Nd(III) and Gd(III) sorption on mesoporous amine-functionalized polymer/SiO$_2$ composite

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Supplementary Material Section
**Table S1.** SEM microphotographs of mesoporous silica gel particles before and after functionalization.

| Material                        | Small radius | Large radius |
|---------------------------------|--------------|--------------|
| SiO$_2$                         | ![Image](image1.png) 86.1 µm | ![Image](image2.png) 93.8 µm |
| Composite functionalized sorbent | ![Image](image3.png) 102 µm | ![Image](image4.png) 115 µm |
**Table S2.** Uptake kinetics modeling – PFORE (pseudo-first order rate equation), PSORE (pseudo-second order rate equation) and RIDE (resistance to intraparticle diffusion equation – Crank equation).

| Model  | Equation | Parameters |
|--------|----------|------------|
| PFORE [1] | \( q(t) = q_{eq,1}(1 - e^{k_1t}) \) | \( q_{eq,1} \) (mg g\(^{-1}\)), \( k_1 \) (min\(^{-1}\)) |
| PSORE [1] | \( q(t) = \frac{q_{eq,2}^2 k_2}{1 + q_{eq,2}^2 k_2} t \) | \( q_{eq,2} \) (mg g\(^{-1}\)), \( k_2 \) (L mg\(^{-1}\) min\(^{-1}\)) |
| RIDE [2] | \( \sum_{n=1}^{\infty} \frac{6\alpha(\alpha+1)\exp\left(-\frac{D_e q_{eq,1}^2 r^2}{t^2}\right)}{9 + 9\alpha + q_{eq,1}^2 \alpha^2} = 1 \) | With \( q_0 \) being the non-zero roots of \( \tan q_n = \frac{3q_n}{3 + \alpha q_n^2} \) and \( \frac{m q}{VC_o} = \frac{1}{1 + \alpha} \) |

Akaike Information Criterion, AIC [3]:

\[
AIC = N \ln \left( \frac{\sum_{i=1}^{N} (y_{i,\text{exp}} - y_{i,\text{model}})^2}{N} \right) + 2N_p + \frac{2N_p(N_p + 1)}{N - N_p - 1}
\]

Where \( N \) is the number of experimental points, \( N_p \) the number of model parameters, \( y_{i,\text{exp}} \) and \( y_{i,\text{model}} \) the experimental and calculated values of the tested variable.

**Table S3.** Sorption isotherm modeling [4,5]

| Model | Langmuir | Freundlich | Sips |
|-------|----------|------------|------|
| Equation | \( q = \frac{q_{m,L} b_L C_{eq}}{1 + b_L C_{eq}} \) | \( q = k_F C_{eq}^{1/n} \) | \( q = q_{m,S} b_S C_{eq}^{1/n_S} \) |
| Parameters | \( q_{m,L} \) (mg g\(^{-1}\))* | \( k_F \) (mg\(^{-1}\) g\(^{-1}\) L\(^{1/n}\)) | \( q_{m,S} \) (mmol g\(^{-1}\))* |
| | \( b_L \) (L mg\(^{-1}\))* | \( n \) (dimensionless) | \( b_S \) (L mg\(^{-1}\))* |
| | | | \( n_S \) (dimensionless) |

*: Sorption capacity at saturation of the monolayer; **: Affinity coefficient
Table S4. Chemical constituents of ore sample collected from Abu Mogherat mining site after burning at 800 °C.

| Metal oxide | Content (%) | Metal oxide | Content (%) |
|-------------|-------------|-------------|-------------|
| SiO$_2$     | 44.98       | Na$_2$O     | 3.09        |
| Al$_2$O$_3$ | 13.71       | K$_2$O      | 0.2         |
| Fe$_2$O$_3$ | 7.33        | ZnO         | 2.93        |
| MnO         | 0.53        | P$_2$O$_5$  | 0.18        |
| CoO         | 0.0019      | REEs        | 2.35        |
| NiO         | 0.0032      | U           | 0.0015      |
| TiO$_2$     | 0.0011      |             |             |
| CuO         | 0.015       |             |             |
| MgO         | 8.23        |             |             |
| CaO         | 12.02       |             |             |

Chemical composition of metal oxides were according the method described by Shapiro [6]: silicate was analyzed from alkaline mineralization while metal oxides (such as Al$_2$O$_3$, TiO$_2$, CaO, MgO, P$_2$O$_5$, and Fe oxides) were measured from acidic solution.

