous Materials* , 252 –253 , 313–320. <https://doi.org/10.1016/j.jhazmat.2013.03.020>

Babu, C. M., Binnemans, K., & Roosen, J. (2018). Ethylenediaminetriacetic Acid-Functionalized Activated Carbon for the Adsorption of Rare Earths from Aqueous Solutions. *Industrial and Engineering Chemistry Research* , 57 (5), 1487–1497. <https://doi.org/10.1021/acs.iecr.7b04274>

Bao, Shengxu, Tang, Y., Zhang, Y., & Liang, L. (2016). Recovery and Separation of Metal Ions from Aqueous Solutions by Solvent-Impregnated Resins. *Chemical Engineering & Technology* , 39 (8), 1377–1392. <https://doi.org/10.1002/ceat.201500324>

Bao, Shuangyou, Wang, Y., Wei, Z., Yang, W., & Yu, Y. (2022). Highly efficient recovery of heavy rare earth elements by using an amino-functionalized magnetic graphene oxide with acid and base resistance. *Journal of Hazardous Materials* , 424 , 127370. <https://doi.org/10.1016/j.jhazmat.2021.127370>

Barrak, H., Ahmedi, R., Chevallier, P., M'nif, A., Laroche, G., & Hamzaoui, A. H. (2019). Highly efficient extraction of rare earth elements and others ions from green phosphoric acid medium using TMSEDTA@GO@Fe₃O₄ core-shell. *Separation and Purification Technology* , 222 , 145–151. <https://doi.org/10.1016/j.seppur.2019.04.016>

Baumann, A. E., Burns, D. A., Liu, B., & Thoi, V. S. (2019). Metal-organic framework functionalization and design strategies for advanced electrochemical energy storage devices. In *Communications Chemistry* (Vol. 2, Issue 1, pp. 1–14). Springer Nature. <https://doi.org/10.1038/s42004-019-0184-6>

Beck, J. S., Vartuli, J. C., Roth, W. J., Leonowicz, M. E., Kresge, C. T., Schmitt, K. D., Chu, C. T. W., Olson, D. H., Sheppard, E. W., McCullen, S. B., Higgins, J. B., & Schlenker, J. L. (1992). A New Family of Mesoporous Molecular Sieves Prepared with Liquid Crystal Templates. *Journal of the American Chemical Society* , 114 (27), 10834–10843. <https://doi.org/10.1021/ja00053a020>

Behdani, F. N., Rafsanjani, A. T., Torab-Mostaedi, M., & Mohammadpour, S. M. A. K. (2013). Adsorption ability of oxidized multiwalled carbon nanotubes towards aqueous Ce(III) and Sm(III). *Korean Journal of Chemical Engineering* , 30 (2), 448–455. <https://doi.org/10.1007/s11814-012-0126-9>

Bertelsen, E. R., Deodhar, G., Kluherz, K. T., Davidson, M., Adams, M. L., Trewyn, B. G., & Shafer, J. C. (2019). Microcolumn lanthanide separation using bis-(2-ethylhexyl) phosphoric acid functionalized ordered mesoporous carbon materials. *Journal of Chromatography A* , 1595 , 248–256. <https://doi.org/10.1016/j.chroma.2019.02.057>

Bezzina, J. P., Ogden, M. D., Moon, E. M., & Soldenhoff, K. L. (2018). REE behavior and sorption on weak acid resins from buffered media. *Journal of Industrial and Engineering Chemistry* , 59 , 440–455. <https://doi.org/10.1016/j.jiec.2017.11.005>

Bhatnagar, A., & Sillanpää, M. (2010). Utilization of agro-industrial and municipal waste materials as potential adsorbents for water treatment-A review. In *Chemical Engineering Journal* (Vol. 157, Issues 2–3, pp. 277–296). Elsevier. <https://doi.org/10.1016/j.cej.2010.01.007>

Biju, V. ., Gladis, J. M., & Rao, T. P. (2003). Ion imprinted polymer particles: synthesis, characterization and dysprosium ion uptake properties suitable for analytical applications. *Analytica Chimica Acta* , 478 (1), 43–51. [https://doi.org/10.1016/S0003-2670\(02\)01416-2](https://doi.org/10.1016/S0003-2670(02)01416-2)

Botelho Junior, A. B., Pinheiro, É. F., Espinosa, D. C. R., Tenório, J. A. S., & Baltazar, M. dos P. G. (2021). Adsorption of lanthanum and cerium on chelating ion exchange resins: kinetic and thermodynamic studies. <https://doi.org/10.1080/01496395.2021.1884720> , 57 (1), 60–69. <https://doi.org/10.1080/01496395.2021.1884720>

Boyd, G. E. (1978). Thermodynamic property changes in lanthanide(III) cation exchange reactions with poly(styrenesulfonic acid) type cation exchangers. *Journal of Physical Chemistry* , 82 (25), 2704–2709. <https://doi.org/10.1021/j100514a015>

- Brown, A. T., & Balkus, K. J. (2021). Critical Rare Earth Element Recovery from Coal Ash Using Microsphere Flower Carbon. *ACS Applied Materials and Interfaces* , 13 (41), 48492–48499. https://doi.org/10.1021/ACSAMI.1C09298/SUPPL_FILE/AM1C09298_SI.001.PDF
- Bunina, Z., Bryleva, K., & Belikov, K. (2021). Synthesis and Adsorption Properties of Gadolinium-Imprinted Divinylbenzene-Based Copolymers. *ACS Omega* , 6 (4), 3336–3344. https://doi.org/10.1021/ACSOMEGA.0C05812/SUPPL_FILE/AO0C05812_SI.001.PDF
- Callura, J. C. (2018). *Ligand-Functionalized Adsorbents for the Extraction and Recovery of Rare Earth Elements* (Issue December). Carnegie Mellon University.
- Callura, J. C., Perkins, K. M., Baltrus, J. P., Washburn, N. R., Dzombak, D. A., & Karamalidis, A. K. (2019). Adsorption kinetics, thermodynamics, and isotherm studies for functionalized lanthanide-chelating resins. *Journal of Colloid and Interface Science* , 557 , 465–477. <https://doi.org/10.1016/j.jcis.2019.08.097>
- Callura, J. C., Perkins, K. M., Noack, C. W., Washburn, N. R., Dzombak, D. A., & Karamalidis, A. K. (2018). Selective adsorption of rare earth elements onto functionalized silica particles. *Green Chemistry* , 20 (7), 1515–1526. <https://doi.org/10.1039/C8GC00051D>
- Callura, J. C., Shi, Q., Dzombak, D. A., & Karamalidis, A. K. (2021). Selective recovery of rare earth elements with ligand-functionalized polymers in fixed-bed adsorption columns. *Separation and Purification Technology* , 265 , 118472. <https://doi.org/10.1016/J.SEPPUR.2021.118472>
- Canfarotta, F., Poma, A., Guerreiro, A., & Piletsky, S. (2016). Solid-phase synthesis of molecularly imprinted nanoparticles. *Nature Protocols* 2016 11:3 , 11 (3), 443–455. <https://doi.org/10.1038/nprot.2016.030>
- Cardoso, C. E. D., Almeida, J. C., Lopes, C. B., Trindade, T., Vale, C., & Pereira, E. (2019). Recovery of Rare Earth Elements by Carbon-Based Nanomaterials—A Review. *Nanomaterials* , 9 (6), 814. <https://doi.org/10.3390/nano9060814>
- Chen, B., He, M., Zhang, H., Jiang, Z., & Hu, B. (2017). Chromatographic Techniques for Rare Earth Elements Analysis. *Physical Sciences Reviews* , 2 (4). <https://doi.org/10.1515/psr-2016-0057>
- Chen, C. L., Wang, X. K., & Nagatsu, M. (2009). Europium adsorption on multiwall carbon nanotube/iron oxide magnetic composite in the presence of polyacrylic acid. *Environmental Science and Technology* , 43 (7), 2362–2367. <https://doi.org/10.1021/es803018a>
- Chen, H., Shao, D., Li, J., & Wang, X. (2014). The uptake of radionuclides from aqueous solution by poly(amidoxime) modified reduced graphene oxide. *Chemical Engineering Journal* , 254 , 623–634. <https://doi.org/10.1016/j.cej.2014.05.091>
- Chen, L., Wang, X., Lu, W., Wu, X., & Li, J. (2016). Molecular imprinting: Perspectives and applications. *Chemical Society Reviews* , 45 (8), 2137–2211. <https://doi.org/10.1039/c6cs00061d>
- Chen, W., Wang, L., Zhuo, M., Liu, Y., Wang, Y., & Li, Y. (2014). Facile and highly efficient removal of trace Gd(III) by adsorption of colloidal graphene oxide suspensions sealed in dialysis bag. *Journal of Hazardous Materials* , 279 , 546–553. <https://doi.org/10.1016/j.jhazmat.2014.06.075>
- Chen, Y., Zhu, B., Wu, D., Wang, Q., Yang, Y., Ye, W., & Guo, J. (2012). Eu(III) adsorption using di(2-thylhexyl) phosphoric acid-immobilized magnetic GMZ bentonite. *Chemical Engineering Journal* , 181 –182 , 387–396. <https://doi.org/10.1016/j.cej.2011.11.100>
- Chen, Z., Li, Z., Chen, J., Tan, H., Wu, J., & Qiu, H. (2022). Selective Adsorption of Rare Earth Elements by Zn-BDC MOF/Graphene Oxide Nanocomposites Synthesized via In Situ Interlayer-Confined Strategy. *Industrial & Engineering Chemistry Research* , 61 (4), 1841–1849. https://doi.org/10.1021/ACS.IECR.1C04180/SUPPL_FILE/IE1C04180_SI.001.PDF
- Chuenchom, L., Kraehnert, R., & Smarsly, B. M. (2012). Recent progress in soft-templating of porous carbon materials. *Soft Matter* , 8 (42), 10801–10812. <https://doi.org/10.1039/c2sm07448f>

- CHUVELEVA, E. A., KHARITONOV, O. V., & FIRSOVA, L. A. (1995). Effect of Diethylenetriamine of Pentaacetic Acid on the Chromatographic-Separation of Rare-Earth Elements on Ku-2 Cation-Exchange Resin. *Zhurnal Fizicheskoi Khimii* , 69 (7), 1322–1326.
- CHUVELEVA, E. A., NAZAROV, P. P., & CHMUTOV, K. V. (1974). CHROMATOGRAPHIC-SEPARATION OF CURIUM, AMERICIUM AND RARE-EARTH ELEMENTS. *Zhurnal Fizicheskoi Khimii* , 48 (12), 3078–3081.
- Coppin, F., Berger, G., Bauer, A., Castet, S., & Loubet, M. (2002). Sorption of lanthanides on smectite and kaolinite. *Chemical Geology* , 182 (1), 57–68. [https://doi.org/10.1016/S0009-2541\(01\)00283-2](https://doi.org/10.1016/S0009-2541(01)00283-2)
- Cotton, S. A., & Harrowfield, J. M. (2012). Lanthanides: Coordination Chemistry. In *Encyclopedia of Inorganic and Bioinorganic Chemistry* . John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781119951438.eibc2062>
- Croissant, J. G., Fatieiev, Y., & Khashab, N. M. (2017). Degradability and Clearance of Silicon, Organosilica, Silsesquioxane, Silica Mixed Oxide, and Mesoporous Silica Nanoparticles. In *Advanced Materials*(Vol. 29, Issue 9, p. 1604634). Wiley-VCH Verlag. <https://doi.org/10.1002/adma.201604634>
- Crundwell, F. K. (2017). On the Mechanism of the Dissolution of Quartz and Silica in Aqueous Solutions. *ACS Omega* , 2 (3), 1116–1127. <https://doi.org/10.1021/acsomega.7b00019>
- Cui, K., Gao, B., Tai, M., & Su, B. (2019). A facile bionic strategy towards Gd (III)-imprinted membranes via interlaced stacking of one-dimensional/two-dimensional nanocomposite materials. *Journal of the Taiwan Institute of Chemical Engineers* , 95 , 652–659. <https://doi.org/10.1016/j.jtice.2018.09.036>
- Dardenne, K., Schäfer, T., Lindqvist-Reis, P., Denecke, M. A., Plaschke, M., Rothe, J., & Kim, J. I. (2002). Low temperature XAFS investigation on the Lutetium binding changes during the 2-line ferrihydrite alteration process. *Environmental Science and Technology* , 36 (23), 5092–5099. <https://doi.org/10.1021/es025513f>
- Davranche, M., Pourret, O., Gruau, G., & Dia, A. (2004). Impact of humate complexation on the adsorption of REE onto Fe oxyhydroxide. *Journal of Colloid and Interface Science* , 277 (2), 271–279. <https://doi.org/10.1016/j.jcis.2004.04.007>
- Davranche, M., Pourret, O., Gruau, G., Dia, A., & Le Coz-Bouhnik, M. (2005). Adsorption of REE(III)-humate complexes onto MnO₂: Experimental evidence for cerium anomaly and lanthanide tetrad effect suppression. *Geochimica et Cosmochimica Acta* , 69 (20), 4825–4835. <https://doi.org/10.1016/j.gca.2005.06.005>
- de Decker, J., de Clercq, J., Vermeir, P., & van der Voort, P. (2016). Functionalized metal-organic-framework CMPO@MIL-101(Cr) as a stable and selective rare earth adsorbent. *Journal of Materials Science* , 51 (10), 5019–5026. <https://doi.org/10.1007/s10853-016-9807-9>
- Dolak, İ., Keçili, R., Hür, D., Ersöz, A., & Say, R. (2015). Ion-Imprinted Polymers for Selective Recognition of Neodymium(III) in Environmental Samples. *Industrial & Engineering Chemistry Research* , 54 (19), 5328–5335. <https://doi.org/10.1021/acs.iecr.5b00212>
- Dong, C., Shi, H., Han, Y., Yang, Y., Wang, R., & Men, J. (2021). Molecularly imprinted polymers by the surface imprinting technique. *European Polymer Journal* , 145 , 110231. <https://doi.org/10.1016/j.eurpolymj.2020.110231>
- Dubey, S. S., & Grandhi, S. (2019). Sorption studies of yttrium(III) ions on surfaces of nano-thorium(IV) oxide and nano-zirconium(IV) oxide. *International Journal of Environmental Science and Technology* , 16 (1), 59–70. <https://doi.org/10.1007/s13762-017-1589-3>
- Dubey, Som Shankar, & Grandhi, S. (2016). Sorption studies of yttrium (III) ions on nano maghemite. *Journal of Environmental Chemical Engineering* , 4 (4), 4719–4730. <https://doi.org/10.1016/j.jece.2016.11.006>
- Dupont, D., Brullot, W., Bloemen, M., Verbiest, T., & Binnemans, K. (2014). Selective Uptake of Rare Earths from Aqueous Solutions by EDTA-Functionalized Magnetic and Nonmagnetic Nanoparticles. *ACS Applied Materials & Interfaces* , 6 (7), 4980–4988. <https://doi.org/10.1021/am406027y>

