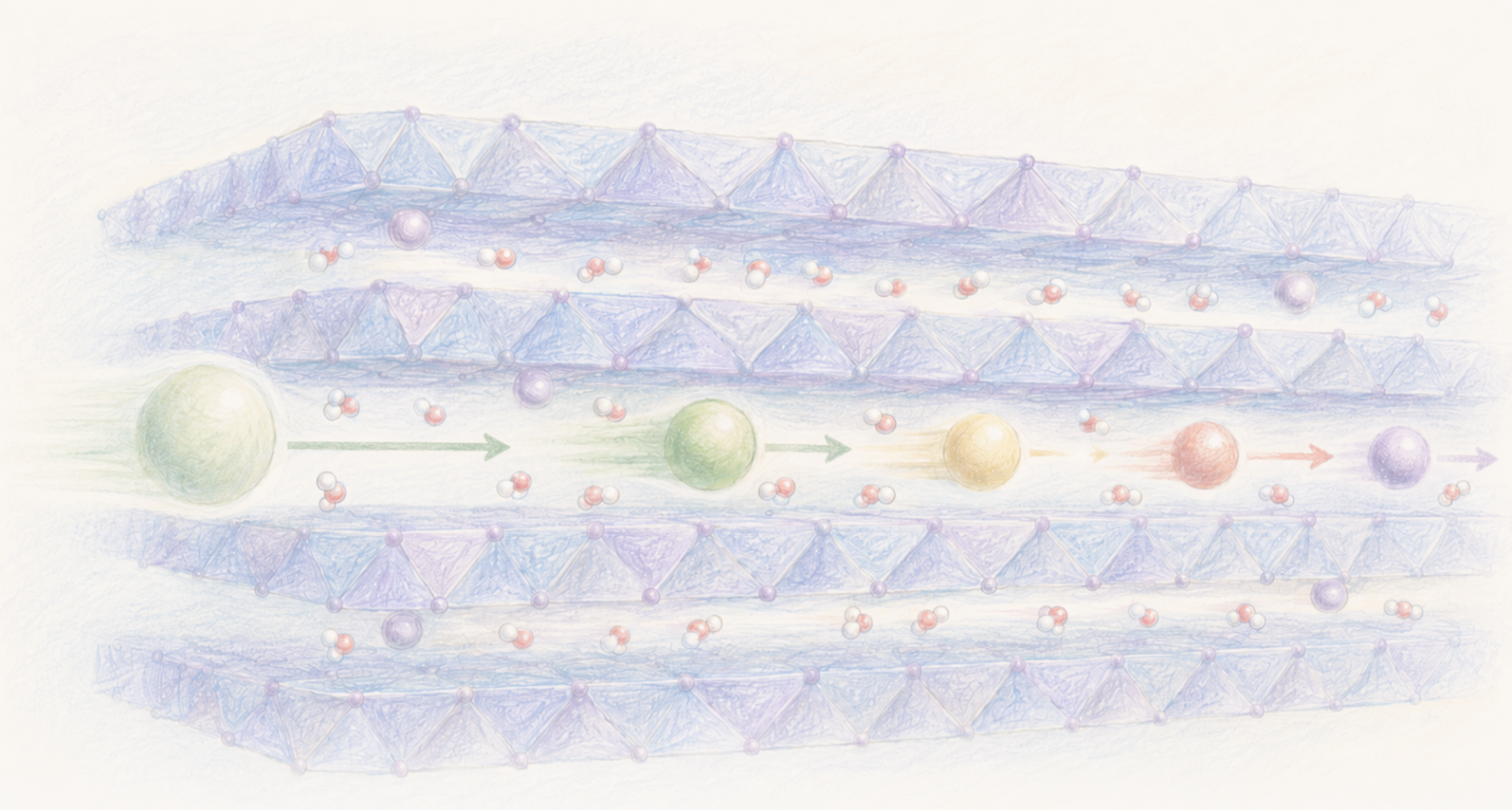

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WHAT THE PAPER SAYS · WHAT IT DOESN'T · WHY IT MATTERS

Channel mineral bishaaniin guutame akka hin banne qabachuun rare-earth ions wal fakkaatan addaan baasuuf gargaare

Magnesium hydrated manganese-oxide gap bal'ina water shell lanthanide ion biraatti qabee, laboratory tests keessatti selected pairwise enrichment improve godhe. Demonstrated work millilitres solution fi milligrams material fayyadame; flow operation, long cycle life fi commercial environmental performance ammallee unproven.