Five hundred mg of sample were digested using HF, HCl and HNO$_3$ until dissolution. The cleared solution was filtrated before being diluted with demineralized water up to 100 mL. The concentrations of metal ions (such as Ni(II), Zn(II), Mn(II), Cu(II),…etc) were determined by a Unicam atomic absorption spectrophotometer model-969 (AAS). Total REE was analyzed by a UV-VIS spectrophotometer (Shimadzu UV-160) using 0.015 % Arsenazo (III) at the wavelength $\lambda$:654 nm with reference to Y [7]. U was measured using the oxidimetric titration method by ammonium metavanadate [8].
Table S5. SEM micrograph and semi-quantitative EDX analysis of mesoporous silica gel particles and composite functionalized sorbent.

| Material | SEM micrograph | EDX semi-quantitative analysis |
|----------|----------------|--------------------------------|
| SiO₂     | ![SEM micrograph](image1) | ![EDX analysis](image2) |
| Sorbent  | ![SEM micrograph](image3) | ![EDX analysis](image4) |
Table S6. Assignments of FTIR peaks (characteristic wavenumber, cm\(^{-1}\)) for mesoporous SiO\(_2\), composite functionalized sorbent (before and after Nd(III) or Gd(III) sorption, and after 5 cycles of sorption/desorption) : – Assignments peaks and characteristic wavenumbers (cm\(^{-1}\)).

| Vibration                                      | Ref.       | Wn. in ref. | SiO\(_2\) | NH/SiO\(_2\) | NH/SiO\(_2\) +Nd(III) Loaded | NH/SiO\(_2\) +Nd(III) Loaded 5 cycles elution | NH/SiO\(_2\) +Gd(III) Loaded | NH/SiO\(_2\) +Gd(III) Loaded 5 cycles elution |
|------------------------------------------------|------------|-------------|------------|--------------|-----------------------------|---------------------------------------------|----------------------------|---------------------------------------------|
| O-H and N-H stretching bands                   | [9] [10]   | 3500-3000   | 3439       | 3453         | 3465                        | 3443                                         | 3518, 3159                  | 3449                                         |
| Stretching C-H aliphatic                       | [10-12]    | 2970–2950   | 2931       | 2932, 2857   | 2935                        | 2939                                         | 2939                       | 2923                                         |
| C=O stretching of ester                        | [11,12]    | 1750–1725   | 1738       | 1727, 1736   | 1736                        | overlapped                                   | 1738                       | 1738                                         |
| C=O Stretching of amide                        | [11,13]    | 1690-1630   | 1632       | 1626         | 1632                        | 1630                                         | 1630                       | 1635                                         |
| C-N of amide and -OH bending (1º and 2º)       | [14,15]    | 1450-1330   | 1452       | 1452         | 1450                        | ==                                           | 1456                       |                                              |
| Si-O- Si bands                                 | [12,16-19] | 1095–500    | 1112, 1109 | 1107         | 1107                        | 1107                                         | 1107, 1109                  | 1109, 1109                                   |
| C-N Stretching + Asymmetric C-O-C stretching   | [10-12,20-22] | 1090-1020   | 1109       | 1107         | 1109                        | 1107                                         | 1107                       | 1107                                         |
| C-C Stretching band                            | [19]       | 1350–1000   | 802        | 798          | 800                         | 800                                          | 800                        | 802                                          |
Table S7. XPS spectra of elements present on mesoporous composite functionalized sorbent before and after sorption of target metal ions.