- Dutta, S., Mohapatra, P. K., Dhekane, G. D., Das, A. K., & Manchanda, V. K. (2008). Solid phase extraction of europium and uranium using Tulsion CH-90 resin. *Desalination* , 232 (1–3), 216–224. <https://doi.org/10.1016/j.desal.2007.10.038>
- Eftekhari, A., & Fan, Z. (2017). Ordered mesoporous carbon and its applications for electrochemical energy storage and conversion. *Materials Chemistry Frontiers* , 1 (6), 1001–1027. <https://doi.org/10.1039/c6qm00298f>
- Egawa, H., Yamabe, K., & Jyo, A. (1994). Studies on selective adsorption resins. XXXIII. Behavior of macroreticular chelating resins containing phosphinic and/or phosphonic acid groups in the adsorption of trivalent lanthanides. *Journal of Applied Polymer Science* ,52 (8), 1153–1164. <https://doi.org/10.1002/app.1994.070520815>
- Ehrlich, G. V., & Lisichkin, G. V. (2017). Sorption in the chemistry of rare earth elements. *Russian Journal of General Chemistry* ,87 (6), 1220–1245. <https://doi.org/10.1134/S1070363217060196>
- El-Nahhal, I. M., & El-Ashgar, N. M. (2007). A review on polysiloxane-immobilized ligand systems: Synthesis, characterization and applications. *Journal of Organometallic Chemistry* ,692 (14), 2861–2886. <https://doi.org/10.1016/j.jorgchem.2007.03.009>
- El Mourabit, S., Guillot, M., Toquer, G., Cambedouzou, J., Goettmann, F., & Grandjean, A. (2012). Stability of mesoporous silica under acidic conditions. *RSC Advances* , 2 (29), 10916–10924. <https://doi.org/10.1039/c2ra21569a>
- Elsaidi, S. K., Sinnwell, M. A., Devaraj, A., Droubay, T. C., Nie, Z., Murugesan, V., McGrail, B. P., & Thallapally, P. K. (2018). Extraction of rare earth elements using magnetite@MOF composites. *Journal of Materials Chemistry A* , 6 (38), 18438–18443. <https://doi.org/10.1039/C8TA04750B>
- ELSOFANY, E. (2008). Removal of lanthanum and gadolinium from nitrate medium using Aliquat-336 impregnated onto Amberlite XAD-4. *Journal of Hazardous Materials* , 153 (3), 948–954. <https://doi.org/10.1016/j.jhazmat.2007.09.046>
- Ensing, K., & De Boer, T. (1999). Tailor-made materials for tailor-made applications: Application of molecular imprints in chemical analysis. *TrAC - Trends in Analytical Chemistry* , 18 (3), 138–145. [https://doi.org/10.1016/S0165-9936\(98\)00103-4](https://doi.org/10.1016/S0165-9936(98)00103-4)
- Fan, Q. H., Shao, D. D., Hu, J., Chen, C. L., Wu, W. S., & Wang, X. K. (2009). Adsorption of humic acid and Eu (III) to multi-walled carbon nanotubes: EFFECT of pH, ionic strength and counterion effect. In *Radiochimica Acta* (Vol. 97, Issue 3, pp. 141–148). <https://doi.org/10.1524/ract.2009.1586>
- Faris, J. P., & Warton, J. W. (1962). Anion Exchange Resin Separation of the Rare Earths, Yttrium, and Scandium in Nitric Acid–Methanol Mixtures. *Analytical Chemistry* , 34 (9), 1077–1080. <https://doi.org/10.1021/ac60189a013>
- Farley, K. J., Dzombak, D. A., & Morel, F. M. M. (1985). A surface precipitation model for the sorption of cations on metal oxides. *Journal of Colloid And Interface Science* , 106 (1), 226–242. [https://doi.org/10.1016/0021-9797\(85\)90400-X](https://doi.org/10.1016/0021-9797(85)90400-X)
- Feng, X., Onel, O., Council-Troche, M., Noble, A., Yoon, R.-H., & Morris, J. R. (2021). A study of rare earth ion-adsorption clays: The speciation of rare earth elements on kaolinite at basic pH. *Applied Clay Science* , 201 , 105920. <https://doi.org/10.1016/j.clay.2020.105920>
- Florek, J., Chalifour, F., Bilodeau, F., Larivière, D., & Kleitz, F. (2014). Nanostructured Hybrid Materials for the Selective Recovery and Enrichment of Rare Earth Elements. *Advanced Functional Materials* ,24 (18), 2668–2676. <https://doi.org/10.1002/adfm.201303602>
- Florek, J., Giret, S., Juère, E., Larivière, D., & Kleitz, F. (2016). Functionalization of mesoporous

materials for lanthanide and actinide extraction. *Dalton Transactions* , 45 (38), 14832–14854. <https://doi.org/10.1039/C6DT00474A>

Florek, J., Larivière, D., Kählig, H., Fiorilli, S. L., Onida, B., Fontaine, F. G., & Kleitz, F. (2020). Understanding Selectivity of Mesoporous Silica-Grafted Diglycolamide-Type Ligands in the Solid-Phase Extraction of Rare Earths. *ACS Applied Materials and Interfaces* ,12 (51), 57003–57016. <https://doi.org/10.1021/acsami.0c16282>

Florek, J., Mushtaq, A., Larivière, D., Cantin, G., Fontaine, F. G., & Kleitz, F. (2015). Selective recovery of rare earth elements using chelating ligands grafted on mesoporous surfaces. *RSC Advances* ,5 (126), 103782–103789. <https://doi.org/10.1039/c5ra21027e>

Fonseka, C., Ryu, S., Choo, Y., Mullett, M., Thiruvengatachari, R., Naidu, G., & Vigneswaran, S. (2021). Selective Recovery of Rare Earth Elements from Mine Ore by Cr-MIL Metal–Organic Frameworks. *ACS Sustainable Chemistry and Engineering* , 9 (50), 16896–16904. https://doi.org/10.1021/ACSSUSCHEMENG.1C04775/SUPPL_FILE/SC1C04775_SI.001.PDF

Friend, M. T., Parker, T. G., Mastren, T., Mocko, V., Brugh, M., Birnbaum, E. R., & Fassbender, M. E. (2020). Extraction chromatography of 225Ac and lanthanides on N,N-diethylglycolamic acid /1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide solvent impregnated resin. *Journal of Chromatography A* , 1624 , 461219. <https://doi.org/10.1016/j.chroma.2020.461219>

Fritz, J. S., & Garraalda, B. B. (1963). Cation-exchange separation of bivalent metal ions from rare earths. *Talanta* , 10 (1), 91–95. [https://doi.org/10.1016/0039-9140\(63\)80209-X](https://doi.org/10.1016/0039-9140(63)80209-X)

Fryxell, G. E., Chouyyok, W., & Rutledge, R. D. (2011). Design and synthesis of chelating diamide sorbents for the separation of lanthanides. *Inorganic Chemistry Communications* , 14 (6), 971–974. <https://doi.org/10.1016/j.inoche.2011.03.045>

Fu, J., Chen, L., Li, J., & Zhang, Z. (2015). Current status and challenges of ion imprinting. *Journal of Materials Chemistry A* ,3 (26), 13598–13627. <https://doi.org/10.1039/c5ta02421h>

Gabor, A., Davidescu, C. M., Negrea, A., Ciopec, M., Muntean, C., Duteanu, N., & Negrea, P. (2016). Sorption properties of Amberlite XAD 7 functionalized with sodium β -glycerophosphate. *Pure and Applied Chemistry* , 88 (12), 1143–1154. <https://doi.org/10.1515/pac-2016-0806>

Gaete, J., Molina, L., Valenzuela, F., & Basualto, C. (2021). Recovery of lanthanum, praseodymium and samarium by adsorption using magnetic nanoparticles functionalized with a phosphonic group. *Hydrometallurgy* , 203 , 105698. <https://doi.org/10.1016/J.HYDROMET.2021.105698>

Gao, Q., Xie, J. F., Shao, Y. T., Chen, C., Han, B., Xia, K. S., & Zhou, C. G. (2017). Ultrafast and high-capacity adsorption of Gd(III) onto inorganic phosphorous acid modified mesoporous SBA-15. *Chemical Engineering Journal* , 313 , 197–206. <https://doi.org/10.1016/j.cej.2016.12.068>

Garcia, R., Pinel, C., Madic, C., & Lemaire, M. (1998). Ionic imprinting effect in gadolinium/lanthanum separation. *Tetrahedron Letters* , 39 (47), 8651–8654. [https://doi.org/10.1016/S0040-4039\(98\)01970-4](https://doi.org/10.1016/S0040-4039(98)01970-4)

Garg, B. S., Sharma, R. K., Bhojak, N., & Mittal, S. (1999). Chelating resins and their applications in the analysis of trace metal ions. *Microchemical Journal* , 61 (2), 94–114. <https://doi.org/10.1006/mchj.1998.1681>

Gasser, M. S., & Aly, M. I. (2013). Separation and recovery of rare earth elements from spent nickel-metal-hydride batteries using synthetic adsorbent. *International Journal of Mineral Processing* ,121 , 31–38. <https://doi.org/10.1016/j.minpro.2013.02.012>

Gasser, M. S., El Sherif, E., & Abdel Rahman, R. O. (2017). Modification of Mg-Fe hydrotalcite using Cyanex 272 for lanthanides separation. *Chemical Engineering Journal* , 316 , 758–769. <https://doi.org/10.1016/j.cej.2017.01.129>

- Ghobadi, M., Gharabaghi, M., Abdollahi, H., Boroumand, Z., & Moradian, M. (2018). MnFe₂O₄-graphene oxide magnetic nanoparticles as a high-performance adsorbent for rare earth elements: Synthesis, isotherms, kinetics, thermodynamics and desorption. *Journal of Hazardous Materials* , 351 , 308–316. <https://doi.org/10.1016/j.jhazmat.2018.03.011>
- Ghobadi, M., Gharabaghi, M., Abdollahi, H., & Shafiee Kisomi, A. (2017). A simple and low-cost route to recycle rare earth elements (La, Ce) from aqueous solution using magnetic nanoparticles of Co_xMn_{1-x}Fe₂O₄ (x = 0.2 and 0.8): synthesis, isotherms, kinetics, thermodynamics and desorption. *New Journal of Chemistry* , 41 (20), 11906–11914. <https://doi.org/10.1039/C7NJ02125A>
- Giret, S., Hu, Y., Masoumifard, N., Boulanger, J. F., Estelle, J., Kleitz, F., & Larivière, D. (2018). Selective Separation and Preconcentration of Scandium with Mesoporous Silica. *ACS Applied Materials and Interfaces* , 10 (1), 448–457. <https://doi.org/10.1021/acsami.7b13336>
- Gismondi, P., Kuzmin, A., Unsworth, C., Rangan, S., Khalid, S., & Saha, D. (2022). Understanding the Adsorption of Rare-Earth Elements in Oligo-Grafted Mesoporous Carbon. *Langmuir* , 38 (1), 203–210. https://doi.org/10.1021/ACS.LANGMUIR.1C02403/SUPPL_FILE/LA1C02403_SI_001.PDF
- Gok, C., Seyhan, S., Merdivan, M., & Yurdakoc, M. (2007). Separation and preconcentration of La³⁺, Ce³⁺ and Y³⁺ using calix[4]resorcinarene impregnated on polymeric support. *Microchimica Acta* , 157 (1–2), 13–19. <https://doi.org/10.1007/s00604-006-0646-2>
- Griffith, C. S., Reyes, M. D. L., Scales, N., Hanna, J. V., & Luca, V. (2010). Hybrid Inorganic-Organic Adsorbents Part 1: Synthesis and Characterization of Mesoporous Zirconium Titanate Frameworks Containing Coordinating Organic Functionalities. *ACS Applied Materials & Interfaces* , 2 (12), 3436–3446. <https://doi.org/10.1021/am100891u>
- Gschneidner, K. A., & Eyring, L. R. (1982). Preface. In *Handbook on the Physics and Chemistry of Rare Earths* (Vol. 5, p. 5). Elsevier. [https://doi.org/10.1016/S0168-1273\(82\)05001-6](https://doi.org/10.1016/S0168-1273(82)05001-6)
- GUO, J., CAI, J., & SU, Q. (2009). Ion imprinted polymer particles of neodymium: synthesis, characterization and selective recognition. *Journal of Rare Earths* , 27 (1), 22–27. [https://doi.org/10.1016/S1002-0721\(08\)60183-0](https://doi.org/10.1016/S1002-0721(08)60183-0)
- Guo, Lanyu, Xu, Y., Zhuo, M., Liu, L., Xu, Q., Wang, L., Shi, C., Ye, B., Fan, X., & Chen, W. (2018). Highly efficient removal of Gd(III) using hybrid hydrosols of carbon nanotubes/graphene oxide in dialysis bags and synergistic enhancement effect. *Chemical Engineering Journal* , 348 , 535–545. <https://doi.org/10.1016/j.cej.2018.04.212>
- Guo, Linru, Liu, Y., Dou, J., Huang, Q., Lei, Y., Chen, J., Wen, Y., Li, Y., Zhang, X., & Wei, Y. (2020). Highly efficient removal of Eu³⁺ ions using carbon nanotubes-based polymer composites synthesized from the combination of Diels-Alder and multicomponent reactions. *Journal of Molecular Liquids* , 308 , 112964. <https://doi.org/10.1016/j.molliq.2020.112964>
- Gupta, N. K., & Sengupta, A. (2017). Understanding the sorption behavior of trivalent lanthanides on amide functionalized multi walled carbon nanotubes. *Hydrometallurgy* , 171 , 8–15. <https://doi.org/10.1016/j.hydromet.2017.03.016>
- Hagiwara, Z. (1969). Elution of heavier rare earths with H.E.D.T.A. eluant at a high temperature. *Journal of Inorganic and Nuclear Chemistry* , 31 (9), 2933–2949. [https://doi.org/10.1016/0022-1902\(69\)80213-7](https://doi.org/10.1016/0022-1902(69)80213-7)
- Hale, W. H., & Hammer, C. A. (1972). Cation exchange elution sequence with DTPA. *Ion Exch. Membranes* , 1 (2), 81–85.
- Harris, D. C., & Lucy, C. A. (2015). *Quantitative Chemical Analysis* (9th ed.). W. H. Freeman. <https://books.google.com/books?id=PJhaMQAACAAJ>