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

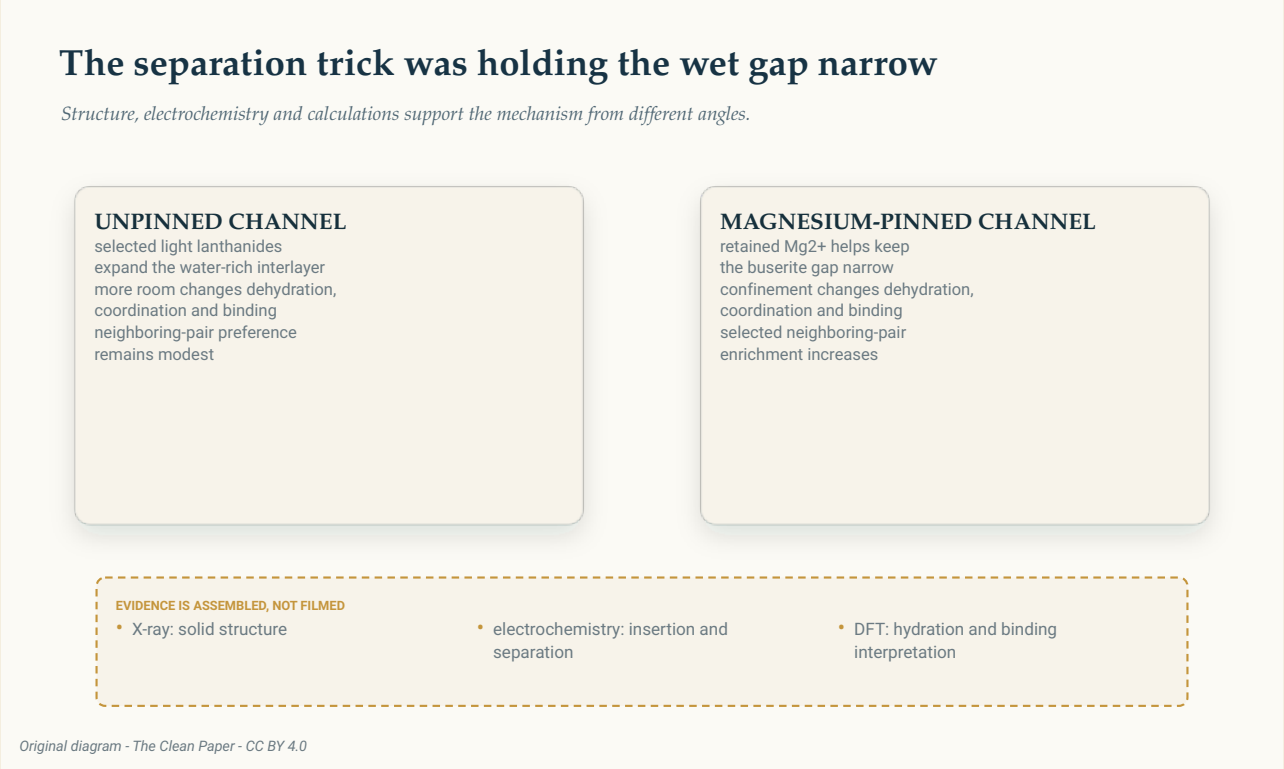
Paper: *Pinning angstrom-size solid ionic channels for rare-earth element separation*, Siqi Zou, Jiadong Liu, Woo Cheol Jeon, Maoyu Wang, Ronghui Wu, Yu Han, Gangbin Yan, Grant T. Hill, Xiaolin Yue, Hua Zhou, George C. Schatz & Chong Liu, Nature Chemical Engineering 3, 402-413 (2026) · DOI: 10.1038/s44286-026-00418-8

Channel mineral bishaaniin guutame akka hin banne qabachuun rare-earth ions wal fakkaatan addaan baasuuf gargaare

Rare-earth ions addaan baasuuf rakkisaa kan ta'an sababuma obboleeyyan fageenya irraa addaan baasuuf rakkisuu danda'anitti: garaagarummaan jira, garuu xiqqaa dha.