| Signal | NH/SiO$_2$ | NH/SiO$_2$+Nd(III) | NH/SiO$_2$+Gd(III) |
|--------|------------|---------------------|---------------------|
| C $1s$ | ![C $1s$ spectrum](image1) | ![C $1s$ spectrum](image2) | ![C $1s$ spectrum](image3) |
| N $1s$ | ![N $1s$ spectrum](image4) | ![N $1s$ spectrum](image5) | ![N $1s$ spectrum](image6) |
| O $1s$ | ![O $1s$ spectrum](image7) | ![O $1s$ spectrum](image8) | ![O $1s$ spectrum](image9) |
| Si $2p$ | ![Si $2p$ spectrum](image10) | ![Si $2p$ spectrum](image11) | ![Si $2p$ spectrum](image12) |
| S $2p$ | ![S $2p$ spectrum](image13) | ![S $2p$ spectrum](image14) | ![S $2p$ spectrum](image15) |
| Na $1s$ | ![Na $1s$ spectrum](image16) | ![Na $1s$ spectrum](image17) | ![Na $1s$ spectrum](image18) |
### Cont’d Table S7

| Signal  | NH/\(\text{SiO}_2\)+Nd(III) | NH/\(\text{SiO}_2\)+Gd(III) |
|---------|----------------------------|----------------------------|
| **M 3d** | ![M 3d Signal](image1) | ![M 3d Signal](image2) |
| **M 4d** | ![M 4d Signal](image3) | ![M 4d Signal](image4) |
| **M 4s** | ![M 4s Signal](image5) | ![M 4s Signal](image6) |
| **Nd 3p** | ![Nd 3p Signal](image7) | ![Nd 3p Signal](image8) |
| **Gd 4p** | ![Gd 4p Signal](image9) | ![Gd 4p Signal](image10) |
Table S8. XPS analysis of signals of mesoporous composite functionalized sorbent before and after sorption of target metal ions (BEs, binding energies and AF, atomic fraction)

| Signal | NH/SiO$_2$ | NH/SiO$_2$+Nd(III) | NH/SiO$_2$+Gd(III) | Assignments |
|--------|------------|---------------------|---------------------|--------------|
|        | BE (eV) AF (%) | BE (eV) AF (%) | BE (eV) AF (%) |               |
| C 1s   | 283.75 (9.24) | 284.48 (85.66) | 284.56 (87.97) | C (C, H)     |
|        | 284.72 (90.76) | 285.82 (9.23) | 286.25 (6.83) | C (N)        |
|        | 287.01 (4.46) | 287.8 (1.22) | 289.55 (3.98) | C(-O, =N)    |
|        | 532.35 (93.27) | 532.47 (91.97) | 532.43 (93.5) | O(C, H,=C, S) SiO$_2$ |
| O 1s   | 533.95 (5.2) | 534.25 (7.07) | 534.3 (5.87) | C-C-O        |
|        | 535.3 (1.53) | 535.75 (0.38) | 534.3 (5.87) | N-C=O        |
|        | 529.3 (0.58) | 529.3 (0.63) | 529.3 (0.63) | O-Nd         |
| N 1s   | 398.36 (94.81) | 398.57 (95.33) | 398.6 (93.45) | N(C,=C, H)  |
|        | 400 (5.19) | 399.95 (1.75) | 399.85 (1.81) | O=C-NH       |
|        | 400.65 (2.92) | 401 (4.74) | 401 (4.74) | N(M)         |
| Si 2p  | 102.94 (97.83) | 103.12 (93.98) | 103.01 (94.81) | Si 2p$^1$  |
|        | 104.5 (2.17) | 104.65 (5.74) | 104.65 (5.19) | Si 2p$^2$  |
|        | 105.85 (0.28) |               |               | Envelop      |
| S 2p   | 165.39 (29.57) | 165.65 (24.87), 167 (13.13) | 164.1 (12.07) | S 2p$^{1/2}$ |
|        | 166.5 (70.43) |               |               | S 2p$^{3/2}$ |
|        | 164.1 (12.07) |               |               | SO$_4^{2-}$  |
|        | 169 (26.21), 168.25 (6.6), 167.85 (17.12) |               |               |               |
| Na 1s  | 1071.84 (100) | 1072.14 (100) |               | O-Na         |
| Signal | NH/SiO$_2$+Nd(III) Assignments | BE (eV) AF (%) | NH/SiO$_2$+Gd(III) Assignments |
|--------|--------------------------------|----------------|--------------------------------|
| M3d    | 980.16 (78.55), 984.05 (5.11) Nd 3d$_{5/2}$ | 1188.17 (76.36) Gd 3d$_{5/2}$ |
|       | 994.7 (1.69), 995.75 (0.95), 989.05 (0.93), 993.3 (0.45), 998.25 (0.47) Satellite peaks | 1214.6 (0.87) Gd$_2$O$_3$ d$_{3/2}$ |
|       | 1000.85 (11.86) Nd 3d$_{7/2}$ | 1216.3 (1.53) Satellite peaks |
| M 4d   | 117.74 (22.6), 118.4 (77.4) Nd 4d | 143.15 (10.29) Gd 4d$_{5/2}$, Gd$_2$O$_3$ |
|        |                                 | 148.6 (8.6) Gd 4d$_{3/2}$ |
|        |                                 | 151.15 (6.65) Satellite peaks |
|        |                                 | 154.02 (73.02) Si |
|        |                                 | 158.15 (1.44) |
| Gd 4p  |                                 | 270.4 (4.54), 271.75 (3.12), 272.85 (2.82) Gd 4p |
|        |                                 | 284.56 (89.52) C 1s |
| M 4s   | 316.21 (100) Nd 4s | 378.72 (9.18), 380 (90.82) Gd 4s |
| Nd 3p3 | 1301.07 (100) Nd 3p3 |
Table S9. Semi-quantitative EDX analysis of mesoporous composite functionalized sorbent before and after loading with Nd(III).

| Material                  | SEM micrograph | EDX semi-quantitative analysis |
|---------------------------|----------------|-------------------------------|
| Sorbent                   | ![Image](image1) | ![Graph](image2)              |
| Sorbent + Nd(III)         | ![Image](image3) | ![Graph](image4)              |
| Sorbent after elution     | ![Image](image5) | ![Graph](image6)              |

| Element | Wt% | At% |
|---------|-----|-----|
| CK      | 10.37 | 19.53 |
| NK      | 4.02 | 4.79 |
| OK      | 39.59 | 45.48 |
| SiK     | 46.02 | 30.2 |

| Element | Wt% | At% |
|---------|-----|-----|
| CK      | 8.54 | 17.48 |
| NK      | 3.93 | 4.29 |
| OK      | 44.12 | 50.67 |
| NaK     | 0.24 | 0.21 |
| SiK     | 40.25 | 25.65 |
| Sk      | 0.9 | 0.56 |
| NdL     | 2.02 | 1.14 |

| Element | Wt% | At% |
|---------|-----|-----|
| CK      | 15.94 | 24.16 |
| NK      | 3.66 | 4.43 |
| OK      | 36.16 | 42.51 |
| SiK     | 40.84 | 26.43 |
| SK      | 0.18 | 0.06 |
| ClK     | 3.22 | 2.41 |
Table S10. Semi-quantitative EDX analysis of mesoporous composite functionalized sorbent before and after loading with Gd(III).

| Material | SEM micrograph | EDX semi-quantitative analysis |
|----------|----------------|--------------------------------|
| Sorbent  | ![Micrograph](148x536 to 302x700) | ![EDX spectrum](314x546 to 517x689) |
| Sorbent + Gd(III) | ![Micrograph](156x386 to 294x524) | ![EDX spectrum](317x381 to 515x529) |
| Sorbent after elution | ![Micrograph](160x229 to 289x369) | ![EDX spectrum](313x224 to 518x373) |
Table S11. Solution-phase properties for selected metal ions – Competitive sorption from multi-component equimolar solutions.

| Aqua complex     | M-O distance | Shannon radius (Å) | Configuration             | Coordination number | Electronegativity | pK_a | pK_s | $\Delta G_{\text{hydr}}$ (kcal/mol) |
|------------------|--------------|--------------------|---------------------------|---------------------|-------------------|------|------|-------------------------------------|
| Nd(H$_2$O)$_{9}^{2+}$ | 2.49         | 1.163              | Tricapped trigonal prism  | 9                   | 3.085             | 8    | 25.2 | 783.9                               |
| Gd(H$_2$O)$_{9}^{2+}$ | 2.415        | 1.053              | Tricapped trigonal prism  | 8                   | 3.111             | -    | 24.5 | 806.6                               |
| Sc(H$_2$O)$_{8}^{3+}$ | 2.17+2.33    | 0.87               | Tricapped trigonal prism  | 8                   | 3.133             | 4.8  | 29.4 | 907                                 |
| Ca(H$_2$O)$_{8}^{2+}$ | 2.46         | 1.12               | Square antiprism          | 8                   | 1.862             | 12.7 | 5.06 | 359.7                               |
| Mg(H$_2$O)$_{6}^{2+}$ | 2.10         | 0.72               | Octaehedron               | 6                   | 2.158             | 11.42| 9.2  | 437.4                               |

Data from Li et al. [23]
Table S12. Sorption properties for Nd(III) – Comparison of performances (q_{inL}, mmol Nd g^{-1}; b_L, L mmol^{-1}).

| Sorbent                                           | pH  | Equilibrium time (min) | q_{inL} | b_L    | Reference |
|---------------------------------------------------|-----|------------------------|---------|--------|-----------|
| Ion-imprinted polymer particles                   | 7.7 | 10                     | 0.24    | 175    | [24]      |
| Sargassum sp.                                     | 5   | 180                    | 0.70    | 27.77  | [25]      |
| Kluyveromyces marxianus                           | 1.5 | 1440                   | 0.083   | 5.63   | [26]      |
| Phosphorus-based sol-gel sorbent                  | 6   | 180                    | 1.13    | -      | [27]      |
| Extractant impregnated magnetic microcapsules     | 4   | 600-720                | 1.04    | 4904   | [28]      |
| Calixarene-functionalized graphene oxide composite| 7   | 240                    | 2.16    | 3.38   | [29]      |
| Cysteine/magnetite NPs                            | 7   | 30                     | 0.59    | 261.4  | [30]      |
| IL-impregnated silica                             | 3.5 | 200                    | 0.145   | 267    | [31]      |
| Fumarated polystyrene                             | 5   | 50                     | 0.30    | 5.87   | [32]      |
| Chlorella vulgaris                                | 5   | 30                     | 0.87    | 4.18   | [33]      |
| Poly-γ glutamic acid sorbent                       | 3   | -                      | 1.64    | 8.47   | [34]      |
| Graphitic-C_{3}N_{4} nanosheets                   | 8   | 360                    | 0.91    | 140    | [35]      |
| Carboxylic acid modified corn stalk gel           | 3   | 360                    | 2.44    | 591    | [36]      |
| Diatomaceous earth                                | 5   | 150                    | 1.17    | 26.1   | [37]      |
| Lanthanide MOF                                    | 6   | 120                    | 0.99    | 5.19   | [38]      |
| Mesoporous composite functionalized sorbent       | 5   | 40                     | 1.06    | 1.24   | This work |
Table S13. Sorption properties for Gd(III) – Comparison of performances (\(q_{\text{mL}}\), mmol Gd g\(^{-1}\); \(b_{L}\), L mmol\(^{-1}\)).

| Sorbent                                      | pH | Equilibrium time (min) | \(q_{\text{mL}}\) | \(b_{L}\) | Reference |
|----------------------------------------------|----|------------------------|---------------------|---------|-----------|
| Sargassum sp.                                | 5  | 180                    | 0.67                | 28.79   | [25]      |
| Kaolinite                                    | 5  | 3600                   | 0.0031              | 17.6    | [39]      |
| Tulsion CH-93 resin                          | a  | 360                    | 0.072               | 396.9   | [40]      |
| Dowex-HCR S/S resin                          | 4  | 40                     | 0.42                | 127.2   | [41]      |
| Carbamoylmethyl phosphonated-based polymer   | 1  | 1200                   | 0.6                 | -       | [42]      |
| Extractant/microcapsules                    | 7  | 3600                   | 0.44                | 1.06    | [43]      |
| Cysteine/magnetite NPs                      | 7  | 30                     | 0.62                | 127.4   | [30]      |
| IL-impregnated silica                        | 3.5| 200                    | 0.154               | 2129    | [31]      |
| Functionalized chitosan                     | 5  | 60                     | 1.48                | 38.3    | [44]      |
| CNT/graphene oxide                           | 5.9| 90                     | 3.40                | 66.0    | [45]      |
| Banana peel                                  | 5.2| 1440                   | 0.294               | 330     | [46]      |
| DTPA-chitosan/magnetite                     | 5  | 120                    | 10.6                | 7.55    | [47]      |
| Crown-ether grafted polystyrene              | 5  | 240                    | 0.0112              | 13.7    | [48]      |
| Functionalized cellulose/magnetite NPs       | 6  | 40                     | 0.43                | 100     | [49]      |
| Imprinted mesoporous carboxymethyl chitosan film | 7  | 360                    | 0.16                | 6.29    | [50]      |
| Amino-phosphonic acid functionalized hollow silica nanospheres | 5  | 20                     | 2.56                | 2.66    | [51]      |
| Mesoporous composite functionalized sorbent  | 5  | 40                     | 1.41                | 0.93    | This work |

a: 0.1 M H\(_3\)PO\(_4\) solution.
Table S14. Semi-quantitative EDX analysis of mesoporous composite functionalized sorbent after loading with equimolar Nd, Gd, Sc, Ca and Mg solution and after treatment with polymetallic (REEs) solution.

| Material | SEM micrograph | EDX semi-quantitative analysis |
|----------|----------------|--------------------------------|
| Sorbent + Nd(III), Gd(III), Sc(III), Ca(II) and Mg(II) at pH 5 | ![SEM micrograph 1](image1.png) | ![EDX analysis 1](image2.png) |
| Sorbent + polymetallic solution (REEs) at pH 5 | ![SEM micrograph 2](image3.png) | ![EDX analysis 2](image4.png) |
**Table S15.** SEM microphotographs of mesoporous composite functionalized sorbent after 5 cycles of sorption and desorption – Stability

| Loaded metal | SEM micrograph | EDX semi-quantitative analysis |
|--------------|----------------|--------------------------------|
| Nd(III)      | ![SEM micrograph](image1) | ![EDX spectrum](image2) |
| Gd(III)      | ![SEM micrograph](image3) | ![EDX spectrum](image4) |
**Table S16.** Semi-quantitative EDX analysis of REEs ore, and after sorption/elution/oxalic acid precipitation.

| Sample | MEB observation (inset) and EDX semi-quantitative analysis |
|--------|-----------------------------------------------------------|
| Unpurified REE (ore) | ![Graph of Unpurified REE (ore)](image) |
| Purified precipitate of REEs (after leaching, sorption, elution and oxalic acid precipitation) | ![Graph of Purified precipitate of REEs](image) |
Figure S1. Geological map for ore sampling (gibbsite materials from Abu Mogherat site in South Western Sinai, Egypt).
Figure S2. Textural analysis of mesoporous silica microbeads and mesoporous composite functionalized sorbent (NH/SiO$_2$): (a) nitrogen adsorption/desorption isotherms, (b) pore size distribution (BJH method with Harkins-Jura thickness equation and Faas correction) for adsorption (ads.) and desorption (des.) isotherms.
Figure S3. Thermogravimetric analysis of mesoporous composite functionalized sorbent: TGA (a), DSC (b).
Figure S4. FTIR spectra of mesoporous SiO$_2$, mesoporous composite functionalized sorbent, before and after Nd(III) sorption, and after 5 cycles of sorption and desorption.
**Figure S5.** FTIR spectra of mesoporous SiO$_2$, mesoporous composite functionalized sorbent, before and after Gd(III) sorption, and after 5 cycles of sorption and desorption.
Figure S6. Acid-base properties – $\text{pH}_{\text{PZC}}$ determined by the pH-drift method (Sorbent dosage, SD: 2 g L$^{-1}$; contact time: 48 h; T: 22 ±2 °C; background salt: NaCl solution at 0.1 and 1 M concentrations).
Figure S7. Speciation diagrams for Nd(III) and Gd(III) under the experimental conditions selected for the study of pH effect (C₀: 0.66 mmol Nd L⁻¹ or 0.63 mmol Gd L⁻¹; sulfate salts, pH controlled with sulfuric acid and sodium hydroxide).
Figure S8. Effect of equilibrium pH on the distribution ratio (D, in log_{10} unit) (C_0: 100 mg L^{-1}; 0.66 mmol Nd L^{-1} or 0.63 mmol Gd L^{-1}; SD: 1.42 g L^{-1}; Contact time: 48 h; agitation speed: 170 rpm; T: 22 ±2 °C).

Figure S9. pH variation during metal sorption (C_0: 100 mg L^{-1}; 0.66 mmol Nd L^{-1} or 0.63 mmol Gd L^{-1}; SD: 1.42 g L^{-1}; Contact time: 48 h; agitation speed: 170 rpm; T: 22 ±2 °C).
Figure S10. Nd(III) and Gd(III) uptake kinetics using mesoporous composite functionalized sorbent - Modeling with the pseudo-second order rate equation ($C_0$: 0.65-0.71 mmol metal L$^{-1}$; pH$_0$: 5; pH$_{eq}$: 4.69-4.76; SD: 0.25 g L$^{-1}$; agitation speed: 170 rpm; T: 22 ±2 °C).
Figure S11. Nd(III) and Gd(III) uptake kinetics using mesoporous composite functionalized sorbent - Modeling with the Crank equation, resistance to intraparticle diffusion model ($C_0$: 0.65-0.71 mmol metal L$^{-1}$; pH$$_0$: 5 ; pH$$_{eq}$: 4.69-4.76; SD: 0.25 g L$^{-1}$; agitation speed: 170 rpm; T: 22 ±2 °C).
Effect of pH on (a) the enrichment factor, and the distribution ratio, \( D \) (EF, L kg\(^{-1}\), EF = \( q \) (mmol kg\(^{-1}\)) / \( C_0 \) (mmol L\(^{-1}\)) of metal ions on the mesoporous composite functionalized sorbent compared to their initial concentration in the solution; \( D \), L g\(^{-1}\) = \( q_{eq} / C_{eq} \) (equimolar multi-component solutions; \( C_0 \): 1 mmol metal L\(^{-1}\); pH\(_0\): 1-5; pH\(_{eq}\): 1.36-4.73; SD: 0.125 g L\(^{-1}\); contact time: 48 h; agitation speed: 170 rpm; T: 22 ±2 °C).

Figure S12. Effect of pH on (a) the enrichment factor, and the distribution ratio, \( D \) (EF, L kg\(^{-1}\), EF = \( q \) (mmol kg\(^{-1}\)) / \( C_0 \) (mmol L\(^{-1}\)) of metal ions on the mesoporous composite functionalized sorbent compared to their initial concentration in the solution; \( D \), L g\(^{-1}\) = \( q_{eq} / C_{eq} \) (equimolar multi-component solutions; \( C_0 \): 1 mmol metal L\(^{-1}\); pH\(_0\): 1-5; pH\(_{eq}\): 1.36-4.73; SD: 0.125 g L\(^{-1}\); contact time: 48 h; agitation speed: 170 rpm; T: 22 ±2 °C).
Figure S13. Speciation diagram for multicomponent equimolar solutions (experimental conditions corresponding to Figure 6 (C₀: 1 mmol metal L⁻¹): metal salts and type of acid and base used for pH control taken into account for speciation calculation).
Figure S14. Atomic fractions (semi-quantitative EDX analysis) of REEs in unpurified ore, mesoporous composite functionalized sorbent and raffinate (acid elution (sorbent)/oxalic acid precipitation/calcination).
Figure S15. Concentration factor (against atomic fraction of REEs in the ore) in the loaded sorbent and in the raffinate.
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