- Helaly, O. S., Abd El-Ghany, M. S., Moustafa, M. I., Abuzaid, A. H., Abd El-Monem, N. M., & Ismail, I. M. (2012). Extraction of cerium(IV) using tributyl phosphate impregnated resin from nitric acid medium. *Transactions of Nonferrous Metals Society of China (English Edition)* , 22 (1), 206–214. [https://doi.org/10.1016/S1003-6326\(11\)61162-X](https://doi.org/10.1016/S1003-6326(11)61162-X)
- Heres, X., Blet, V., Di Natale, P., Ouattou, A., Mazouz, H., Dhiba, D., & Cuer, F. (2018). Selective Extraction of Rare Earth Elements from Phosphoric Acid by Ion Exchange Resins. *Metals* , 8 (9), 682. <https://doi.org/10.3390/met8090682>
- Hermassi, M., Granados, M., Valderrama, C., Ayora, C., & Cortina, J. L. (2021). Recovery of Rare Earth Elements from acidic mine waters by integration of a selective chelating ion-exchanger and a solvent impregnated resin. *Journal of Environmental Chemical Engineering* ,9 (5), 105906. <https://doi.org/10.1016/J.JECE.2021.105906>
- Hidayah, N. N., & Abidin, S. Z. (2017). The evolution of mineral processing in extraction of rare earth elements using solid-liquid extraction over liquid-liquid extraction: A review. In *Minerals Engineering* (Vol. 112, pp. 103–113). Elsevier Ltd. <https://doi.org/10.1016/j.mineng.2017.07.014>
- Hoffmann, F., Cornelius, M., Morell, J., & Froba, M. (2006). Silica-Based Mesoporous Organic-Inorganic Hybrid Materials. *Angewandte Chemie International Edition* , 45 (20), 3216–3251. <https://doi.org/10.1002/anie.200503075>
- Hovey, J. L., Dardona, M., Allen, M. J., & Dittrich, T. M. (2021). Sorption of rare-earth elements onto a ligand-associated media for pH-dependent extraction and recovery of critical materials. *Separation and Purification Technology* , 258 , 118061. <https://doi.org/10.1016/j.seppur.2020.118061>
- Hu, Y., Drouin, E., Lariviere, D., Kleitz, F., & Fontaine, F. G. (2017). Highly Efficient and Selective Recovery of Rare Earth Elements Using Mesoporous Silica Functionalized by Preorganized Chelating Ligands. *ACS Applied Materials and Interfaces* , 9 (44), 38584–38593. <https://doi.org/10.1021/acsami.7b12589>
- Hu, Y., Florek, J., Lariviere, D., Fontaine, F.-G., & Kleitz, F. (2018). Recent Advances in the Separation of Rare Earth Elements Using Mesoporous Hybrid Materials. *The Chemical Record* ,18 (7–8), 1261–1276. <https://doi.org/10.1002/tcr.201800012>
- Hu, Y., Misal Castro, L. C., Drouin, E., Florek, J., Kahlig, H., Lariviere, D., Kleitz, F., & Fontaine, F.-G. (2019). Size-Selective Separation of Rare Earth Elements Using Functionalized Mesoporous Silica Materials. *ACS Applied Materials & Interfaces* , 11 (26), 23681–23691. <https://doi.org/10.1021/acsami.9b04183>
- Hua, W., Zhang, T., Wang, M., Zhu, Y., & Wang, X. (2019). Hierarchically structural PAN/UiO-66-(COOH)₂ nanofibrous membranes for effective recovery of Terbium(III) and Europium(III) ions and their photoluminescence performances. *Chemical Engineering Journal* ,370 , 729–741. <https://doi.org/10.1016/j.cej.2019.03.255>
- Huang, L., Liu, L., Huang, W., Zhao, B., Shen, Z., Bao, Y., & Znad, H. (2021). Recovery of lanthanum cations by functionalized magnetic multi-walled carbon nanotube bundles. *RSC Advances* , 11 (8), 4751–4759. <https://doi.org/10.1039/D0RA09902C>
- Huang, R., Shao, N., Hou, L., & Zhu, X. (2019). Fabrication of an efficient surface ion-imprinted polymer based on sandwich-like graphene oxide composite materials for fast and selective removal of lead ions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* ,566 , 218–228. <https://doi.org/10.1016/j.colsurfa.2019.01.011>
- Hubicka, H., & Drobek, D. (1997). Anion-exchange method for separation of ytterbium from holmium and erbium. *Hydrometallurgy* ,47 (1), 127–136. [https://doi.org/10.1016/S0304-386X\(97\)00040-6](https://doi.org/10.1016/S0304-386X(97)00040-6)
- Hubicka, H., & Drobek, D. (1998). Studies on separation of iminodiacetate complexes of lanthanum (III) from neodymium (III) and praseodymium (III) on anion-exchangers. *Hydrometallurgy* ,50 (1), 51–60. [https://doi.org/10.1016/S0304-386X\(98\)00045-0](https://doi.org/10.1016/S0304-386X(98)00045-0)

- Hubicka, H., & Drobek, D. (1999). Separation of Y(III) complexes from Dy(III), Ho(III) and Er(III) complexes with iminodiacetic acid on the anion-exchangers type 1 and type 2. *Hydrometallurgy* ,53 (1), 89–100. [https://doi.org/10.1016/S0304-386X\(99\)00035-3](https://doi.org/10.1016/S0304-386X(99)00035-3)
- HUBICKA, H., & HUBICKI, Z. (1986). SEPARATION OP RARE EARTH - POLYALZDTCARBOXYLIC ACIDS COMPLEXES OK VARIOUS TYPES OF ANION-EXCHANGERS. *Solvent Extraction and Ion Exchange* ,4 (2), 383–399. <https://doi.org/10.1080/07366298608917872>
- Hubicka, H., & Kołodyńska, D. (2004). Separation of rare-earth element complexes with trans-1,2-diaminocyclohexane-N,N,N',N'-tetraacetic acid on polyacrylate anion exchangers. *Hydrometallurgy* ,71 (3–4), 343–350. [https://doi.org/10.1016/S0304-386X\(03\)00086-0](https://doi.org/10.1016/S0304-386X(03)00086-0)
- Hubicka, H., & Kołodyńska, D. (2008). Application of monodispersive anion exchangers in sorption and separation of Y3+ from Nd3+ and Sm3+ complexes with dcta. *Journal of Rare Earths* , 26 (5), 619–625. [https://doi.org/10.1016/S1002-0721\(08\)60149-0](https://doi.org/10.1016/S1002-0721(08)60149-0)
- Hubicki, Z., & Olszak, M. (1998). Studies of the sorption of rare earth element nitrate complexes in the C2H5OH-HNO3 system on the strongly basic anion exchanger Wofatit SBW. *Adsorption Science and Technology* , 16 (6), 487–492. <https://doi.org/10.1177/026361749801600606>
- Hubicki, Z., & Olszak, M. (2002). Studies on separation of rare earth elements on various types of anion-exchangers in the C3H7OH-7 M HNO3 systems. *Journal of Chromatography A* , 955 (2), 257–262. [https://doi.org/10.1016/S0021-9673\(02\)00212-1](https://doi.org/10.1016/S0021-9673(02)00212-1)
- Huo, Q., Margolese, D. I., & Stucky, G. D. (1996). Surfactant Control of Phases in the Synthesis of Mesoporous Silica-Based Materials. *Chemistry of Materials* , 8 (5), 1147–1160. <https://doi.org/10.1021/cm960137h>
- Ide, M., El-Roz, M., De Canck, E., Vicente, A., Planckaert, T., Bogaerts, T., Van Driessche, I., Lynen, F., Van Speybroeck, V., Thybault-Starzyk, F., & Van Der Voort, P. (2013). Quantification of silanol sites for the most common mesoporous ordered silicas and organosilicas: Total versus accessible silanols. *Physical Chemistry Chemical Physics* , 15 (2), 642–650. <https://doi.org/10.1039/c2cp42811c>
- Iftekhar, S., Ramasamy, D. L., Srivastava, V., Asif, M. B., & Sillanpää, M. (2018). Understanding the factors affecting the adsorption of Lanthanum using different adsorbents: A critical review. In *Chemosphere* (Vol. 204, pp. 413–430). <https://doi.org/10.1016/j.chemosphere.2018.04.053>
- Iftekhar, S., Srivastava, V., Casas, A., & Sillanpää, M. (2018). Synthesis of novel GA-g-PAM/SiO2 nanocomposite for the recovery of rare earth elements (REE) ions from aqueous solution. *Journal of Cleaner Production* , 170 , 251–259. <https://doi.org/10.1016/j.jclepro.2017.09.166>
- Iftekhar, S., Srivastava, V., & Sillanpää, M. (2017a). Enrichment of lanthanides in aqueous system by cellulose based silica nanocomposite. *Chemical Engineering Journal* , 320 , 151–159. <https://doi.org/10.1016/j.cej.2017.03.051>
- Iftekhar, S., Srivastava, V., & Sillanpää, M. (2017b). Synthesis and application of LDH intercalated cellulose nanocomposite for separation of rare earth elements (REEs). *Chemical Engineering Journal* ,309 , 130–139. <https://doi.org/10.1016/j.cej.2016.10.028>
- Ihara, T., Jyo, A., & Yamabe, K. (2001). METAL ION SELECTIVITY OF MACRORETICULAR CHELATING CATION EXCHANGE RESINS WITH PHOSPHONIC ACID GROUPS ATTACHED TO PHENYL GROUPS OF A STYRENE-DIVINYLBENZENE COPOLYMER MATRIX. *Separation Science and Technology* , 36 (15), 3511–3528. <https://doi.org/10.1081/SS-100107917>
- İnan, S., Tel, H., Sert, Çetinkaya, B., Sengül, S., Özkan, B., & Altaş, Y. (2018). Extraction and separation studies of rare earth elements using Cyanex 272 impregnated Amberlite XAD-7 resin. *Hydrometallurgy* , 181 (April), 156–163. <https://doi.org/10.1016/j.hydromet.2018.09.005>

- Jackson, M. L. (1954). Ion Exchangers in Analytical Chemistry. *Soil Science Society of America Journal* , 18 (1), 99. <https://doi.org/10.2136/sssaj1954.03615995001800010025x>
- James, D. B., Powell, J. E., & Spedding, F. H. (1961). Cation-exchange elution sequences-I Divalent and rare-earth cations with EDTA, hedta and citrate. *Journal of Inorganic and Nuclear Chemistry* ,19 (1–2), 133–141. [https://doi.org/10.1016/0022-1902\(61\)80055-9](https://doi.org/10.1016/0022-1902(61)80055-9)
- Jia, Q., Wang, Z. H., Li, D. Q., & Niu, C. J. (2004). Adsorption of heavy rare earth(III) with extraction resin containing bis(2,4,4-trimethylpentyl) monothiophosphinic acid. *Journal of Alloys and Compounds* , 374 (1–2), 434–437. <https://doi.org/10.1016/j.jallcom.2003.11.056>
- Jiang, L., Zhang, W., Luo, C., Cheng, D., & Zhu, J. (2016). Adsorption toward Trivalent Rare Earth Element from Aqueous Solution by Zeolitic Imidazolate Frameworks. *Industrial & Engineering Chemistry Research* , 55 (22), 6365–6372. <https://doi.org/10.1021/acs.iecr.6b00422>
- Johannesson, K. H., Lyons, W. B., Stetzenbach, K. J., & Byrne, R. H. (1995). The solubility control of rare earth elements in natural terrestrial waters and the significance of PO₄³⁻ and CO₃²⁻ in limiting dissolved rare earth concentrations: A review of recent information. *Aquatic Geochemistry* , 1 (2), 157–173. <https://doi.org/10.1007/BF00702889>
- Juère, E., Florek, J., Larivière, D., Kim, K., & Kleitz, F. (2016). Support effects in rare earth element separation using diglycolamide-functionalized mesoporous silica. *New Journal of Chemistry* , 40 (5), 4325–4334. <https://doi.org/10.1039/c5nj03147h>
- Jyo, A., Yamabe, K., & Egawa, H. (1997). Metal Ion Selectivity of a Macroreticular Styrene-Divinylbenzene Copolymer-Based Methylenephosphonic Acid Resin. *Separation Science and Technology* , 32 (6), 1099–1105. <https://doi.org/10.1080/01496399708000948>
- Kabay, N., Cortina, J. L., Trochimczuk, A., & Streat, M. (2010). Solvent-impregnated resins (SIRs) - Methods of preparation and their applications. *Reactive and Functional Polymers* , 70 (8), 484–496. <https://doi.org/10.1016/j.reactfunctpolym.2010.01.005>
- Kala, R., Biju, V. M., & Rao, T. P. (2005). Synthesis, characterization, and analytical applications of erbium(III) ion imprinted polymer particles prepared via γ -irradiation with different functional and crosslinking monomers. *Analytica Chimica Acta* ,549 (1–2), 51–58. <https://doi.org/10.1016/j.aca.2005.06.024>
- Kala, R., Mary Gladis, J., & Prasada Rao, T. (2004). Preconcentrative separation of erbium from Y, Dy, Ho, Tb and Tm by using ion imprinted polymer particles via solid phase extraction. *Analytica Chimica Acta* , 518 (1–2), 143–150. <https://doi.org/10.1016/j.aca.2004.05.029>
- Kaneko, T., Hikosaka, R., Nagata, F., Inagaki, M., & Kato, K. (2019). Effective adsorption of dysprosium ions on amino and carboxyl functionalized mesoporous silica sheets. *Journal of Asian Ceramic Societies* , 7 (2), 213–220. <https://doi.org/10.1080/21870764.2019.1606139>
- Kaneko, T., Nagata, F., Kugimiya, S., & Kato, K. (2018). Optimization of carboxyl-functionalized mesoporous silica for the selective adsorption of dysprosium. *Journal of Environmental Chemical Engineering* , 6 (5), 5090–5098. <https://doi.org/10.1016/j.jece.2018.09.018>
- Karraker, R. H. (1961). *Stability constants of some rare-earth-metal chelates* . 1961 , 105. <https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=2968&context=rtd>
- Kavun, V., van der Veen, M. A., & Repo, E. (2021). Selective recovery and separation of rare earth elements by organophosphorus modified MIL-101(Cr). *Microporous and Mesoporous Materials* , 312 , 110747. <https://doi.org/10.1016/j.micromeso.2020.110747>
- Kazantsev, E. I., Fisenko, V. V., & Mal'tsev, G. I. (1974). Complexing of rare earth ions with carboxylic cationite KB-2x7. *Izv. Vyssh. Uchebn. Zaved., Khim. Khim. Tekhnol* , 17 (9), 1304–1306. https://inis.iaea.org/search/search.aspx?orig_q=RN:6174755

- Keçili, R., Dolak, İ., Ziyadanoğulları, B., Ersöz, A., & Say, R. (2018). Ion imprinted cryogel-based supermacroporous traps for selective separation of cerium(III) in real samples. *Journal of Rare Earths* , 36 (8), 857–862. <https://doi.org/10.1016/j.jre.2018.02.008>
- Kegl, T., Ban, I., Lobnik, A., & Košak, A. (2019). Synthesis and characterization of novel Γ -Fe₂O₃-NH₄OH@SiO₂(APTMS) nanoparticles for dysprosium adsorption. *Journal of Hazardous Materials* ,378 , 120764. <https://doi.org/10.1016/j.jhazmat.2019.120764>
- Kharitonov, O. V., Firsova, L. A., & Chuveleva, E. A. (2009a). The accumulation of the competing displacer ion in the retaining ion zone in the separation of rare-earth metals by complex formation displacement chromatography. *Russian Journal of Physical Chemistry A* ,83 (7), 1217–1219. <https://doi.org/10.1134/S0036024409070309>
- Kharitonov, O. V., Firsova, L. A., & Chuveleva, E. A. (2009b). The influence of a competing eluting ion content on the efficiency of separation of rare-earth metals in displacement complex forming chromatography. *Russian Journal of Physical Chemistry A* ,83 (6), 1030–1031. <https://doi.org/10.1134/S0036024409060284>
- Khawassek, Y. M., Eliwa, A. A., Haggag, E. S. A., Omar, S. A., & Abdel-Wahab, S. M. (2019). Adsorption of rare earth elements by strong acid cation exchange resin thermodynamics, characteristics and kinetics. *SN Applied Sciences* , 1 (1), 51. <https://doi.org/10.1007/s42452-018-0051-6>
- Kilian, K., Pyrżyńska, K., & Pegier, M. (2017). Comparative Study of Sc(III) Sorption onto Carbon-based Materials. *Solvent Extraction and Ion Exchange* , 35 (6), 450–459. <https://doi.org/10.1080/07366299.2017.1354580>
- Kim, H., Lee, J., & Jung, H. (2019). Study on the carbamoyl phosphine oxide moiety functionalized mesoporous graphene for the removal of rare earth elements. *Journal of Porous Materials* , 26 (4), 931–939. <https://doi.org/10.1007/s10934-018-0691-3>
- Kogan, L., & Ratner, R. (1971). The separation of yttrium from the lanthanides by ion exchange with diethylenetriaminepentaacetic acid as eluant. I. Separation of yttrium-erbium mixtures. *Journal of Chromatography A* , 62 (3), 449–457. [https://doi.org/10.1016/S0021-9673\(00\)91397-9](https://doi.org/10.1016/S0021-9673(00)91397-9)
- Kołodnyńska, D., Hubicki, Z., & Fila, D. (2019). Recovery of rare earth elements from acidic solutions using macroporous ion exchangers. *Separation Science and Technology* , 54 (13), 2059–2076. <https://doi.org/10.1080/01496395.2019.1604753>
- Koochaki-Mohammadpour, S. M. A., Torab-Mostaedi, M., Talebizadeh-Rafsanjani, A., & Naderi-Behdani, F. (2014). Adsorption Isotherm, Kinetic, Thermodynamic, and Desorption Studies of Lanthanum and Dysprosium on Oxidized Multiwalled Carbon Nanotubes. *Journal of Dispersion Science and Technology* , 35 (2), 244–254. <https://doi.org/10.1080/01932691.2013.785361>
- Koodynska, D., & Hubicki, Z. (2012). Investigation of Sorption and Separation of Lanthanides on the Ion Exchangers of Various Types. In *Ion Exchange Technologies: Vol. i* (Issue tourism). InTech. <https://doi.org/10.5772/50857>
- Korkisch, J., Feik, F., & Ahluwalia, S. S. (1967). Cation-exchange behaviour of several elements in nitric acid-organic solvent media. *Talanta* , 14 (9), 1069–1081. [https://doi.org/10.1016/0039-9140\(67\)80145-0](https://doi.org/10.1016/0039-9140(67)80145-0)
- Kosmulski, M. (1997a). Standard enthalpies of adsorption of di- and trivalent cations on alumina. *Journal of Colloid and Interface Science* , 192 (1), 215–227. <https://doi.org/10.1006/jcis.1997.4994>
- Kosmulski, M. (1997b). Adsorption of Trivalent Cations on Silica. *Journal of Colloid and Interface Science* , 195 (2), 395–403. <https://doi.org/10.1006/jcis.1997.5155>
- Kostenko, L., Kobylinska, N., Khainakov, S., & Granda, S. G. (2019). Magnetite nanoparticles with aminomethylenephosphonic groups: synthesis, characterization and uptake of europium(III) ions from aqueous media. *Microchimica Acta* , 186 (7), 474. <https://doi.org/10.1007/s00604-019-3520-8>

- Kowal-Fouchard, A., Drot, R., Simoni, E., Marmier, N., Fromage, F., & Ehrhardt, J. J. (2004). Structural identification of europium(III) adsorption complexes on montmorillonite. *New Journal of Chemistry* , 28 (7), 864–869. <https://doi.org/10.1039/b400306c>
- Kumar, B. N., Radhika, S., Kantam, M. L., & Reddy, B. R. (2011). Solid-liquid extraction of terbium from phosphoric acid solutions using solvent-impregnated resin containing TOPS 99. *Journal of Chemical Technology & Biotechnology* , 86 (4), 562–569. <https://doi.org/10.1002/jctb.2553>
- Kumar, D., Schumacher, K., Du Fresne von Hohenesche, C., Grün, M., & Unger, K. K. (2001). MCM-41, MCM-48 and related mesoporous adsorbents: their synthesis and characterisation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* , 187 –188 , 109–116. [https://doi.org/10.1016/S0927-7757\(01\)00638-0](https://doi.org/10.1016/S0927-7757(01)00638-0)
- Lee, G. S., Uchikoshi, M., Mimura, K., & Isshiki, M. (2009). Distribution coefficients of La, Ce, Pr, Nd, and Sm on Cyanex 923-, D2EHPA-, and PC88A-impregnated resins. *Separation and Purification Technology* , 67 (1), 79–85. <https://doi.org/10.1016/j.seppur.2009.03.033>
- Lee, G. S., Uchikoshi, M., Mimura, K., & Isshiki, M. (2010a). Preparation and evaluation of high-purity La₂O₃. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science* , 41 (3), 509–519. <https://doi.org/10.1007/s11663-010-9348-6>
- Lee, G. S., Uchikoshi, M., Mimura, K., & Isshiki, M. (2010b). Separation of major impurities Ce, Pr, Nd, Sm, Al, Ca, Fe, and Zn from La using bis(2-ethylhexyl)phosphoric acid (D2EHPA)-impregnated resin in a hydrochloric acid medium. *Separation and Purification Technology* , 71 (2), 186–191. <https://doi.org/10.1016/j.seppur.2009.11.020>
- Lee, Y.-R., Yu, K., Ravi, S., & Ahn, W.-S. (2018). Selective Adsorption of Rare Earth Elements over Functionalized Cr-MIL-101 [Research-article]. *ACS Applied Materials & Interfaces* ,10 (28), 23918–23927. <https://doi.org/10.1021/acsami.8b07130>
- Lee, Y. R., Zhang, S., Yu, K., Choi, J., & Ahn, W. S. (2019). Poly(amidoamine) dendrimer immobilized on mesoporous silica foam (MSF) and fibrous nano-silica KCC-1 for Gd³⁺ adsorption in water. *Chemical Engineering Journal* , 378 , 122133. <https://doi.org/10.1016/j.cej.2019.122133>
- Li, C., Zhuang, Z., Huang, F., Wu, Z., Hong, Y., & Lin, Z. (2013). Recycling rare earth elements from industrial wastewater with flowerlike nano-Mg(OH)₂. *ACS Applied Materials and Interfaces* , 5 (19), 9719–9725. <https://doi.org/10.1021/am4027967>
- Li, D., Zhang, B., & Xuan, F. (2015). The sorption of Eu(III) from aqueous solutions by magnetic graphene oxides: A combined experimental and modeling studies. *Journal of Molecular Liquids* , 211 , 203–209. <https://doi.org/10.1016/j.molliq.2015.07.012>
- Li, J., Gong, A., Li, F., Qiu, L., Zhang, W., Gao, G., Liu, Y., & Li, J. (2018). Synthesis and characterization of magnetic mesoporous Fe₃O₄@mSiO₂-DODGA nanoparticles for adsorption of 16 rare earth elements. *RSC Advances* , 8 (68), 39149–39161. <https://doi.org/10.1039/c8ra07762b>
- Li, J., Gong, A., Qiu, L., Zhang, W., Shi, G., Li, X., Li, J., Gao, G., & Bai, Y. (2020). Selective extraction and column separation for 16 kinds of rare earth element ions by using N, N-diethyl diglycolic acid grafted silica gel particles as the stationary phase. *Journal of Chromatography A* , 1627 . <https://doi.org/10.1016/j.chroma.2020.461393>
- Li, K., Gao, Q., Yadavalli, G., Shen, X., Lei, H., Han, B., Xia, K., & Zhou, C. (2015). Selective Adsorption of Gd³⁺ on a Magnetically Retrievable Imprinted Chitosan/Carbon Nanotube Composite with High Capacity. *ACS Applied Materials and Interfaces* , 7 (38), 21047–21055. <https://doi.org/10.1021/acsami.5b07560>
- Li, X., Lu, T., Wang, Y., & Yang, Y. (2019). Study on the controllable synthesis of SH-MCM-41 mesoporous materials and their adsorption properties of the La³⁺, Gd³⁺ and Yb³⁺. *Chinese Chemical Letters* ,30 (12), 2318–2322. <https://doi.org/10.1016/j.ccl.2019.05.056>

- Liao, C., Nie, H., Jiao, Y., Liang, Y., & Yang, S. (2010). Study on the diffusion kinetics of adsorption of heavy rare earth with Cyanex272-P507 impregnated resin. *Journal of Rare Earths* , 28 (SUPPL. 1), 120–124. [https://doi.org/10.1016/S1002-0721\(10\)60290-6](https://doi.org/10.1016/S1002-0721(10)60290-6)
- Liu, J., Martin, P. F., & Peter McGrail, B. (2021). Rare-earth element extraction from geothermal brine using magnetic core-shell nanoparticles-techno-economic analysis. *Geothermics* , 89 , 101938. <https://doi.org/10.1016/j.geothermics.2020.101938>
- Liu, Y., Zhu, L., Sun, X., Chen, J., & Luo, F. (2009). Silica materials doped with bifunctional ionic liquid extractant for yttrium extraction. *Industrial and Engineering Chemistry Research* , 48 (15), 7308–7313. <https://doi.org/10.1021/ie900468c>
- Liu, Zhanmeng, Chen, G., Li, X., & Lu, X. (2021). Removal of rare earth elements by MnFe₂O₄ based mesoporous adsorbents: Synthesis, isotherms, kinetics, thermodynamics. *Journal of Alloys and Compounds* , 856 , 158185. <https://doi.org/10.1016/J.JALLCOM.2020.158185>
- Liu, Zhanmeng, Gao, Z., Xu, L., & Hu, F. (2020). Efficient and rapid adsorption of rare earth elements from water by magnetic Fe₃O₄/MnO₂ decorated reduced graphene oxide. *Journal of Molecular Liquids* , 313 , 113510. <https://doi.org/10.1016/j.molliq.2020.113510>
- Liu, Zhaowang, Feng, Y., & Li, H. (2021). Application of titanium phosphate prepared from acidic titanium dioxide wastewater to remove cerium (III) in aqueous solution. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* , 630 , 127613. <https://doi.org/10.1016/J.COLSURFA.2021.127613>
- Liu, Zhe, Liu, Y., & Gong, A. (2019). Preparation of diglycolamide polymer modified silica and its application as adsorbent for rare earth ions. *Designed Monomers and Polymers* , 22 (1), 1–7. <https://doi.org/10.1080/15685551.2018.1564425>
- Lokshin, E. P., Ivanenko, V. I., Tareeva, O. A., & Korneikov, R. I. (2013). Sorption of rare earth elements of waste solution of leaching uranium. *Russian Journal of Applied Chemistry* , 86 (3), 450–452. <https://doi.org/10.1134/S1070427213030269>
- Losev, V., Buyko, O., Metelitsa, S., Borodina, E., Kuzmin, N., & Shimanskiy, A. (2020). Novel silica based adsorbent layer-by-layer modified with polyhexamethylene guanidine and Arsenazo reagents for solid-phase extraction of lanthanides from lignites and products of their processing. *Separation Science and Technology (Philadelphia)* . <https://doi.org/10.1080/01496395.2020.1785500>
- Lou, Z., Xiao, X., Huang, M., Wang, Y., Xing, Z., & Xiong, Y. (2019). Acrylic Acid-Functionalized Metal–Organic Frameworks for Sc(III) Selective Adsorption [Research-article]. *ACS Applied Materials & Interfaces* , 11 (12), 11772–11781. <https://doi.org/10.1021/acsami.9b00476>
- Louis, R. E., & Duyckaerts, G. (1984). Some parameters affecting the extraction chromatographic performance of TBP impregnated macroporous XAD-4 columns for Am(III)-Eu(III) separations. *Journal of Radioanalytical and Nuclear Chemistry Articles* , 81 (2), 305–315. <https://doi.org/10.1007/BF02135383>
- Louis, R. E., & Duyckaerts, G. (1985). Some parameters affecting column distribution ratios of Am(III) and Eu(III) and column resolution of TBP impregnated macroporous XAD-4 polymers. *Journal of Radioanalytical and Nuclear Chemistry Articles* , 90 (1), 105–112. <https://doi.org/10.1007/BF02037325>
- Ma, T. Y., Liu, L., & Yuan, Z. Y. (2013). Direct synthesis of ordered mesoporous carbons. *Chemical Society Reviews* , 42 (9), 3977–4003. <https://doi.org/10.1039/c2cs35301f>
- Mackey, J. L., Key, M. A. C., Lirai, J., & Of, A. S. (1960). *A study of the rare-earth chelate stability constants of some aminopolycarboxylic acids exactly as received* .
- Mahmoud, M. E., Mohamed, A. K., Amira, M. F., & Seleim, S. M. (2019). Novel Nanostructured Metal–Organic Framework-Bonded Silica Amine and Polymer: Facile Synthesis, Kinetics, Isotherms, and Thermody-

- namics Evaluation for Adsorption of Yttrium(III) Ions [Research-article]. *Journal of Chemical & Engineering Data* , 64 (12), 6060–6070. <https://doi.org/10.1021/acs.jced.9b00918>
- Marmier, N., Dumonceau, J., & Fromage, F. (1997). Surface complexation modeling of Yb(III) sorption and desorption on hematite and alumina. *Journal of Contaminant Hydrology* , 26 (1–4), 159–167. [https://doi.org/10.1016/S0169-7722\(96\)00065-4](https://doi.org/10.1016/S0169-7722(96)00065-4)
- Marmier, Nicolas, Delisée, A., & Fromage, F. (1999). Surface Complexation Modeling of Yb(III) and Cs(I) Sorption on Silica. *Journal of Colloid and Interface Science* , 212 (2), 228–233. <https://doi.org/10.1006/jcis.1999.6086>
- Marmier, Nicolas, & Fromage, F. (1999). Comparing Electrostatic and Nonelectrostatic Surface Complexation Modeling of the Sorption of Lanthanum on Hematite. *Journal of Colloid and Interface Science* , 212 (2), 252–263. <https://doi.org/10.1006/jcis.1998.6039>
- Martell, A. E., & Hancock, R. D. (1996). Metal Complexes in Aqueous Solutions. In *Metal Complexes in Aqueous Solutions* . Springer US. <https://doi.org/10.1007/978-1-4899-1486-6>
- Martynenko, L. I., Kupriyanova, G. N., & Prutkova, N. M. (1972). Non-ion exchange sorption of mononitroacetates of rare-earth elements on cationite. *Zhurnal Neorganicheskoy Khimii* , 17 (1), 214–217. http://inis.iaea.org/Search/search.aspx?orig_q=RN:3033722
- Martynenko, L. I., Mitrofanova, N. D., & Spitsyn, V. I. (1968). Mechanism of the ion-exchange separation of mixtures of rare earth elements during elution with solutions of nitrilotriacetic acid. *Bulletin of the Academy of Sciences of the USSR Division of Chemical Science* , 17 (9), 1854–1861. <https://doi.org/10.1007/BF00904970>
- Marwani, H. M., Albishri, H. M., Jalal, T. A., & Soliman, E. M. (2017). Study of isotherm and kinetic models of lanthanum adsorption on activated carbon loaded with recently synthesized Schiff's base. *Arabian Journal of Chemistry* , 10 , S1032–S1040. <https://doi.org/10.1016/j.arabjc.2013.01.008>
- Marwani, H. M., & Alsafrani, A. E. (2013). New solid phase extractor based on ionic liquid functionalized silica gel surface for selective separation and determination of lanthanum. *Journal of Analytical Science and Technology* , 4 (1), 1–10. <https://doi.org/10.1186/2093-3371-4-13>
- Marwani, H. M., Bakhsh, E. M., Khan, S. B., Danish, E. Y., & Asiri, A. M. (2018). Cerium oxide-cadmium oxide nanomaterial as efficient extractant for yttrium ions. *Journal of Molecular Liquids* , 269 , 252–259. <https://doi.org/10.1016/j.molliq.2018.08.046>
- Masi, A. N., & Olsina, R. A. (1993). Preconcentration and determination of Ce, La and Pr by X-ray fluorescence analysis, using Amberlite XAD resins loaded with 8-Quinolinol and 2-(2-(5-chloropyridylazo)-5-dimethylamino)-phenol. *Talanta* , 40 (6), 931–934. [https://doi.org/10.1016/0039-9140\(93\)80054-U](https://doi.org/10.1016/0039-9140(93)80054-U)
- Mathur, J. N., & Khopkar, P. K. (1985). Ion Exchange Behaviour of Chelating Resin Dowex A-1 with Actinides and Lanthanides. *Solvent Extraction and Ion Exchange* , 3 (5), 753–762. <https://doi.org/10.1080/07366298508918538>
- Mehmood, A., Ghafar, H., Yaqoob, S., Gohar, U. F., & Ahmad, B. (2017). Mesoporous Silica Nanoparticles: A Review. *Journal of Developing Drugs* , 06 (02). <https://doi.org/10.4172/2329-6631.1000174>
- Meng, M., Meng, X., Liu, Y., Liu, Z., Han, J., Wang, Y., Luo, M., Chen, R., Ni, L., & Yan, Y. (2014). An ion-imprinted functionalized SBA-15 adsorbent synthesized by surface imprinting technique via reversible addition-fragmentation chain transfer polymerization for selective removal of Ce(III) from aqueous solution. *Journal of Hazardous Materials* , 278 , 134–143. <https://doi.org/10.1016/j.jhazmat.2014.06.002>
- Metwally, S. S., & Rizk, H. E. (2014). Preparation and Characterization of Nano-Sized Iron–Titanium Mixed Oxide for Removal of Some Lanthanides from Aqueous Solution. *Separation Science and Technology* , 49 (15), 2426–2436. <https://doi.org/10.1080/01496395.2014.926457>

- Meynen, V., Cool, P., & Vansant, E. F. (2009). Verified syntheses of mesoporous materials. *Microporous and Mesoporous Materials* ,125 (3), 170–223. <https://doi.org/10.1016/j.micromeso.2009.03.046>
- Miklishanskii, A. Z., Yakovlev, Y. V., Dogadkin, N. N., Leikin, Y. A., & Davankov, A. B. (1968). Investigation of the sorption of the rare-earth elements and uranium by phosphorus-containing cation-exchange resins. *Bulletin of the Academy of Sciences of the USSR Division of Chemical Science* , 17 (7), 1373–1376. <https://doi.org/10.1007/BF00907827>
- Minczewski, J, Chwastowska, J., Dybczynski, R., & Masson, M. R. (1982). *Separation and preconcentration methods in inorganic trace analysis* . E. Horwood ; Halsted Press.
- Minczewski, Jerzy, & Dybczyński, R. (1962). Separation of rare earths on anion exchange resins II. Anion exchange behaviour of the rare earth complexes with ethylenediaminetetraacetic acid. *Journal of Chromatography A* , 7 (C), 98–111. [https://doi.org/10.1016/s0021-9673\(01\)86386-x](https://doi.org/10.1016/s0021-9673(01)86386-x)
- Miraoui, A., Didi, M. A., & Villemin, D. (2016). Neodymium(III) removal by functionalized magnetic nanoparticles. *Journal of Radioanalytical and Nuclear Chemistry* , 307 (2), 963–971. <https://doi.org/10.1007/s10967-015-4267-2>
- Mohamed, W. R., Metwally, S. S., Ibrahim, H. A., El-Sherief, E. A., Mekhamer, H. S., Moustafa, I. M. I., & Mabrouk, E. M. (2017). Impregnation of task-specific ionic liquid into a solid support for removal of neodymium and gadolinium ions from aqueous solution. *Journal of Molecular Liquids* , 236 , 9–17. <https://doi.org/10.1016/j.molliq.2017.04.013>
- Mohammedi, H., Miloudi, H., Tayeb, A., Bertagnolli, C., & Boos, A. (2019). Study on the extraction of lanthanides by a mesoporous MCM-41 silica impregnated with Cyanex 272. *Separation and Purification Technology* , 209 (February 2018), 359–367. <https://doi.org/10.1016/j.seppur.2018.07.035>
- Molina, L., Gaete, J., Alfaro, I., Ide, V., Valenzuela, F., Parada, J., & Basualto, C. (2019). Synthesis and characterization of magnetite nanoparticles functionalized with organophosphorus compounds and its application as an adsorbent for La (III), Nd (III) and Pr (III) ions from aqueous solutions. *Journal of Molecular Liquids* , 275 , 178–191. <https://doi.org/10.1016/j.molliq.2018.11.074>
- Moloney, M. P., Causse, J., Loubat, C., & Grandjean, A. (2014). Sodium “Activation” of Silano-Phosphonate Modified Mesoporous TiO₂ Leading to Improved Rare-Earth Element Extraction. *European Journal of Inorganic Chemistry* , 2014 (13), 2268–2277. <https://doi.org/10.1002/ejic.201400027>
- Mondal, S., Ghar, A., Satpati, A. K., Sinharoy, P., Singh, D. K., Sharma, J. N., Sreenivas, T., & Kain, V. (2019). Recovery of rare earth elements from coal fly ash using TEHDGA impregnated resin. *Hydrometallurgy* , 185 , 93–101. <https://doi.org/10.1016/j.hydromet.2019.02.005>
- Mosai, A. K., Chimuka, L., Cukrowska, E. M., Kotzé, I. A., & Tutu, H. (2019). The Recovery of Rare Earth Elements (REEs) from Aqueous Solutions Using Natural Zeolite and Bentonite. *Water, Air, and Soil Pollution* , 230 (8). <https://doi.org/10.1007/s11270-019-4236-4>
- Moussa, M., Ndiaye, M. M., Pinta, T., Pichon, V., Vercouter, T., & Delaunay, N. (2017). Selective solid phase extraction of lanthanides from tap and river waters with ion imprinted polymers. *Analytica Chimica Acta* , 963 , 44–52. <https://doi.org/10.1016/j.aca.2017.02.012>
- Muraviev, D. (1998). Surface impregnated sulfonate ion exchangers: Preparation, properties and application. *Solvent Extraction and Ion Exchange* , 16 (1), 381–457. <https://doi.org/10.1080/07366299808934533>
- Muraviev, D., Ghantous, L., & Valiente, M. (1998). Stabilization of solvent-impregnated resin capacities by different techniques. *Reactive and Functional Polymers* , 38 (2–3), 259–268. [https://doi.org/10.1016/s1381-5148\(98\)00075-3](https://doi.org/10.1016/s1381-5148(98)00075-3)
- Narayan, R., Nayak, U. Y., Raichur, A. M., & Garg, S. (2018). Mesoporous silica nanoparticles: A comprehensive review on synthesis and recent advances. *Pharmaceutics* , 10 (3), 1–49. <https://doi.org/10.3390/ph10030033>

ps://doi.org/10.3390/pharmaceutics10030118

Naser, A. A., El-deen, G. E. S., Bhran, A. A., Metwally, S. S., & El-Kamash, A. M. (2015). Elaboration of Impregnated Composite for Sorption of Europium and Neodymium Ions from Aqueous Solutions. *Journal of Industrial and Engineering Chemistry* , 32 , 264–272. <https://doi.org/10.1016/j.jiec.2015.08.024>

Nash, K. L. (1993). A review of the basic chemistry and recent developments in trivalent f-elements separations. *Solvent Extraction and Ion Exchange* , 11 (4), 729–768. <https://doi.org/10.1080/07366299308918184>

Nelson, F. (1965). Ion-exchange procedures. *Journal of Chromatography A* , 20 , 378–383. [https://doi.org/10.1016/s0021-9673\(01\)97426-6](https://doi.org/10.1016/s0021-9673(01)97426-6)

Ngomsik, A. F., Bee, A., Talbot, D., & Cote, G. (2012). Magnetic solid-liquid extraction of Eu(III), La(III), Ni(II) and Co(II) with maghemite nanoparticles. *Separation and Purification Technology* , 86 , 1–8. <https://doi.org/10.1016/j.seppur.2011.10.013>

Ni, C., Liu, Q., Ren, Z., Hu, H., Sun, B., Liu, C., Shao, P., Yang, L., Pavlostathis, S. G., & Luo, X. (2021). Selective removal and recovery of La(III) using a phosphonic-based ion imprinted polymer: Adsorption performance, regeneration, and mechanism. *Journal of Environmental Chemical Engineering* , 9 (6), 106701. <https://doi.org/10.1016/J.JECE.2021.106701>

Nik Mustapa, N. R., Malek, N. F. A., Yusoff, M. M., & Rahman, M. L. (2016). Ion imprinted polymers for selective recognition and separation of lanthanum and cerium ions from other lanthanide. *Separation Science and Technology (Philadelphia)* , 51 (17), 2762–2771. <https://doi.org/10.1080/01496395.2016.1225091>

Nishihama, S., Kohata, K., & Yoshizuka, K. (2013). Separation of lanthanum and cerium using a coated solvent-impregnated resin. *Separation and Purification Technology* , 118 , 511–518. <https://doi.org/10.1016/j.seppur.2013.07.047>

Niu, F., Xie, Z., Fu, C., Xu, H., Liu, D., Zhang, X., Yang, Y., & Shen, L. (2021). Adsorption–Desorption of La³⁺, Eu³⁺, and Y³⁺ by Mg(OH)₂-Pretreated TP207 Resin. *JOM* , 73 (1), 32–38. <https://doi.org/10.1007/s11837-020-04472-2>

Noack, C. W., Dzombak, D. A., & Karamalidis, A. K. (2014). Rare earth element distributions and trends in natural waters with a focus on groundwater. *Environmental Science and Technology* , 48 (8), 4317–4326. <https://doi.org/10.1021/es4053895>

Noack, C. W., Perkins, K. M., Callura, J. C., Washburn, N. R., Dzombak, D. A., & Karamalidis, A. K. (2016). Effects of Ligand Chemistry and Geometry on Rare Earth Element Partitioning from Saline Solutions to Functionalized Adsorbents. *ACS Sustainable Chemistry & Engineering* , 4 (11), 6115–6124. <https://doi.org/10.1021/acssuschemeng.6b01549>

Ochsenkühn-Petropulu, M., Lyberopulu, T., & Parissakis, G. (1995). Selective separation and determination of scandium from yttrium and lanthanides in red mud by a combined ion exchange/solvent extraction method. *Analytica Chimica Acta* , 315 (1–2), 231–237. [https://doi.org/10.1016/0003-2670\(95\)00309-N](https://doi.org/10.1016/0003-2670(95)00309-N)

Ogata, T., Narita, H., & Tanaka, M. (2014). Immobilization of diglycol amic acid on silica gel for selective recovery of rare earth elements. *Chemistry Letters* , 43 (9), 1414–1416. <https://doi.org/10.1246/cl.140446>

Ogata, T., Narita, H., & Tanaka, M. (2015a). Adsorption behavior of rare earth elements on silica gel modified with diglycol amic acid. *Hydrometallurgy* , 152 , 178–182. <https://doi.org/10.1016/j.hydromet.2015.01.005>

Ogata, T., Narita, H., & Tanaka, M. (2015b). Rapid and selective recovery of heavy rare earths by using an adsorbent with diglycol amic acid group. *Hydrometallurgy* , 155 , 105–109. <https://doi.org/10.1016/j.hydromet.2015.04.015>

Ogata, T., Narita, H., Tanaka, M., Hoshino, M., Kon, Y., & Watanabe, Y. (2016). Selective recovery of heavy rare earth elements from apatite with an adsorbent bearing immobilized tridentate amido ligands. *Separation and Purification Technology* , 159 , 157–160. <https://doi.org/10.1016/j.seppur.2016.01.008>

- Ohta, A., & Kawabe, I. (2001). REE(III) adsorption onto Mn dioxide (δ -MnO₂) and Fe oxyhydroxide: Ce(III) oxidation by δ -MnO₂. *Geochimica et Cosmochimica Acta* , 65 (5), 695–703. [https://doi.org/10.1016/S0016-7037\(00\)00578-0](https://doi.org/10.1016/S0016-7037(00)00578-0)
- Page, M. J., Quinn, J. E., & Soldenhoff, K. H. (2019). The impact of sulfate ions on the ion exchange of rare earth elements. *Hydrometallurgy* , 186 , 12–20. <https://doi.org/10.1016/j.hydromet.2019.03.003>
- Page, M. J., Soldenhoff, K., & Ogden, M. D. (2017). Comparative study of the application of chelating resins for rare earth recovery. *Hydrometallurgy* , 169 , 275–281. <https://doi.org/10.1016/j.hydromet.2017.02.006>
- Pallavicini, P., Dacarro, G., Diaz-Fernandez, Y. A., & Taglietti, A. (2014). Coordination chemistry of surface-grafted ligands for antibacterial materials. In *Coordination Chemistry Reviews* (Vol. 275, pp. 37–53). Elsevier. <https://doi.org/10.1016/j.ccr.2014.04.013>
- Pan, J., Zou, X., Li, C., Liu, Y., Yan, Y., & Han, J. (2010). Synthesis and applications of Ce(III)-imprinted polymer based on attapulgite as the sacrificial support material for selective separation of cerium(III) ions. *Microchimica Acta* , 171 (1), 151–160. <https://doi.org/10.1007/s00604-010-0416-z>
- PARK, J., HAN, C., LEE, J., KIM, S., KIM, J., & WEE, J. (2005). Synthesis of extraction resin containing 2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester and its performance for separation of rare earths (Gd, Tb). *Separation and Purification Technology* , 43 (2), 111–116. <https://doi.org/10.1016/j.seppur.2004.10.007>
- Parsons-Moss, T., Wang, J., Jones, S., May, E., Olive, D., Dai, Z., Zavarin, M., Kersting, A. B., Zhao, D., & Nitsche, H. (2014). Sorption interactions of plutonium and europium with ordered mesoporous carbon. *Journal of Materials Chemistry A* , 2 (29), 11209–11221. <https://doi.org/10.1039/c4ta01740d>
- Patra, S., Roy, E., Madhuri, R., & Sharma, P. K. (2017). Removal and Recycling of Precious Rare Earth Element from Wastewater Samples Using Imprinted Magnetic Ordered Mesoporous Carbon [Research-article]. *ACS Sustainable Chemistry and Engineering* , 5 (8), 6910–6923. <https://doi.org/10.1021/acssuschemeng.7b01124>
- Pearson, R. G. (1963). Hard and Soft Acids and Bases. *Journal of the American Chemical Society* , 85 (22), 3533–3539. <https://doi.org/10.1021/ja00905a001>
- Peng, X., Mo, S., Li, R., Li, J., Tian, C., Liu, W., & Wang, Y. (2020). Effective removal of the rare earth element dysprosium from wastewater with polyurethane sponge-supported graphene oxide–titanium phosphate. *Environmental Chemistry Letters* , 1–10. <https://doi.org/10.1007/s10311-020-01073-y>
- Perreault, L. L., Giret, S., Gagnon, M., Florek, J., Larivière, D., & Kleitz, F. (2017). Functionalization of Mesoporous Carbon Materials for Selective Separation of Lanthanides under Acidic Conditions. *ACS Applied Materials and Interfaces* , 9 (13), 12003–12012. <https://doi.org/10.1021/acsami.6b16650>
- Piasecki, W., & Sverjensky, D. A. (2008). Speciation of adsorbed yttrium and rare earth elements on oxide surfaces. *Geochimica et Cosmochimica Acta* , 72 (16), 3964–3979. <https://doi.org/10.1016/j.gca.2008.05.049>
- Polido Legaria, E., Rocha, J., Tai, C. W., Kessler, V. G., & Seisenbaeva, G. A. (2017). Unusual seeding mechanism for enhanced performance in solid-phase magnetic extraction of Rare Earth Elements. *Scientific Reports* , 7 (January), 1–13. <https://doi.org/10.1038/srep43740>
- Polido Legaria, E., Samouhos, M., Kessler, V. G., & Seisenbaeva, G. A. (2017). Toward Molecular Recognition of REEs: Comparative Analysis of Hybrid Nano-adsorbents with the Different Complexonate Ligands EDTA, DTPA, and TTHA. *Inorganic Chemistry* , 56 (22), 13938–13948. <https://doi.org/10.1021/acs.inorgchem.7b02056>
- Qin, Y., Wang, X., Shi, M., Huang, Y., Liu, X., & Li, X. (2022). Preparation and Adsorption Properties of Lanthanide Ion Surface-Imprinted Polymer Based on Reaming MCM-41. *Journal of Inorganic and Organometallic Polymers and Materials* , 32 (1), 161–168. <https://doi.org/10.1007/S10904-021-02108-9/FIGURES/7>

- Quinn, K. A., Byrne, R. H., & Schijf, J. (2006). Sorption of yttrium and rare earth elements by amorphous ferric hydroxide: Influence of solution complexation with carbonate. *Geochimica et Cosmochimica Acta* , 70 (16), 4151–4165. <https://doi.org/10.1016/j.gca.2006.06.014>
- Quinn, K. A., Byrne, R. H., & Schijf, J. (2007). Sorption of Yttrium and Rare Earth Elements by Amorphous Ferric Hydroxide: Influence of Temperature. *Environmental Science & Technology* , 41 (2), 541–546. <https://doi.org/10.1021/es0618191>
- Rahman, M. M., Awual, M. R., & Asiri, A. M. (2020). Preparation and evaluation of composite hybrid nanomaterials for rare-earth elements separation and recovery. *Separation and Purification Technology* ,253 , 117515. <https://doi.org/10.1016/j.seppur.2020.117515>
- Ramasamy, D. L., Khan, S., Repo, E., & Sillanpää, M. (2017). Synthesis of mesoporous and microporous amine and non-amine functionalized silica gels for the application of rare earth elements (REE) recovery from the waste water-understanding the role of pH, temperature, calcination and mechanism in Light REE and Hea. *Chemical Engineering Journal* ,322 , 56–65. <https://doi.org/10.1016/j.cej.2017.03.152>
- Ramasamy, D. L., Puhakka, V., Doshi, B., Iftekhar, S., & Sillanpää, M. (2019). Fabrication of carbon nanotubes reinforced silica composites with improved rare earth elements adsorption performance. *Chemical Engineering Journal* , 365 (January), 291–304. <https://doi.org/10.1016/j.cej.2019.02.057>
- Ramasamy, D. L., Puhakka, V., Iftekhar, S., Wojtuś, A., Repo, E., Ben Hammouda, S., Iakovleva, E., & Sillanpää, M. (2018). N- and O- ligand doped mesoporous silica-chitosan hybrid beads for the efficient, sustainable and selective recovery of rare earth elements (REE) from acid mine drainage (AMD): Understanding the significance of physical modification and conditioning of th. *Journal of Hazardous Materials* , 348 (October 2017), 84–91. <https://doi.org/10.1016/j.jhazmat.2018.01.030>
- Ramasamy, D. L., Puhakka, V., Repo, E., Ben Hammouda, S., & Sillanpää, M. (2018). Two-stage selective recovery process of scandium from the group of rare earth elements in aqueous systems using activated carbon and silica composites: Dual applications by tailoring the ligand grafting approach. *Chemical Engineering Journal* ,341 (February), 351–360. <https://doi.org/10.1016/j.cej.2018.02.024>
- Ramasamy, D. L., Puhakka, V., Repo, E., Khan, S., & Sillanpää, M. (2017). Coordination and silica surface chemistry of lanthanides (III), scandium (III) and yttrium (III) sorption on 1-(2-pyridylazo)-2-naphthol (PAN) and acetylacetone (acac) immobilized gels. *Chemical Engineering Journal* , 324 , 104–112. <https://doi.org/10.1016/j.cej.2017.05.025>
- Ramasamy, D. L., Puhakka, V., Repo, E., & Sillanpää, M. (2018). Selective separation of scandium from iron, aluminium and gold rich wastewater using various amino and non-amino functionalized silica gels – A comparative study. *Journal of Cleaner Production* ,170 (January), 890–901. <https://doi.org/10.1016/j.jclepro.2017.09.199>
- Ramasamy, D. L., Repo, E., & Sillanpää, M. (2020). Selective recovery of rare-earth elements from diluted aqueous streams using N- and O-coordination ligand-grafted organic-inorganic hybrid composites. In *Advanced Water Treatment* (pp. 565–664). Elsevier. <https://doi.org/10.1016/B978-0-12-819216-0.00008-4>
- Ramasamy, D. L., Repo, E., Srivastava, V., & Sillanpää, M. (2017). Chemically immobilized and physically adsorbed PAN/acetylacetone modified mesoporous silica for the recovery of rare earth elements from the waste water-comparative and optimization study. *Water Research* , 114 , 264–276. <https://doi.org/10.1016/j.watres.2017.02.045>
- Rao, T. P., Kala, R., & Daniel, S. (2006). Metal ion-imprinted polymers–Novel materials for selective recognition of inorganics. *Analytica Chimica Acta* , 578 (2), 105–116. <https://doi.org/10.1016/j.aca.2006.06.065>
- Ravi, S., Lee, Y. R., Yu, K., Ahn, J. W., & Ahn, W. S. (2018). Benzene triamido-tetraphosphonic acid immobilized on mesoporous silica for adsorption of Nd3+ ions in aqueous solution. *Microporous and Mesoporous Materials* , 258 , 62–71. <https://doi.org/10.1016/j.micromeso.2017.09.006>

- Ravi, S., Zhang, S., Lee, Y. R., Kang, K. K., Kim, J. M., Ahn, J. W., & Ahn, W. S. (2018). EDTA-functionalized KCC-1 and KIT-6 mesoporous silicas for Nd³⁺ ion recovery from aqueous solutions. *Journal of Industrial and Engineering Chemistry* , 67 (June), 210–218. <https://doi.org/10.1016/j.jiec.2018.06.031>
- Ridley, M. K., Machesky, M. L., Wesolowski, D. J., & Palmer, D. A. (2005). Surface complexation of neodymium at the rutile-water interface: A potentiometric and modeling study in NaCl media to 250°C. *Geochimica et Cosmochimica Acta* , 69 (1), 63–81. <https://doi.org/10.1016/j.gca.2004.06.028>
- Roosen, J., Spooren, J., & Binnemans, K. (2014). Adsorption performance of functionalized chitosan-silica hybrid materials toward rare earths. *J. Mater. Chem. A* , 2 (45), 19415–19426. <https://doi.org/10.1039/C4TA04518A>
- Roosen, J., Van Roosendael, S., Borra, C. R., Van Gerven, T., Mullens, S., & Binnemans, K. (2016). Recovery of scandium from leachates of Greek bauxite residue by adsorption on functionalized chitosan-silica hybrid materials. *Green Chemistry* , 18 (7), 2005–2013. <https://doi.org/10.1039/c5gc02225h>
- Ryu, S., Fonseka, C., Naidu, G., Loganathan, P., Moon, H., Kandasamy, J., & Vigneswaran, S. (2021). Recovery of rare earth elements (Lu, Y) by adsorption using functionalized SBA-15 and MIL-101 (Cr). *Chemosphere* , 281 , 130869. <https://doi.org/10.1016/J.CHEMOSPHERE.2021.130869>
- Sarmadi, N., Gharabaghi, M., Tamadoni Saray, M., Darestani, M., Garman, D., Koshy, P., S. Mofarah, S., & Sorrell, C. C. (2021). Highly Mesoporous Hybrid Transition Metal Oxide Nanowires for Enhanced Adsorption of Rare Earth Elements from Wastewater. *Inorganic Chemistry* , 60 (1), 175–184. <https://doi.org/10.1021/acs.inorgchem.0c02762>
- Schaeffer, N., Grimes, S. M., & Cheeseman, C. R. (2017). Use of extraction chromatography in the recycling of critical metals from thin film leach solutions. *Inorganica Chimica Acta* , 457 , 53–58. <https://doi.org/10.1016/j.ica.2016.11.020>
- Schoeb, V. R. (1965). *The stability constants of rare-earths with some carboxylic acids. Retrospective Theses and Dissertations. 3376* . <https://lib.dr.iastate.edu/rtd/3376%0A>
- Schrobilgen, G. J., & Lang, C. E. (1968). Lanthanide distribution coefficients on Dowex chelating resin A-1. *Journal of Inorganic and Nuclear Chemistry* , 30 (11), 3127–3130. [https://doi.org/10.1016/0022-1902\(68\)80183-6](https://doi.org/10.1016/0022-1902(68)80183-6)
- Sert, Ş., Altaş, Y., Tel, H., Inan, S., Çetinkaya, B., Sengül, S., & Özkan, B. (2021). Investigation of sorption behaviors of La, Pr, Nd, Sm, Eu and Gd on D2EHPA-impregnated XAD7 resin in nitric acid medium. *Separation Science and Technology (Philadelphia)* , 56 (1), 26–35. <https://doi.org/10.1080/01496395.2019.1708107>
- Shinozaki, T., Ogata, T., Kakinuma, R., Narita, H., Tokoro, C., & Tanaka, M. (2018). Preparation of Polymeric Adsorbents Bearing Diglycolamic Acid Ligands for Rare Earth Elements [Research-article]. *Industrial & Engineering Chemistry Research* , 57 (33), 11424–11430. <https://doi.org/10.1021/acs.iecr.8b01797>
- Shu, Q., Khayambashi, A., Wang, X., & Wei, Y. (2018). Studies on adsorption of rare earth elements from nitric acid solution with macroporous silica-based bis(2-ethylhexyl)phosphoric acid impregnated polymeric adsorbent. *Adsorption Science & Technology* , 36 (3–4), 1049–1065. <https://doi.org/10.1177/0263617417748112>
- Shu, Q., Khayambashi, A., Zou, Q., Wang, X., Wei, Y., He, L., & Tang, F. (2017). Studies on adsorption and separation characteristics of americium and lanthanides using a silica-based macroporous bi(2-ethylhexyl) phosphoric acid (HDEHP) adsorbent. *Journal of Radioanalytical and Nuclear Chemistry* , 313 (1), 29–37. <https://doi.org/10.1007/s10967-017-5293-z>
- SHU, Z., XIONG, C., SHEN, Q., YAO, C., & GU, Z. (2007). Adsorption behavior and mechanism of D113 resin for lanthanum. *Rare Metals* , 26 (6), 601–606. [https://doi.org/10.1016/S1001-0521\(08\)60013-3](https://doi.org/10.1016/S1001-0521(08)60013-3)