Lanthanides periodic table keessatti wal bira jiru, yeroo baay'ee ions charge wal-fakkaataa qabu. Sizes isaanii series keessatti suuta jijjiirama, chemical amala isaanii immoo wal fakkaataa ta'ee hafa. Industrial refining kanaaf separation tarkaanfiiwwan irra deddeebi'aman hedduu irratti hirkata.

Laaboraatoorii qorannoo haaraan rakkoo kana confinement karaa itti seene. Researchers stacked sheets manganese oxide gidduu water-filled gap qabu fayyadaman. Rare-earth ion tokko gap kana bira yeroo dhufu water molekiyuulota'n marfameera. Brace malee sheets addaan fagaachuu danda'u, ion sana accommodate gochuuf. Magnesium ions brace fakkaatanii hojjatan: sheets gidduu yeroo hafu gap narrow ta'ee akka turu gargaara. Rare-earth ions adda addaa sana booda water muraasa of irraa baasu, channel keessa seenu fi oksijiinii atoms jajjabaa keessa jiran waliin bind gochuuf anniisaa costs adda adda kaffalu.



Unpinned fi magnesium-pinned channels mechanistic interpretations caasaa, electrochemistry fi shallaggiiwwan'n supported dha. Tokko yaalii tokko guutuu molekiyuulii sequence hin ilaalne.

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Tested pair tokkoof, lanthanum fi neodymium, **pinning** kun enrichment faaktara 1.6 irraa gara **5.4**tti ol kaase. Lanthanum fi praseodymium'f 1.5 irraa gara **4.2**tti ol ka'e. Enrichment faaktara reeshiyoo ions lama booda separation, reeshiyoo dura separation waliin walbira qaba. Gatii 1 lakki preference

jechuudha; 5.4 jechuun captured maateriyaalii neodymium lanthanum caalaa starting mixture irratti ture caalaa 5.4 yeroowwan strongly caalatti filatu jechuu dha.

Kun hiika qabu pair-specific laaboraatoorii bu'aawwan dha. Every muraasa lafa amma cleanly separated ta'uu, flow adeemsa demonstrated ta'uu ykn solvent extraction replaced ta'uu ragaa miti.

Yaada barruu keessaa strongest refinery caalaa xiqqaa dha: wet mineral gap akka hin banne qabi.

Ion bishaan keessa jiru bare atom caalaa guddaa dha

Rare-earth elements lanthanides plus scandium fi yttrium dabalatu. Qorannoo positively charged lanthanide ions kudha lama lanthanum irraa ytterbium'tti qore. Cerium oxidation haala salphaatti jijjiiru waan ta'eef excluded; radioactive promethium excluded.

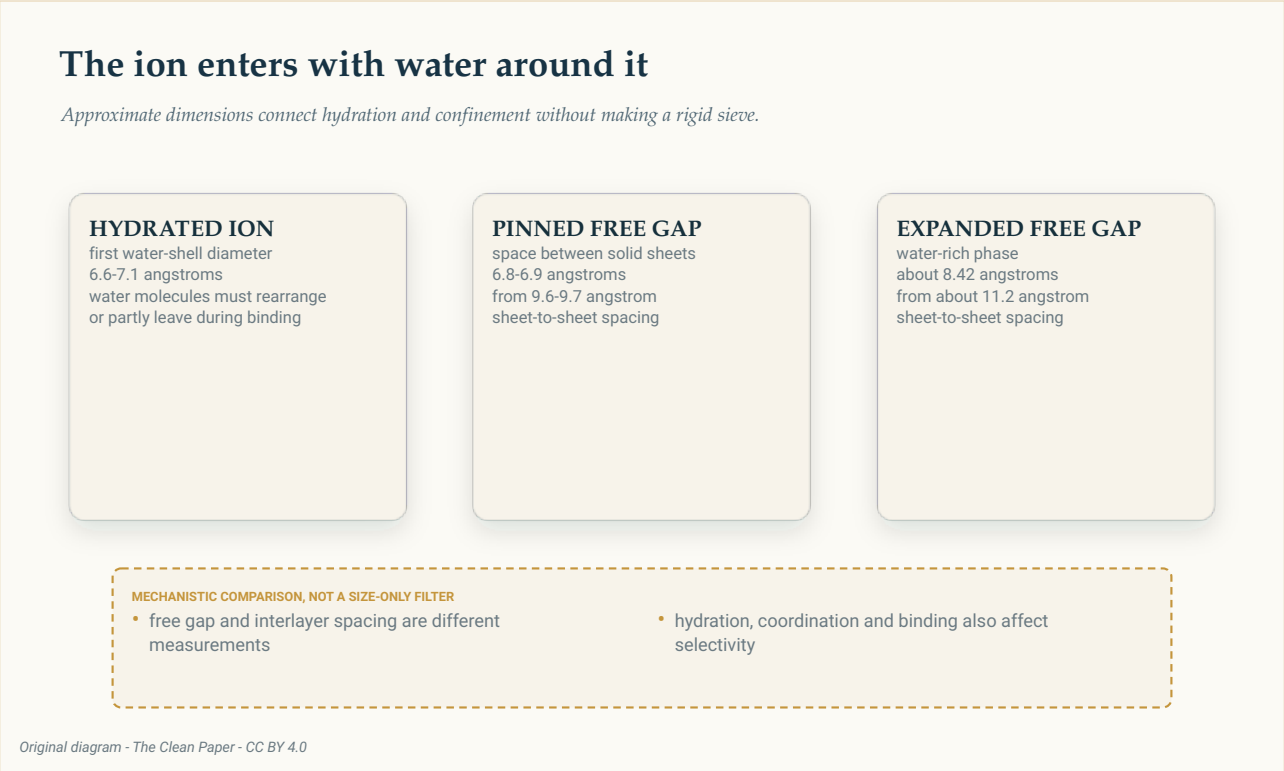
Bishaan keessatti, ion kophaa hin deemu. Water molekiyuulota charge isaa naannoo arranged ta'anii **hydration qola** uumu. Narrow channel keessa seenu fi jajjabaa waliin bind gochuuf, ion water layer sana keessaa gartokkee rearrange ykn shed gochuu qaba. Anniisaa cost ion fi surroundings isaa lamaan irratti hunda'a.

Dimensions **angstroms (Å)** keessatti safaramu. Tokko angstrom tokko ten-billionth of a metre dha (**1 Å =** 10^{-10} **m**). Jalqabaa hydration shells tested lanthanides keessatti gara **6.6 hanga 7.1 Å** jechuun gabaafame.

Researchers hydrated layered manganese oxide buserite jedhame fayyadaman. Stacked sheets isaa repeating sheet position tokko irraa next position'tti **9.6 hanga 9.7 angstroms** apart turan. Garuu sheet itself space fudhata. Free water-filled gap jiru sheets gidduu qofa waa'ee **6.8 hanga 6.9 angstroms** ture.

Garaagarummaan kun barbaachisaa dha. 9.7-angstrom interlayer spacing jechuun 9.7-angstrom banaa channel miti.

Lighter lanthanides muraasni caasaa caalaa water-rich sadarkaa ta'etti expand godhan. Achitti sheet-to-sheet spacing waa'ee **11.2 angstroms**, tilmaamame free gap waa'ee **8.42 angstroms**. Narrower related caasaa, birnessite, free gap around **4.42 angstroms** qaba ture.



Walbira qabuu approximate hydration-shell diameter fi free water-filled gap gidduu dha; bare ion fi guutuu sheet-to-sheet spacing gidduu miti. Hammamtaa adeemsa hojii keessaa kutaa dha, explanation guutuu miti.

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Mineral'n ion irratti adapt gochuu danda'a

Magnesium pinning malee, channel rigid sieve miti: stacked sheets sochoosu danda'u. Yaaliiwwan keessatti, lighter ions lanthanum, praseodymium fi neodymium maateriyaalii caalaa water akka fudhatu, wider akka banu godhan. Heavier ions europium irraa ytterbium'tti yeroo baay'ee narrower channel intact dhiisan. Samarium deebiiwwan lamaan gidduu ture.

Barruu deebii jalqabaa **Garee I**, lammaffaa **Garee II** jedha. Isaan labels ions maateriyaalii particular kana akkamitti deebii kennu taasisan qofa; periodic table garee lakkoofsota miti. Daangaa haalawwan yaalii biroo jalatti jijjiiramuu danda'a.

Garaagarummaan caasaa sun cimdii gareewwan adda addaa gidduutti illee gargaare. Kallattii ion exchange keessatti, gabaafame enrichment faaktara **7.8** lanthanum fi dysprosium gidduutti, **5.7** praseodymium fi dysprosium gidduutti, **4.5** neodymium fi dysprosium gidduutti fi **2.6** neodymium fi europium gidduutti ture.

Neighbouring pairs baay'een baay'ee rakkisaa turan, enrichment wantoota dhiibbaa qaban near 1.1 waliin. Faaktara near 1 little preference jechuudha. Maateriyaalii ions lama adda channel caasaalee favor yeroo godhan salphaatti adda baasu, wal-fakkaataa deebii garee keessatti walitti dhihoo yeroo ta'an caalaa.

Magnesium channel pin godha

Researchers sana booda **electrochemical intercalation** fayyadaman: electrical reaction ions jajjabaa layers gidduu galchu. Rare-earth ions yeroo seenan magnesium ions channel keessatti hafe. Magnesium retained sun buserite spacing expand akka hin goone gargaare.

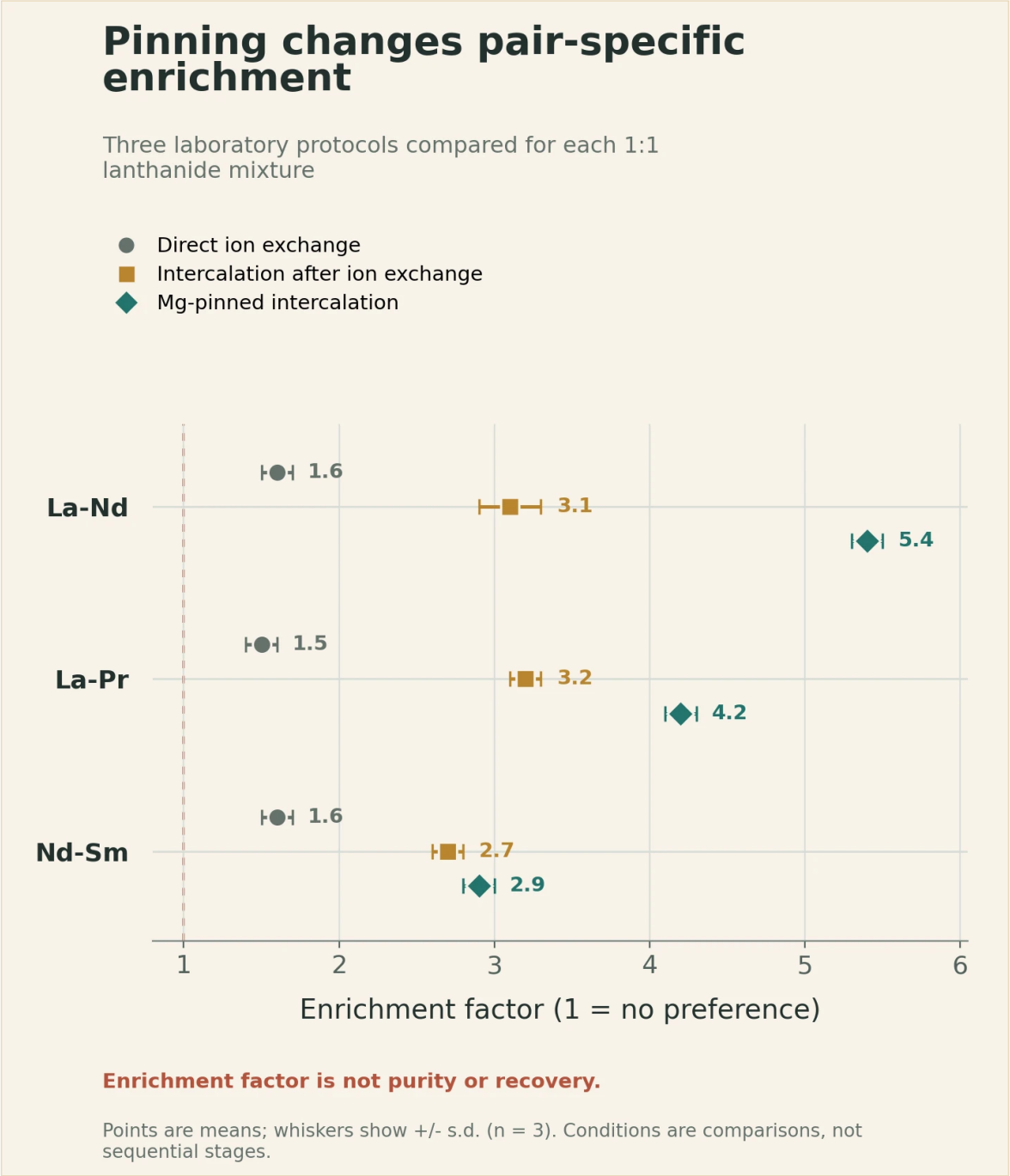
Narrower wet gap sana keessatti, incoming hydrated ion space xiqqaa qaba. Proposed adeemsa hojii confinement, partial dehydration, coordination fi binding combine godha. **Coordination** jechuun nearby atoms, yeroo baay'ee oksijiinii, ion kallattiin marsee interact godhan.

Ragaa gosa hojii hedduu irraa dhufa. X-ray safartuuwwan jajjabaa caasaa hordofan. Electrochemical yaaliiwwan insertion fi separation safaran. **Density hojii-qabeessa tiyoorii**, quantum-mechanical shallaggii, caasaalee, hydration fi binding walbira qaba. Shallaggiiwwan adeemsa hojii hiikuuf gargaara; ion tokko channel keessa moving kallattii movie miti.

Adeemsa hojii'n simply "smaller ions pass, guddaa caalaa ions stop" illee miti. Water qola, layers akkamitti deebii kennu, dehydration cost hammam, fi ion jajjabaa waliin akkamitti coordinate godhu hundi contribution godhu.

Pinning selected neighbouring pairs fooyyesse

Isa guddaa highlighted jijjiirama lanthanum fi neodymium'f: enrichment **1.6 +/- 0.1** pinning malee irraa gara **5.4 +/- 0.1** magnesium pinning waliin ol ka'e. Lanthanum fi praseodymium gidduutti **1.5 +/- 0.1** irraa gara **4.2 +/- 0.1**. Neodymium fi samarium gidduutti **1.6 +/- 0.1** irraa gara **2.9 +/- 0.1**.



Row tokko tokko adda laaboraatoorii protocols sadii walbira qaba; adeemsa tokko sequential stages miti. Faaktara 1 lakki preference; ol-aanaa gatiiwwan pair-specific enrichment stronger agarsiisu. Qabxiilee means, whiskers +/- istaandaardii deviation (n = 3) agarsiisu.

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pH 2 irratti lanthanum-neodymium gatii **5.6 +/- 0.2** ture. Electrical saffisa fivefold, 0.1C irraa 0.5C, ol kaasuun **5.4 +/- 0.1** irraa gara **4.3 +/- 0.4** gadi buuse. C-rate applied electrical ammaa maateriyaalii dandeettii waliin walbira qaba. Ol-aanaa saffisa ions fi jajjabaa deebii kennuuf yeroo xiqqaa kenna.

Tokko gatii tokko maateriyaalii universally hin ibsu. Enrichment pair, jajjabaa caasaa, acidity fi operating saffisa irratti hunda'a.

Barruu maateriyaalii abundant non-rare-earth ions waliin illee qormaata keessa galche. