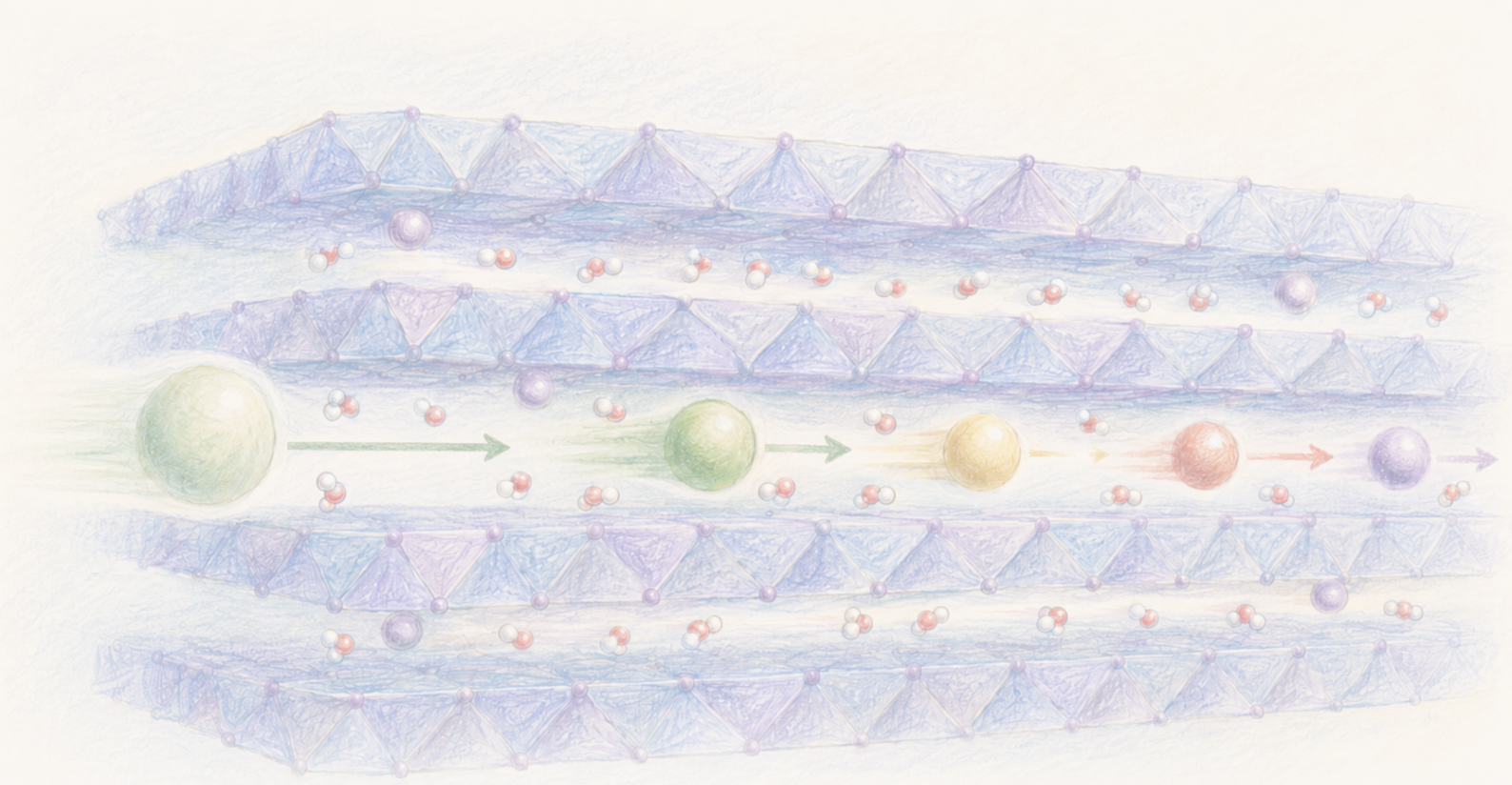


The Clean Paper

WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

Kulle wata tashar ma'adani mai cike da ruwa ya taimaka wajen ware rare-earth ions masu kama da juna

Magnesium ya rike hydrated manganese-oxide gap kusa da width na water shell na lanthanide ion kuma ya improve selected pairwise enrichment a laboratory tests. Demonstrated work ya use millilitres na solution da milligrams na material; flow operation, long cycle life da commercial environmental performance har yanzu ba proven ba.

Written by Laura Nesso · Cross-checked by Cinzia Vaglio · Edited by Michele Renda · Figures by Laura Nesso and Nova Vela · AI-assisted, human-reviewed

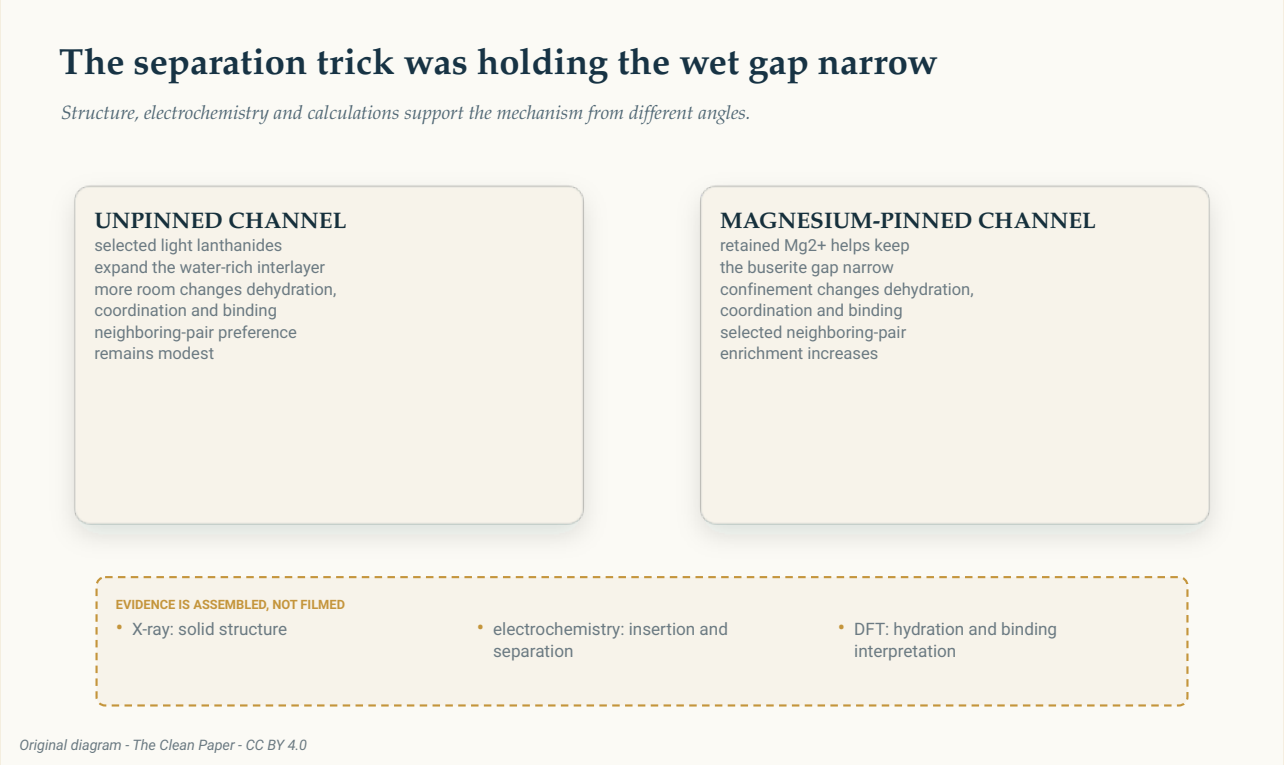
Paper: *Pinning angstrom-size solid ionic channels for rare-earth element separation*, Siqi Zou, Jiadong Liu, Woo Cheol Jeon, Maoyu Wang, Ronghui Wu, Yu Han, Gangbin Yan, Grant T. Hill, Xiaolin Yue, Hua Zhou, George C. Schatz & Chong Liu, Nature Chemical Engineering 3, 402-413 (2026) · DOI: 10.1038/s44286-026-00418-8

Tsayar da wata ƙaramar tashar ma’adinai mai cike da ruwa ya taimaka wajen raba ions na rare earth masu kama da juna

Ions na rare earth suna da wahalar rabuwa saboda dalili iri ɗaya da yake sa ’yan’uwa masu kama da juna su yi wahalar bambancewa daga nesa: bambance-bambancen suna nan, amma ƙanana ne.

Lanthanides suna jere kusa da juna a periodic table kuma galibi suna samar da ions masu charge iri ɗaya. Girman ions ɗin yana sauyawa a hankali daga wani element zuwa wani, yayin da halayensu na sinadarai suka kasance masu kama. Saboda haka, tsarin tace su a masana’antu yana buƙatar matakan rabuwa masu yawa da ake maimaitawa.

Wani sabon gwajin dakin bincike ya tunkari matsalar ta hanyar **confinement**, wato takaita sararin da ion zai iya shiga. Masu binciken sun yi amfani da zanen manganese oxide da aka jera sama da juna, tare da wata ƙaramar rata mai cike da ruwa a tsakaninsu. Ion na rare earth yana kusantar wannan rata yayin da ƙwayoyin ruwa suka kewaye shi. Idan babu abin da ke riƙe zanen, za su iya buɗewa su ƙara nisa domin su ba ion ɗin sarari. Ions na magnesium sun yi aiki kamar abin ɗaurewa: idan suka ci gaba da kasancewa tsakanin zanen, sun taimaka wajen riƙe ratar ta kasance ƙanƙanta. Hakan ya sa ions daban-daban na rare earth su biya kuɗin makamashi daban-daban domin su rage wani ɓangare na ruwan da ke kewaye da su, su shiga tashar, sannan su ɗaure da atoms na oxygen a cikin solid ɗin.



Tashar da ba a ɗaure ba da wadda magnesium ya ɗaure fassarori ne na mechanism da ma’aunin structure, electrochemistry da calculations suke goyon baya. Babu gwaji guda ɗaya da ya kalli dukan jerin matakan molecular kai tsaye.

Ga pair ɗaya da aka gwada, lanthanum da neodymium, wannan **pinning** ya ƙara enrichment factor daga 1.6 zuwa

5.4. Ga lanthanum da praseodymium, ya tashi daga 1.5 zuwa **4.2**. Enrichment factor yana kwatanta ratio na ions biyun bayan rabuwa da ratio ɗinsu kafin rabuwa. Daraja 1 za ta nuna cewa babu fifiko; 5.4 yana nufin material ɗin da aka kama ya fi fifita neodymium a kan lanthanum sau 5.4 fiye da yadda mixture na farko ya yi.

Waɗannan sakamako ne masu ma'ana ga pairs takamaimai a dakin bincike. Ba shaida ba ce cewa yanzu za a iya raba kowane rare earth cikin sauƙi, cewa an nuna continuous flow process, ko kuma cewa za a iya maye gurbin solvent extraction.

Babban ra'ayin takardar ta fi ƙaramin refinery: a hana wata rata mai ruwa a cikin ma'adini buɗewa.

Ion da ke cikin ruwa ya fi bare atom girma

Rare-earth elements sun haɗa da lanthanides tare da scandium da yttrium. Binciken ya gwada ions 12 masu positive charge daga lanthanum zuwa ytterbium. An cire cerium saboda yana sauya oxidation state cikin sauƙi, sannan an cire promethium saboda radioactive ne.

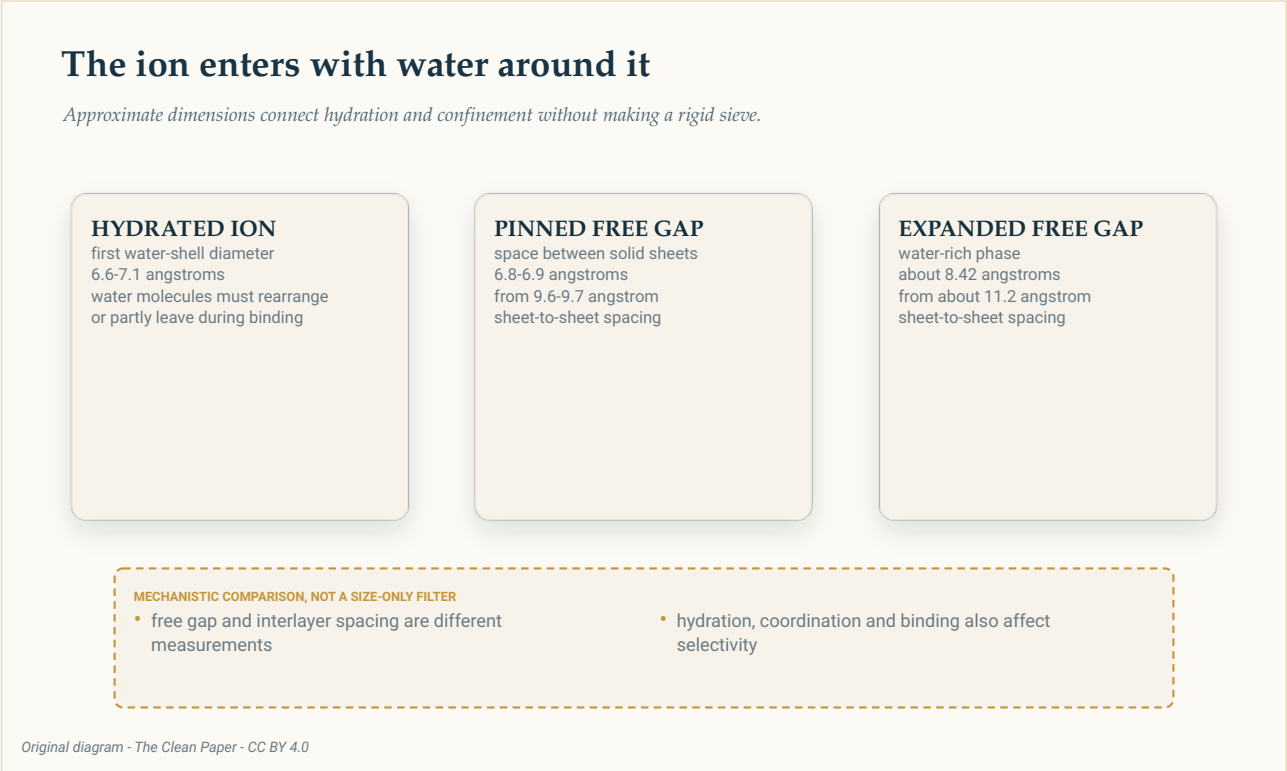
A cikin ruwa, ion ba ya tafiya shi kaɗai. Molecules na ruwa suna jera kansu a kewaye da charge ɗinsa su samar da **hydration shell**. Domin shiga wata ƙaramar tashar kuma ya ɗaure da solid, ion na iya buƙatar sake tsara wannan ruwan ko ya bar wani ɓangare nasa. Kuɗin makamashi na wannan ya dogara da ion ɗin da kuma muhallin da yake ciki.

Ana auna irin waɗannan girma da **angstroms (Å)**. Angstrom ɗaya kashi ɗaya ne cikin biliyan goma na mita (**1 Å = 10^{-10} m**). An ruwaito cewa na farko hydration shells na lanthanides da aka gwada suna da diamita kusan **6.6 zuwa 7.1 Å**.

Masu binciken sun yi amfani da hydrated layered manganese oxide da ake kira buserite. Zanen da aka jera a cikinsa suna kusan **9.6 zuwa 9.7 angstroms** daga juna idan aka auna daga matsayi mai maimaituwa na wani sheet zuwa na gaba. Amma sheet ɗin kansa yana ɗaukar sarari. Ratar da ruwa zai iya cika a zahiri tsakanin sheets ɗin tana kusan **6.8 zuwa 6.9 angstroms** kawai.

Wannan bambanci yana da muhimmanci. Interlayer spacing na 9.7 angstroms ba yana nufin an sami buɗaɗɗiyar tashar 9.7 angstroms ba.

Wasu lanthanides masu sauƙi sun sa structure ɗin ya faɗaɗa zuwa phase mai ƙarin ruwa. A nan nisan sheet zuwa sheet ya kasance kusan **11.2 angstroms**, yayin da estimated free gap ya kasance kusan **8.42 angstroms**. Wani related structure mai ƙanƙantar rata, birnessite, yana da free gap kusan **4.42 angstroms**.



Kwatancen yana tsakanin kusan diamitan hydration shell da free water-filled gap, ba tsakanin bare ion da cikakken nisan sheet zuwa sheet ba. Girma wani ɓangare ne na mechanism, ba cikakken bayaninsa ba.

Ma’adinin na iya daidaita kansa da ion

Idan babu magnesium pinning, tashar ba rigid sieve ba ce: sheets ɗin da aka jera za su iya motsawa. A gwaje-gwajen, ions masu sauƙi—lanthanum, praseodymium da neodymium—sun sa material ɗin ya ɗauki ƙarin ruwa kuma ya buɗe. Ions masu nauyi daga europium zuwa ytterbium sun fi barin ƙaramar tashar yadda take. Samarium ya kasance tsakanin waɗannan halayen biyu.

takardar ta kira halin farko **Group I**, na biyu kuma **Group II**. Waɗannan sunaye ne na yadda ions suka sa wannan material takamaimai ya amsa, ba group numbers na periodic table ba. Iyakar tsakanin groups ɗin ma na iya sauyawa a wasu experimental conditions.

Wannan bambancin structure ya taimaka ga pairs da ke cikin groups daban. A direct ion exchange, enrichment factor da aka ruwaito ya kasance **7.8** ga lanthanum da dysprosium, **5.7** ga praseodymium da dysprosium, **4.5** ga neodymium da dysprosium, da **2.6** ga neodymium da europium.

Yawancin pairs masu makwabtaka sun fi wahala sosai, tare da enrichment factors kusa da 1.1. Factor kusa da 1 yana nufin ƙaramin fifiko. Material ɗin ya fi iya bambance ions biyu idan kowannensu ya fi dacewa da structure na tashar daban, fiye da idan suna kusa da juna a response group iri ɗaya.

Magnesium ya rike tashar a wuri

Daga nan masu binciken suka yi amfani da **electrochemical intercalation**: electrical reaction da ke saka ions tsakanin layers na solid. Ions na magnesium sun ci gaba da kasancewa a tashar yayin da ions na rare earth suke shiga. Magnesium din da ya rage ya taimaka wajen hana buserite spacing fadadawa.

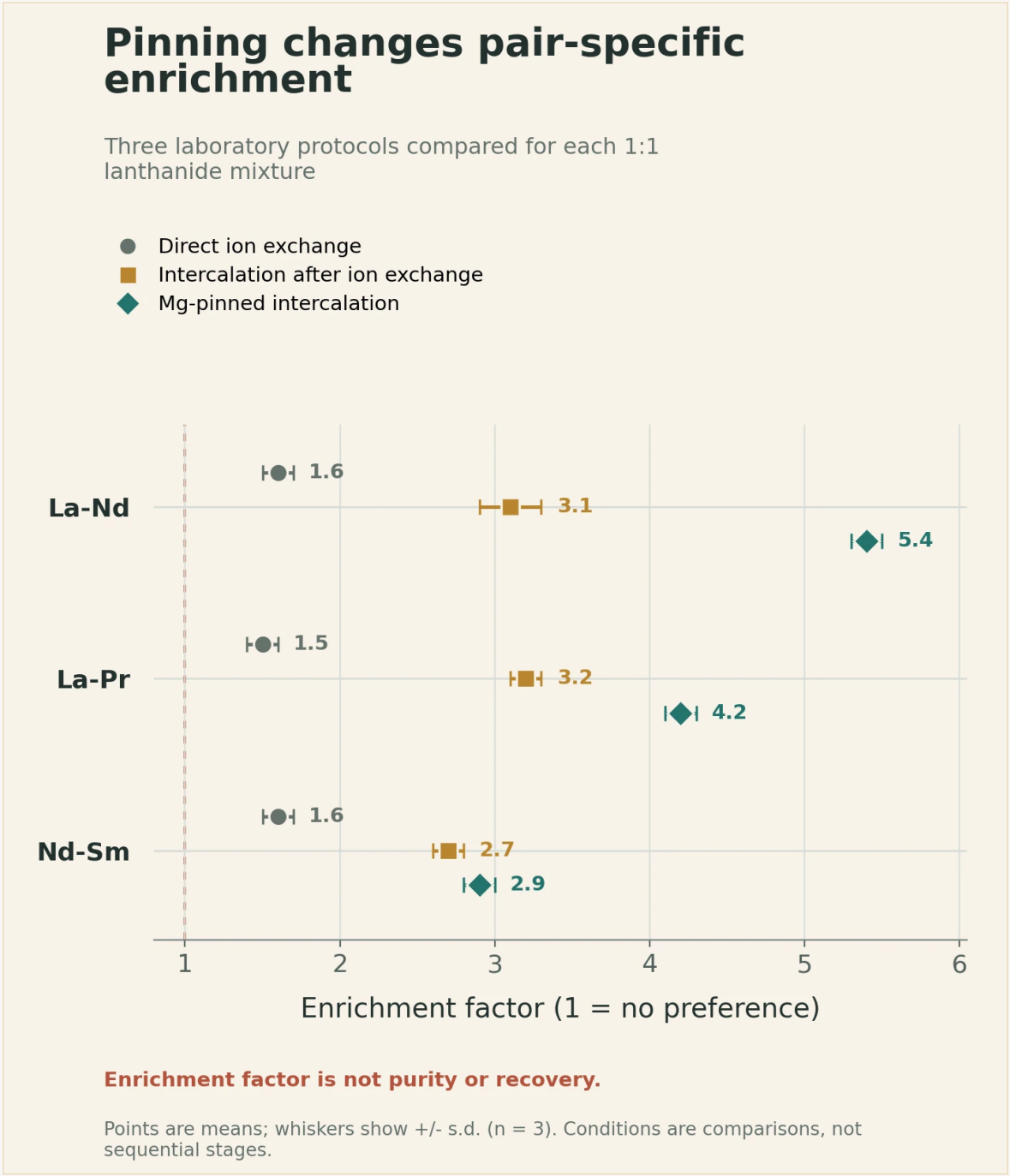
A cikin wannan karamar rata mai ruwa, hydrated ion da ke shigowa yana da karamin sarari. Mechanism da aka gabatar ya hada confinement, partial dehydration, coordination da binding. **Coordination** yana nufin atoms da ke kusa—sau da yawa oxygen—wadanda suke kewaye ion kai tsaye kuma suke huldа da shi.

Shaidar ta fito daga nau'ikan gwaji da dama. Ma'aunin X-ray ya bibiyi structure na solid. Gwaje-gwajen electrochemistry sun auna insertion da separation. **Density functional theory**, wani quantum-mechanical calculation, ya kwatanta structures, hydration da binding. Calculations din suna taimaka wajen fassara mechanism; ba hoton kai tsaye ba ne na ion guda yana bi ta tashar.

Haka kuma mechanism din ba kawai "kananan ions suna wucewa, manya suna tsaya" ba ne. Water shell, yadda layers suke amsawa, kuɗin makamashin dehydration da yadda ion yake yin coordination da solid duk suna bayar da gudummawa.

Pinning ya inganta wasu pairs masu makwabtaka

Babban canjin da takardar ta haskaka shi ne lanthanum da neodymium: enrichment ya tashi daga **1.6 +/- 0.1** ba tare da pinning ba zuwa **5.4 +/- 0.1** tare da magnesium pinning. Lanthanum da praseodymium ya tashi daga **1.5 +/- 0.1** zuwa **4.2 +/- 0.1**. Neodymium da samarium ya tashi daga **1.6 +/- 0.1** zuwa **2.9 +/- 0.1**.



Kowane row yana kwatanta laboratory protocols uku daban, ba matakai uku da ke biyo juna a process guda ba. Factor 1 yana nufin babu fifiko; manyan darajoji suna nuna stronger pair-specific enrichment. Points suna nuna means, whiskers kuma suna nuna +/- standard deviation (n = 3).

A pH 2, darajar lanthanum-neodymium ta kasance **5.6 +/- 0.2**. Ƙara electrical rate sau biyar, daga 0.1C zuwa 0.5C, ya rage ta daga **5.4 +/- 0.1** zuwa **4.3 +/- 0.4**. C-rate yana kwatanta applied electrical current da capacity na material. Rate mafi girma yana bar wa ions da solid ɗin ƙaramin lokaci su amsa.

Babu daraja guda ɗaya da ke bayyana material ɗin a kowane yanayi. Enrichment yana dogara da pair ɗin, structure na solid, acidity da operating rate.

takardar ta kuma gwada material ɗin a gaban ions na yau da kullum masu yawa waɗanda ba rare earth ba ne. Mixtures na farko suna da ion rare-earth guda ɗaya ga kowane competing ions 1,000. Selectivity ƙimomi da aka ruwaito sun kasance kusan **1,200** idan aka kwatanta da sodium, **6,500** da calcium, da **1,700** da magnesium.

Wannan shaida ce mai amfani cewa ions na yau da kullum ba sa rinjayar separation kai tsaye a waɗannan laboratory conditions. Amma ba gwaji ba ne a cikakken liquid da aka samu daga ore tare da duk metals, acidity da contaminants ɗinsa.

Enrichment, separation, purity, depletion da recovery sakamako ne daban-daban

takardar tana amfani da ma'aunin performance da dama, kuma ba za a maye gurbin ɗaya da wani ba.

Enrichment factor yana kwatanta ratio na ions biyu bayan separation da ratio ɗinsu kafin separation. Daraja 5.4 tana nufin captured material ya fi fifita ɗaya daga cikin pair ɗin sau 5.4 fiye da mixture na farko.

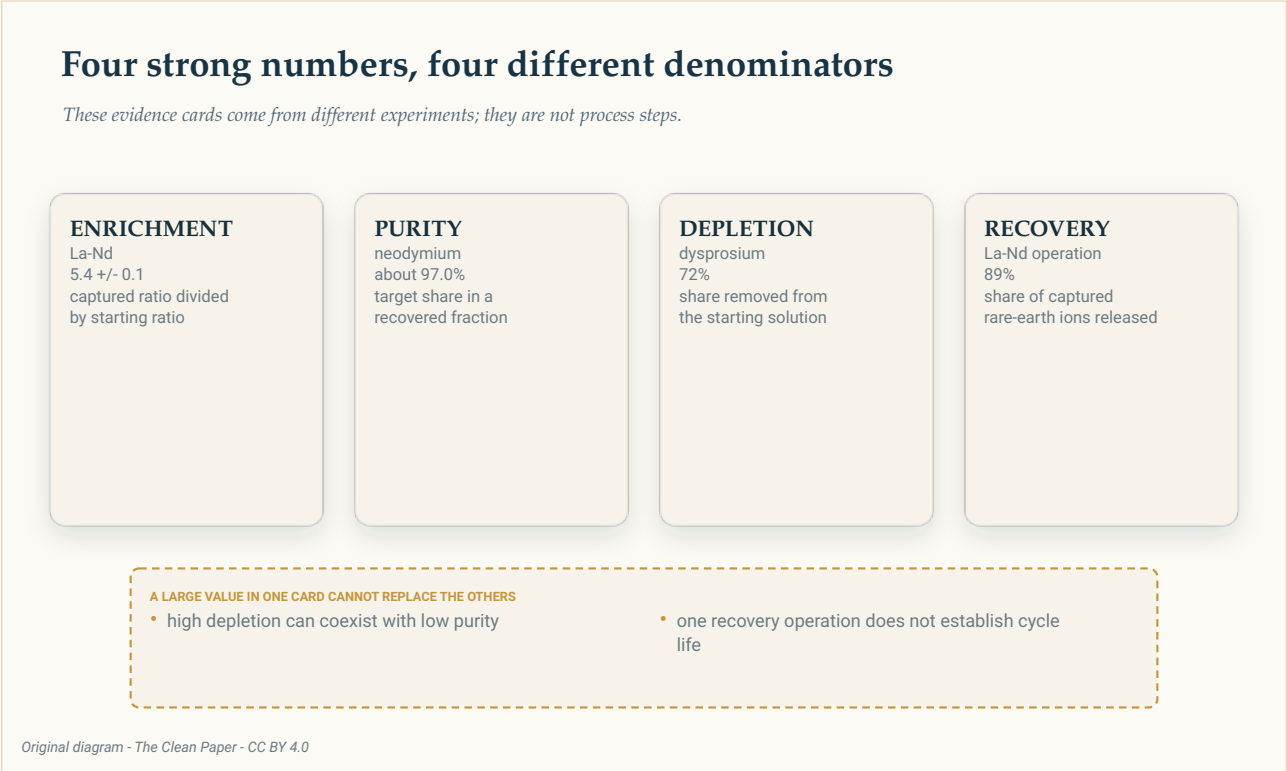
Separation factor yana kuma la'akari da abin da ya rage a liquid: yana kwatanta adadin kowane ion da aka kama da adadin da bai kama ba, sannan ya kwatanta waɗannan balances biyu. Saboda haka zai iya ƙaruwa yayin da ake cire ƙarin material ko da enrichment factor yana bin wani pattern dabam.

Purity shi ne kaso na ion da ake so a recovered fraction. Two-stage demonstrations sun kai kusan **97.0% neodymium purity** da **92.3% dysprosium purity** a specified paths ɗinsu.

Depletion shi ne kaso da aka cire daga solution na farko. Kara powder 10 milligrams sau takwas a jere ya cire **72% na dysprosium** a gwajin neodymium-dysprosium kuma ya samar da accumulated separation factor na 10.8.

Recovery yana tambayar nawa daga ion da aka kama za a iya sake saki daga baya. Reverse ion exchange ya dawo da **80%** a wani operation na neodymium-dysprosium. Electrochemical removal ya dawo da **89%** a wani operation na lanthanum-neodymium.

Recovery yana nuna reversibility. Ba ya tabbatar sau nawa za a iya sake amfani da electrode ba tare da performance ta lalace ba.



Ma'aunai huɗu da aka ruwaito suna amfani da denominators daban kuma sun fito daga gwaje-gwaje daban. Shaidu ne daban-daban, ba matakai da ke biyo juna a process guda ba.

> **Me ya sa percentages biyu masu ban sha'awa za su iya nufin abubuwa daban?**
>
> A ce wani process ya cire 90% na ion guda daga liquid na farko. Wannan high depletion ne. Idan ions marasa so da yawa suka zo tare da shi, recovered material na iya har yanzu yana da low purity. Akasin haka, ƙaramin fraction mai tsananin purity na iya nufin poor recovery idan yawancin target ɗin ya rage a baya. Domin tantance process, ana buƙatar duk waɗannan balances, ba lamba mafi girma kaɗai ba.

Na'urar da aka nuna har yanzu gwajin beaker ce

Gwaje-gwajen electrochemical da suka fi mai da hankali kan scale sun fara da **millilitres 5** na solution mai millimoles 25 a litre na kowane ion. Electrodes ɗin suna ɗauke da kusan **25 zuwa 40 milligrams** na active material.

Electrode guda ɗaya ya cire kusan 40% na neodymium. Electrodes uku da aka yi amfani da su a jere sun kai kusan **90% depletion** da accumulated separation factor na **16.6 +/- 0.4**. Gwargwadon operating rate, reactions sun ɗauki daga **minutes 200 zuwa hours 13**.

Waɗannan girma da lokuta suna cikin babban labarin domin su ne ke fayyace abin da aka nuna a zahiri.

Supplement ɗin ya kuma nuna mass-transfer limit. Domin target na beaker mai higher concentration, an kiyasta cewa kaiwa 50% total depletion zai buƙaci **electrode mai milligrams 266**, ko **milligrams 532 na active material**

ga kowane square centimetre. Saka material mai yawa haka a kan ƙaramin electrode zai sa dissolved ions su yi wahalar isa duk sassan. Saboda haka marubutan suka koma solution mai dilution mafi yawa domin beaker gwaji.

Hypothetical flow cell ya bayyana ne kawai a matsayin projection. Ga assumed cell mai millilitres 1.25 tare da electrode 5 by 5 centimetres, supplement ɗin ya kiyasta kusan **minutes 20 a 1C** ko **minutes 40 a 0.5C** domin kusan 90% depletion. Ba a ruwaito irin wannan flow-cell gwaji ba.

Matakan shaidar suna ƙarewa a wata iyaka: akwai binary da staged laboratory shaida, yayin da flow timing da environmental performance har yanzu projections ko scenario-based estimates ne, ba abin da aka nuna a plant scale ba.

Kwatancen muhalli scenario ne, ba sakamakon plant ba

Supplementary life-cycle assessment yana kwatanta separation steps da suka ƙare a rare-earth oxides kuma yana ba da inputs ga kowane **kilogram 1 na neodymium oxide**.

Ba ya haɗa mining, ore pretreatment ko cikakken commercial refining chain. An wakilci laboratory process ta assumptions da aka tattara daga sources da yawa. Electrode lifetimes na **cycles 10, 20 da 100** scenario da sensitivity ƙimomi ne, ba durability da aka auna a wannan binciken ba. samfurin yana ɗauka cewa magnesium recovery solution za a iya sake amfani da shi har concentration ya sauya da 10%, yana ɗauka **95% water recycling**, kuma yana haɗa calcination a 450-600 degrees Celsius na hours biyu, duk da cewa ba a nuna calcination a gwaji a nan ba.

Life-cycle assessment yana lissafa environmental burdens a cikin system boundary da aka bayyana. Amsarsa tana da faɗi gwargwadon wannan boundary kuma amincinta yana dogara da inventory da scale assumptions.

Nazarin zai iya nuna inda energy, materials da reuse suka fi muhimmanci. Ba zai iya tabbatar cewa commercial version zai sami lower environmental impact fiye da industrial solvent extraction ba.

Mechanism, laboratory platform, da doguwar hanyar engineering

takardar ta nuna cewa za a iya sarrafa spacing da chemical environment na hydrated layered solid da gangan domin a inganta separation na wasu lanthanide pairs. Magnesium pinning bai ƙara chemical binding site kawai ba: ya takaita structure ɗin da ions masu water shell dole su bi.

Wannan sakamako yana buɗe tambayoyin practical. Shin performance za ta ci gaba a real ore-derived mixtures? Za a iya ƙera electrodes da workable mass loading? Yaya manganese oxide zai tsaya bayan insertion da release cycles da yawa? Continuous cell zai iya rike selectivity, throughput da water balance? Yaya environmental comparison zai kasance idan an sami measured pilot-scale inventories?

Gwajin bai amsa waɗannan tambayoyin ba. Ya sa su zama takamaimai kuma masu gwadawa.

Nasarar ba finished rare-earth refinery ba ce. Shaida ce cewa wasu ’yan angstroms na sarari mai cike da ruwa da aka sarrafa za su iya sauya separation mai wahala.

Taƙaitaccen bayani

Masu binciken sun yi amfani da hydrated layered manganese oxide domin raba wasu lanthanide-ion pairs a cikin ruwa. Free gap na material ɗin ya kasance kusan 6.8-6.9 angstroms, kusa da reported 6.6-7.1-angstrom diameter na na farko hydration shells na ions. Magnesium da aka rike a tashar ya taimaka wajen hana ratar buɗewa kuma ya inganta pair-specific enrichment, ciki har da lanthanum-neodymium daga 1.6 zuwa 5.4 da lanthanum-praseodymium daga 1.5 zuwa 4.2. Binciken ya kuma ruwaito gwaje-gwaje da ions na yau da kullum masu yawa, staged purity, sequential depletion da recovery operations. Scale da aka nuna ya ci gaba da kasancewa beaker tests na millilitres 5 tare da active material milligrams 25-40 da reaction times daga minutes 200 zuwa hours 13. Flow-cell timing projection ne, ba a gwada reuse a cycles da yawa ba, kuma life-cycle comparison ya dogara da laboratory-scale assumptions. takardar tana goyon bayan confinement mechanism da laboratory platform, ba industrial replacement na solvent extraction ba.

Binciken ba tare da ƙarin gishiri ba

Abin da takardar ta nuna: Rike hydrated manganese-oxide gap kusa da 6.8-6.9 angstroms tare da magnesium da ya rage ya sauya separation na wasu lanthanide pairs. Structural ma'aunai, electrochemistry da calculations suna goyon bayan mechanism da ya haɗa confinement, dehydration, coordination da binding.

Abin da ya yi performance mafi kyau: A specified conditions, lanthanum-neodymium enrichment ya kai 5.4 +/- 0.1, lanthanum-praseodymium kuma 4.2 +/- 0.1. Darajojin sauran pairs sun bambanta. Gwaje-gwaje daban sun ruwaito purity, depletion da recovery sakamako waɗanda suke amfani da denominators daban.

Abin da bai nuna ba: Universal separator ga duk rare earths; operation a cikakken ore stream; demonstrated continuous flow cell; electrodes masu jure cycles da yawa; maye gurbin solvent extraction; ko tabbatacce commercial environmental superiority.

Manyan iyakokin scale: Gwaje-gwajen da aka nuna sun yi amfani da solution millilitres 5, active material kusan milligrams 25-40 da reaction times daga minutes 200 zuwa hours 13. Target mai higher concentration ya nuna loading problem na milligrams 532 per square centimetre. Flow times extrapolated ne. Electrode lifetime da manyan recycling inputs a life-cycle assessment assumptions ne.

Yaya yawan amincewa ya kamata mai karatu gaba ɗaya ya yi? Babban amincewa ga laboratory ma'aunai da aka ruwaito ga pairs da conditions da aka ambata. Matsakaicin amincewa ga proposed molecular interpretation, domin yana haɗa direct structure da electrochemistry da calculations. Ƙaramin amincewa cewa current bayanai suna iya hasashen industrial throughput, lifetime ko environmental performance.

Majiyoyi

Zou et al., Pinning angstrom-size solid ionic channels for rare-earth element separation, Nature Chemical Engineering 3, 402-413 (2026)
https://doi.org/10.1038/s44286-026-00418-8