- Shumilova, Y. B., Gelis, V. M., Milyutin, V. V., Kharitonov, O. V., & Firsova, L. A. (2012). Separation of rare-earth and transplutonium elements by displacement chromatography on S-957 phosphonic ion exchanger. *Radiochemistry* , 54 (2), 164–167. <https://doi.org/10.1134/S1066362212020129>
- Sivaraman, N., Kumar, R., Subramaniam, S., & Vasudeva Rao, P. R. (2002). Separation of lanthanides using ion-interaction chromatography with HDEHP coated columns. *Journal of Radioanalytical and Nuclear Chemistry* , 252 (3), 491–495. <https://doi.org/10.1023/A:1015894418606>
- Smith, H. L., & Hoffman, D. C. (1956). Ion-exchange separations of the lanthanides and actinides by elution with ammonium alpha-hydroxy-isobutyrate. *Journal of Inorganic and Nuclear Chemistry* , 3 (3–4), 243–247. [https://doi.org/10.1016/0022-1902\(56\)80025-0](https://doi.org/10.1016/0022-1902(56)80025-0)
- Sparfel, D., & Cote, G. (2004). Synthesis and properties of new highly hydrophobic 7-substituted 8-quinolinols. *Solvent Extraction and Ion Exchange* , 22 (1), 1–12. <https://doi.org/10.1081/SEI-120027570>
- Spedding, F. H., & Powell, J. E. (1954). The Separation of Rare Earths by Ion Exchange. VIII. Quantitative Theory of the Mechanism Involved in Elution by Dilute Citrate Solutions. *Journal of the American Chemical Society* , 76 (9), 2550–2557. <https://doi.org/10.1021/ja01638a074>
- Spedding, F. H., Powell, J. E., & Wheelwright, E. J. (1954). The Separation of Adjacent Rare Earths with Ethylenediamine-tetraacetic Acid by Elution from an Ion-exchange Resin. *Journal of the American Chemical Society* , 76 (2), 612–613. <https://doi.org/10.1021/ja01631a091>
- Spedding, F. H., Voigt, A. F., Gladrow, E. M., & Sleight, N. R. (1947). The Separation of Rare Earths by Ion Exchange.1,2I. Cerium and Yttrium. *Journal of the American Chemical Society* , 69 (11), 2777–2781. <https://doi.org/10.1021/ja01203a058>
- Strelow, F. W. E. (1960). An Ion Exchange Selectivity Scale of Cations Based on Equilibrium Distribution Coefficients. *Analytical Chemistry* , 32 (9), 1185–1188. <https://doi.org/10.1021/ac60165a042>
- Strelow, F. W. E., & Bothma, C. J. C. (1964). Separation of Scandium from Yttrium, Lanthanum, and the Rare Earths by Cation Exchange Chromatography. *Analytical Chemistry* , 36 (7), 1217–1220. <https://doi.org/10.1021/ac60213a015>
- Strelow, F. W. E., Rethemeyer, R., & Bothma, C. J. C. (1965). Ion Exchange Selectivity Scales for Cations in Nitric Acid and Sulfuric Acid Media with a Sulfonated Polystyrene Resin. *Analytical Chemistry* , 37 (1), 106–111. <https://doi.org/10.1021/ac60220a027>
- Strelow, F. W. E., & Victor, A. H. (1990). Separation of yttrium and neodymium from samarium and the heavier lanthanides by cation-exchange chromatography with hydroxyethylenediaminetriacetate in mono-chloroacetate buffer. *Talanta* , 37 (12), 1155–1161. [https://doi.org/10.1016/0039-9140\(90\)80185-I](https://doi.org/10.1016/0039-9140(90)80185-I)
- Sun, M., Chen, C., Chen, L., & Su, B. (2016). Hierarchically porous materials: Synthesis strategies and emerging applications. *Frontiers of Chemical Science and Engineering* , 10 (3), 301–347. <https://doi.org/10.1007/s11705-016-1578-y>
- SUN, X., JI, Y., CHEN, J., & MA, J. (2009). Solvent impregnated resin prepared using task-specific ionic liquids for rare earth separation. *Journal of Rare Earths* , 27 (6), 932–936. [https://doi.org/10.1016/S1002-0721\(08\)60365-8](https://doi.org/10.1016/S1002-0721(08)60365-8)
- Sun, X., Peng, B., Ji, Y., Chen, J., & Li, D. (2008). The solid-liquid extraction of yttrium from rare earths by solvent (ionic liquid) impregnated resin coupled with complexing method. *Separation and Purification Technology* , 63 (1), 61–68. <https://doi.org/10.1016/j.seppur.2008.03.038>
- Sun, Y., Shao, D., Chen, C., Yang, S., & Wang, X. (2013). Highly efficient enrichment of radionuclides on graphene oxide-supported polyaniline. *Environmental Science and Technology* , 47 (17), 9904–9910. <https://doi.org/10.1021/es401174n>

- Sun, Y., Wang, Q., Chen, C., Tan, X., & Wang, X. (2012). Interaction between Eu(III) and graphene oxide nanosheets investigated by batch and extended X-ray absorption fine structure spectroscopy and by modeling techniques. *Environmental Science and Technology* , 46 (11), 6020–6027. <https://doi.org/10.1021/es300720f>
- Suzuki, Y., Yokoi, S., Katoh, M., Minato, M., & Takizawa, N. (1980). Stability Constants of Rare-Earth Complexes with Some Organic Ligands. In G. J. McCarthy, J. J. Rhyne, & H. B. Silber (Eds.), *The Rare Earths in Modern Science and Technology* (pp. 121–126). Springer US. https://doi.org/10.1007/978-1-4613-3054-7_22
- Svoboda, K., Kyrš, M., & Vaňura, P. (1997). Synergism in the sorption of europium on chromatographic supports impregnated with dicarbollide acid and bidentate phosphororganic extractant. *Journal of Radio-analytical and Nuclear Chemistry* , 220 (1), 47–54. <https://doi.org/10.1007/BF02035346>
- Tan, X., Fang, M., Li, J., Lu, Y., & Wang, X. (2009). Adsorption of Eu(III) onto TiO₂: Effect of pH, concentration, ionic strength and soil fulvic acid. *Journal of Hazardous Materials* , 168 (1), 458–465. <https://doi.org/10.1016/j.jhazmat.2009.02.051>
- Thakkar, J., Wissler, B., Dudenas, N., Yin, X., Vailhe, M., Bricker, J., & Zhang, X. (2019). Recovery of Critical Rare-Earth Elements Using ETS-10 Titanosilicate [Rapid-communication]. *Industrial and Engineering Chemistry Research* , 58 , 11121–11126. <https://doi.org/10.1021/acs.iecr.9b02623>
- Tong, S., Zhao, S., Zhou, W., Li, R., & Jia, Q. (2011). Modification of multi-walled carbon nanotubes with tannic acid for the adsorption of La, Tb and Lu ions. *Microchimica Acta* , 174 (3), 257–264. <https://doi.org/10.1007/s00604-011-0622-3>
- Trewyn, B. G., Slowing, I. I., Giri, S., Chen, H. T., & Lin, V. S. Y. (2007). Synthesis and functionalization of a mesoporous silica nanoparticle based on the sol-gel process and applications in controlled release. *Accounts of Chemical Research* , 40 (9), 846–853. <https://doi.org/10.1021/ar600032u>
- Trochimczuk, A. W., Kabay, N., Arda, M., & Streat, M. (2004). Stabilization of solvent impregnated resins (SIRs) by coating with water soluble polymers and chemical crosslinking. *Reactive and Functional Polymers* , 59 (1), 1–7. <https://doi.org/10.1016/j.reactfunctpolym.2003.12.011>
- Trochimczuk, Andrzej W. (2000). Synthesis of functionalized phenylphosphinic acid resins through Michael reaction and their ion-exchange properties. *Reactive and Functional Polymers* , 44 (1), 9–19. [https://doi.org/10.1016/S1381-5148\(99\)00072-3](https://doi.org/10.1016/S1381-5148(99)00072-3)
- Trochimczuk, Andrzej W., & Alexandratos, S. D. (1994). Synthesis of bifunctional ion-exchange resins through the Arbusov reaction: Effect on selectivity and kinetics. *Journal of Applied Polymer Science* , 52 (9), 1273–1277. <https://doi.org/10.1002/app.1994.070520912>
- Tu, Y. J., & Johnston, C. T. (2018). Rapid recovery of rare earth elements in industrial wastewater by CuFe₂O₄ synthesized from Cu sludge. *Journal of Rare Earths* , 36 (5), 513–520. <https://doi.org/10.1016/j.jre.2017.11.009>
- Turanov, A. N., Karandashev, V. K., & Bondarenko, N. A. (2008). Extraction of rare-earth, yttrium, and scandium perchlorates by podands bearing diphenylphosphorylacetamide terminal groups. *Russian Journal of Inorganic Chemistry* , 53 (11), 1801–1808. <https://doi.org/10.1134/S0036023608110223>
- Turanov, Alexander N., Karandashev, V. K., Sukhinina, N. S., Masalov, V. M., & Emelchenko, G. A. (2016). Adsorption of lanthanides and scandium ions by silica sol-gel material doped with novel bifunctional ionic liquid, trioctylmethylammonium 1-phenyl-3-methyl-4-benzoyl-5-onate. *Journal of Environmental Chemical Engineering* , 4 (4), 3788–3796. <https://doi.org/10.1016/j.jece.2016.08.024>
- Turanov, Alexander N., Karandashev, V. K., Sukhinina, N. S., Masalov, V. M., Zhokhov, A. A., & Emelchenko, G. A. (2015). A novel sorbent for lanthanide adsorption based on tetraoctyldiglycolamide, modified carbon inverse opals. *RSC Advances* , 5 (1), 529–535. <https://doi.org/10.1039/c4ra11999a>

- Unsworth, C. E., Kuo, C. C., Kuzmin, A., Khalid, S., & Saha, D. (2020). Adsorption of Rare Earth Elements onto DNA-Functionalized Mesoporous Carbon. *ACS Applied Materials and Interfaces* , 12 (38), 43180–43190. https://doi.org/10.1021/ACSAMI.0C09393/SUPPL_FILE/AM0C09393_SI_001.PDF
- Vasylyeva, H., Mironyuk, I., Mykytyn, I., & Savka, K. (2021). Equilibrium studies of yttrium adsorption from aqueous solutions by titanium dioxide. *Applied Radiation and Isotopes* , 168 , 109473. <https://doi.org/10.1016/j.apradiso.2020.109473>
- Velisek-Carolan, J., Hanley, T. L., & Luca, V. (2014). Zirconium organophosphonates as high capacity, selective lanthanide sorbents. *Separation and Purification Technology* , 129 , 150–158. <https://doi.org/10.1016/j.seppur.2014.03.028>
- Vigneau, O., Pinel, C., & Lemaire, M. (2001). Ionic imprinted resins based on EDTA and DTPA derivatives for lanthanides(III) separation. *Analytica Chimica Acta* , 435 (1), 75–82. [https://doi.org/10.1016/S0003-2670\(00\)01279-4](https://doi.org/10.1016/S0003-2670(00)01279-4)
- Vigneau, O., Pinel, C., & Lemaire, M. (2002). Solid-Liquid Separation of Lanthanide/Lanthanide and Lanthanide/Actinide Using Ionic Imprinted Polymer Based on a DTPA Derivative. *Chemistry Letters* , 31 (2), 202–203. <https://doi.org/10.1246/cl.2002.202>
- Wackerlig, J., & Schirhagl, R. (2016). Applications of Molecularly Imprinted Polymer Nanoparticles and Their Advances toward Industrial Use: A Review. *Analytical Chemistry* , 88 (1), 250–261. <https://doi.org/10.1021/acs.analchem.5b03804>
- WAKUI, Y., MATSUNAGA, H., & SUZUKI, T. M. (1988). Distribution of rare earth elements between (2-ethylhexyl hydrogen 2-ethylhexylphosphonate)-impregnated resin and acid aqueous solution. *Analytical Sciences* , 4 (3), 325–327. <https://doi.org/10.2116/analsci.4.325>
- Wan, Y., & Zhao, D. (2007). On the controllable soft-templating approach to mesoporous silicates. *Chemical Reviews* , 107 (7), 2821–2860. <https://doi.org/10.1021/cr068020s>
- WANG, F., WANG, W., ZHU, Y., & WANG, A. (2017). Evaluation of Ce(III) and Gd(III) adsorption from aqueous solution using CTS-g-(AA-co-SS)/ISC hybrid hydrogel adsorbent. *Journal of Rare Earths* , 35 (7), 697–708. [https://doi.org/10.1016/S1002-0721\(17\)60966-9](https://doi.org/10.1016/S1002-0721(17)60966-9)
- Wang, H., & Gao, P. (2007). Adsorption of D113 resin for dysprosium(III). *Journal Wuhan University of Technology, Materials Science Edition* , 22 (4), 653–656. <https://doi.org/10.1007/s11595-006-4653-2>
- Wang, Q., Wilfong, W. C., Kail, B. W., Yu, Y., & Gray, M. L. (2017). Novel Polyethylenimine-Acrylamide/SiO₂ Hybrid Hydrogel Sorbent for Rare-Earth-Element Recycling from Aqueous Sources. *ACS Sustainable Chemistry and Engineering* , 5 (11), 10947–10958. <https://doi.org/10.1021/acssuschemeng.7b02851>
- Wang, X., Xu, D., Chen, L., Tan, X., Zhou, X., Ren, A., & Chen, C. (2006). Sorption and complexation of Eu(III) on alumina: Effects of pH, ionic strength, humic acid and chelating resin on kinetic dissociation study. *Applied Radiation and Isotopes* , 64 (4), 414–421. <https://doi.org/10.1016/j.apradiso.2005.08.010>
- Wang, Y., Chen, L., Yan, Y., Chen, J., Dai, J., & Dai, X. (2020). Separation of adjacent heavy rare earth Lutetium (III) and Ytterbium (III) by task-specific ionic liquid Cyphos IL 104 embedded polymer inclusion membrane. *Journal of Membrane Science* , 610 , 118263. <https://doi.org/10.1016/j.memsci.2020.118263>
- Wang, Z. ., Ma, G. ., Lu, J., Liao, W. ., & Li, D. . (2002). Separation of heavy rare earth elements with extraction resin containing 1-hexyl-4-ethyloctyl isopropylphosphonic acid. *Hydrometallurgy* , 66 (1–3), 95–99. [https://doi.org/10.1016/S0304-386X\(02\)00109-3](https://doi.org/10.1016/S0304-386X(02)00109-3)
- Wang, Z., Ma, G., & Li, D. (1998). Extraction and separation of heavy rare earth(III) with extraction resin containing di(2,4,4-trimethyl pentyl) phosphinic acid (cyanex 272). *Solvent Extraction and Ion Exchange* , 16 (3), 813–828. <https://doi.org/10.1080/07366299808934554>

- Wheelwright, E. J. (1969). A comparison of eluting agents for the ion-exchange purification of promethium. *Journal of Inorganic and Nuclear Chemistry* , 31 (10), 3287–3293. [https://doi.org/10.1016/0022-1902\(69\)80115-6](https://doi.org/10.1016/0022-1902(69)80115-6)
- Wheelwright, E. J., Spedding, F. H., & Schwarzenbach, G. (1953). The Stability of the Rare Earth Complexes with Ethylenediaminetetraacetic Acid. *Journal of the American Chemical Society* , 75 (17), 4196–4201. <https://doi.org/10.1021/ja01113a020>
- Wódkiewicz, L., & Dybczyński, R. (1968). Anion exchange behaviour of the rare earth complexes with trans-1,2-diaminocyclohexane-N,N'-tetraacetic acid. *Journal of Chromatography A* , 32 (C), 394–402. [https://doi.org/10.1016/s0021-9673\(01\)80506-9](https://doi.org/10.1016/s0021-9673(01)80506-9)
- Wood, S. A. (1993). The aqueous geochemistry of the rare-earth elements: Critical stability constants for complexes with simple carboxylic acids at 25°C and 1 bar and their application to nuclear waste management. *Engineering Geology* , 34 (3–4), 229–259. [https://doi.org/10.1016/0013-7952\(93\)90092-Q](https://doi.org/10.1016/0013-7952(93)90092-Q)
- Wu, D., Sun, Y., & Wang, Q. (2013). Adsorption of lanthanum (III) from aqueous solution using 2-ethylhexyl phosphonic acid mono-2-ethylhexyl ester-grafted magnetic silica nanocomposites. *Journal of Hazardous Materials* , 260 , 409–419. <https://doi.org/10.1016/j.jhazmat.2013.05.042>
- Wu, J., Li, Z., Tan, H., Du, S., Liu, T., Yuan, Y., Liu, X., & Qiu, H. (2021). Highly selective separation of rare earth elements by Zn-BTC metal-organic framework/nanoporous graphene via in situ green synthesis. *Analytical Chemistry* , 93 (3), 1732–1739. https://doi.org/10.1021/ACS.ANALCHEM.0C04407/SUPPL.-FILE/AC0C04407_SI001.PDF
- XIAO, Y., HUANG, L., LONG, Z., FENG, Z., & WANG, L. (2016). Adsorption ability of rare earth elements on clay minerals and its practical performance. *Journal of Rare Earths* , 34 (5), 543–548. [https://doi.org/10.1016/S1002-0721\(16\)60060-1](https://doi.org/10.1016/S1002-0721(16)60060-1)
- Xie, F., Zhang, T. A., Dreisinger, D., & Doyle, F. (2014). A critical review on solvent extraction of rare earths from aqueous solutions. *Minerals Engineering* , 56 , 10–28. <https://doi.org/10.1016/j.mineng.2013.10.021>
- Xiong, C., Chen, X., & Yao, C. (2011). Enhanced adsorption behavior of Nd(III) onto D113-III resin from aqueous solution. *Journal of Rare Earths* , 29 (10), 979–985. [https://doi.org/10.1016/S1002-0721\(10\)60582-0](https://doi.org/10.1016/S1002-0721(10)60582-0)
- Xiong, C., Yao, C., & Wang, Y. (2006). Sorption behaviour and mechanism of ytterbium(III) on iminodiacetic acid resin. *Hydrometallurgy* , 82 (3–4), 190–194. <https://doi.org/10.1016/j.hydromet.2006.03.012>
- XIONG, Chun-hua, WANG, G., & YAO, C. (2011). Adsorption of ytterbium (III) from aqueous solution by SQD-85 resin. *Transactions of Nonferrous Metals Society of China* , 21 (12), 2764–2771. [https://doi.org/10.1016/S1003-6326\(11\)61121-7](https://doi.org/10.1016/S1003-6326(11)61121-7)
- XIONG, Chunhua. (2008). Study on sorption of D155 resin for gadolinium. *Journal of Rare Earths* , 26 (2), 258–263. [https://doi.org/10.1016/S1002-0721\(08\)60077-0](https://doi.org/10.1016/S1002-0721(08)60077-0)
- XIONG, Chunhua, LIU, X., & YAO, C. (2008). Effect of pH on sorption for RE(III) and sorption behaviors of Sm(III) by D152 resin. *Journal of Rare Earths* , 26 (6), 851–856. [https://doi.org/10.1016/S1002-0721\(09\)60020-X](https://doi.org/10.1016/S1002-0721(09)60020-X)
- XIONG, Chunhua, MENG, Y., YAO, C., & SHEN, C. (2009). Adsorption of erbium(III) on D113-III resin from aqueous solutions: batch and column studies. *Journal of Rare Earths* , 27 (6), 923–931. [https://doi.org/10.1016/S1002-0721\(08\)60364-6](https://doi.org/10.1016/S1002-0721(08)60364-6)
- Xu, H., & Guo, D. (2012). Synthesis and characterization of an ion-imprinted polymer for selective adsorption of copper ions in aqueous solution. *Adsorption Science and Technology* , 30 (4), 293–306. <https://doi.org/10.1260/0263-6174.30.4.293>
- Xu, J., Koivula, R., Zhang, W., Wiikinkoski, E., Hietala, S., & Harjula, R. (2018). Separation of cobalt, neodymium and dysprosium using amorphous zirconium phosphate. *Hydrometallurgy* , 175 (November 2017),

170–178. <https://doi.org/10.1016/j.hydromet.2017.11.010>

Yadav, K. K., Dasgupta, K., Singh, D. K., Anitha, M., Varshney, L., & Singh, H. (2015). Solvent impregnated carbon nanotube embedded polymeric composite beads: An environment benign approach for the separation of rare earths. *Separation and Purification Technology* , 143 , 115–124. <https://doi.org/10.1016/j.seppur.2015.01.032>

Yang, B., Wu, S.-Z., Liu, X.-Y., Yan, Z.-X., Liu, Y.-X., Li, Q.-S., Yu, F.-S., & Wang, J.-L. (2020). Solid-phase extraction and separation of heavy rare earths from chloride media using P227-impregnated resins. *Rare Metals* , 1–12. <https://doi.org/10.1007/s12598-020-01549-4>

Yang, S., Zong, P., Ren, X., Wang, Q., & Wang, X. (2012). Rapid and Highly Efficient Preconcentration of Eu(III) by Core-Shell Structured Fe₃O₄@Humic Acid Magnetic Nanoparticles. *ACS Applied Materials & Interfaces* , 4 (12), 6891–6900. <https://doi.org/10.1021/am3020372>

Yang, Xiaodong, Wan, Y., Zheng, Y., He, F., Yu, Z., Huang, J., Wang, H., Ok, Y. S., Jiang, Y., & Gao, B. (2019). Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy metals from aqueous solutions: A critical review. *Chemical Engineering Journal* , 366 (February), 608–621. <https://doi.org/10.1016/j.cej.2019.02.119>

Yang, Xinwei, Debeli, D. K., Shan, G., & Pan, P. (2020). Selective adsorption and high recovery of La³⁺ using graphene oxide/poly (N-isopropyl acrylamide-maleic acid) cryogel. *Chemical Engineering Journal* , 379 , 122335. <https://doi.org/10.1016/j.cej.2019.122335>

Yantasee, W., Fryxell, G. E., Addleman, R. S., Wiacek, R. J., Koonsiripai boon, V., Pattamakomsan, K., Sukwarotwat, V., Xu, J., & Raymond, K. N. (2009). Selective removal of lanthanides from natural waters, acidic streams and dialysate. *Journal of Hazardous Materials* , 168 (2–3), 1233–1238. <https://doi.org/10.1016/j.jhazmat.2009.03.004>

Yao, C. (2010). Adsorption and desorption properties of D151 resin for Ce(III). *Journal of Rare Earths* , 28 (SUPPL. 1), 183–188. [https://doi.org/10.1016/S1002-0721\(10\)60324-9](https://doi.org/10.1016/S1002-0721(10)60324-9)

Yin, W., Liu, L., Zhang, H., Tang, S., & Chi, R. (2020). A facile solvent-free and one-step route to prepare amino-phosphonic acid functionalized hollow mesoporous silica nanospheres for efficient Gd(III) removal. *Journal of Cleaner Production* , 243 . <https://doi.org/10.1016/j.jclepro.2019.118688>

Yu, Q., Ning, S., Zhang, W., Wang, X., & Wei, Y. (2018). Recovery of scandium from sulfuric acid solution with a macro porous TRPO/SiO₂-P adsorbent. *Hydrometallurgy* , 181 (May), 74–81. <https://doi.org/10.1016/j.hydromet.2018.07.025>

Yuan, Y., Liu, J., Zhou, B., Yao, S., Li, H., & Xu, W. (2010). Synthesis of coated solvent impregnated resin for the adsorption of indium (III). *Hydrometallurgy* , 101 (3–4), 148–155. <https://doi.org/10.1016/j.hydromet.2009.12.010>

Yusoff, M. M., Mostapa, N. R. N., Sarkar, M. S., Biswas, T. K., Rahman, M. L., Arshad, S. E., Sarjadi, M. S., & Kulkarni, A. D. (2017). Synthesis of ion imprinted polymers for selective recognition and separation of rare earth metals. *Journal of Rare Earths* , 35 (2), 177–186. [https://doi.org/10.1016/S1002-0721\(17\)60897-4](https://doi.org/10.1016/S1002-0721(17)60897-4)

Zhang, Wei, Yu, S., Zhang, S., Zhou, J., Ning, S., Wang, X., & Wei, Y. (2019). Separation of scandium from the other rare earth elements with a novel macro-porous silica-polymer based adsorbent HDEHP/SiO₂-P. *Hydrometallurgy* , 185 (January), 117–124. <https://doi.org/10.1016/j.hydromet.2019.01.012>

Zhang, Wenzhong, Avdibegović, D., Koivula, R., Hatanpää, T., Hietala, S., Regadío, M., Binnemans, K., & Harjula, R. (2017). Titanium alkylphosphate functionalised mesoporous silica for enhanced uptake of rare-earth ions. *Journal of Materials Chemistry A* , 5 (45), 23805–23814. <https://doi.org/10.1039/C7TA08127H>

Zhang, Wenzhong, Hietala, S., Khriachtchev, L., Hatanpää, T., Doshi, B., & Koivula, R. (2018). Intralanthanide Separation on Layered Titanium(IV) Organophosphate Materials via a Selective Transmetalation Pro-

- cess. *ACS Applied Materials & Interfaces* , 10 (26), 22083–22093. <https://doi.org/10.1021/acsami.8b04480>
- Zhang, Wenzhong, Koivula, R., Wiikinkoski, E., Xu, J., Hietala, S., Lehto, J., & Harjula, R. (2017). Efficient and Selective Recovery of Trace Scandium by Inorganic Titanium Phosphate Ion-Exchangers from Leachates of Waste Bauxite Residue. *ACS Sustainable Chemistry & Engineering* , 5 (4), 3103–3114. <https://doi.org/10.1021/acssuschemeng.6b02870>
- Zhang, X., Li, C., Yan, Y., Pan, J., Xu, P., & Zhao, X. (2010). A Ce³⁺-imprinted functionalized potassium tetratitanate whisker sorbent prepared by surface molecularly imprinting technique for selective separation and determination of Ce³⁺. *Microchimica Acta* ,169 (3), 289–296. <https://doi.org/10.1007/s00604-010-0352-y>
- Zhang, Z., Fenter, P., Cheng, L., Sturchio, N. C., Bedzyk, M. J., Předota, M., Bandura, A., Kubicki, J. D., Lvov, S. N., Cummings, P. T., Chialvo, A. A., Ridley, M. K., Bénézeth, P., Anovitz, L., Palmer, D. A., Machesky, M. L., & Wesolowski, D. J. (2004). Ion Adsorption at the Rutile-Water Interface: Linking Molecular and Macroscopic Properties. *Langmuir* , 20 (12), 4954–4969. <https://doi.org/10.1021/la0353834>
- Zhao, L., Azhar, M. R., Li, X., Duan, X., Sun, H., Wang, S., & Fang, X. (2019). Adsorption of cerium (III) by HKUST-1 metal-organic framework from aqueous solution. *Journal of Colloid and Interface Science* ,542 , 421–428. <https://doi.org/10.1016/j.jcis.2019.01.117>
- Zhao, X., Jiang, X., Peng, D., Teng, J., & Yu, J. (2021). Behavior and mechanism of graphene oxide-tris(4-aminophenyl)amine composites in adsorption of rare earth elements. *Journal of Rare Earths* ,39 (1), 90–97. <https://doi.org/10.1016/j.jre.2020.02.006>
- Zhao, Z., Sun, X., Dong, Y., & Wang, Y. (2016). Synergistic Effect of Acid–Base Coupling Bifunctional Ionic Liquids in Impregnated Resin for Rare Earth Adsorption. *ACS Sustainable Chemistry & Engineering* ,4 (2), 616–624. <https://doi.org/10.1021/acssuschemeng.5b01253>
- Zheng, X., Song, Z., Liu, E., Zhang, Y., & Li, Z. (2020). Preparation of Phosphoric Acid-Functionalized SBA-15 and Its High Efficient Selective Adsorption Separation of Lanthanum Ions. *Journal of Chemical and Engineering Data* , 65 (2), 746–756. <https://doi.org/10.1021/acs.jced.9b00976>
- Zheng, X., Wang, C., Dai, J., Shi, W., & Yan, Y. (2015). Design of mesoporous silica hybrid materials as sorbents for the selective recovery of rare earth metals. *Journal of Materials Chemistry A* ,3 (19), 10334–10335. <https://doi.org/10.1039/c4ta06860b>
- Zheng, X., Zhang, Y., Zhang, F., Li, Z., & Yan, Y. (2018). Dual-template docking oriented ionic imprinted bilayer mesoporous films with efficient recovery of neodymium and dysprosium. *Journal of Hazardous Materials* , 353 (March), 496–504. <https://doi.org/10.1016/j.jhazmat.2018.04.022>
- Zheng, Z., & Xiong, C. (2011). Adsorption behavior of ytterbium (III) on gel-type weak acid resin. *Journal of Rare Earths* ,29 (5), 407–412. [https://doi.org/10.1016/S1002-0721\(10\)60469-3](https://doi.org/10.1016/S1002-0721(10)60469-3)
- ZHOU, H., LI, D., TIAN, Y., & CHEN, Y. (2008). Extraction of scandium from red mud by modified activated carbon and kinetics study. *Rare Metals* , 27 (3), 223–227. [https://doi.org/10.1016/S1001-0521\(08\)60119-9](https://doi.org/10.1016/S1001-0521(08)60119-9)
- Zhou, J., Liu, H., Liu, D., Yuan, P., Bu, H., Du, P., Fan, W., & Li, M. (2022). Sorption/desorption of Eu(III) on halloysite and kaolinite. *Applied Clay Science* , 216 , 106356. <https://doi.org/10.1016/J.CLAY.2021.106356>
- ZHU, L., & CHEN, J. (2011). Adsorption of Ce(IV) in nitric acid medium by imidazolium anion exchange resin. *Journal of Rare Earths* ,29 (10), 969–973. [https://doi.org/10.1016/S1002-0721\(10\)60580-7](https://doi.org/10.1016/S1002-0721(10)60580-7)
- Zhu, L. L., Guo, L., Zhang, Z. J., Chen, J., & Zhang, S. M. (2012). The preparation of supported ionic liquids (SILs) and their application in rare metals separation. *Science China Chemistry* , 55 (8), 1479–1487. <https://doi.org/10.1007/s11426-012-4632-8>

- Zhu, X., & Alexandratos, S. D. (2014). The role of polarizability in determining metal ion affinities in polymer-supported reagents: Phosphorylated ethylene glycol. *Reactive and Functional Polymers* ,81 (1), 77–81. <https://doi.org/10.1016/j.reactfunctpolym.2014.05.001>
- Zhu, X., & Alexandratos, S. D. (2015). Development of a new ion-exchange/coordinating phosphate ligand for the sorption of U(VI) and trivalent ions from phosphoric acid solutions. *Chemical Engineering Science* , 127 , 126–132. <https://doi.org/10.1016/j.ces.2015.01.027>
- Zhu, Y., Wang, W., Zheng, Y., Wang, F., & Wang, A. (2016). Rapid enrichment of rare-earth metals by carboxymethyl cellulose-based open-cellular hydrogel adsorbent from HIPEs template. *Carbohydrate Polymers* , 140 , 51–58. <https://doi.org/10.1016/j.carbpol.2015.12.003>
- Zulfikar, M. A., Zarlina, R., Rusnadi, Handayani, N., Alni, A., & Wahyuningrum, D. (2017). Separation of Yttrium from Aqueous Solution Using Ionic Imprinted Polymers. *Russian Journal of Non-Ferrous Metals* , 58 (6), 614–624. <https://doi.org/10.3103/S1067821217060189>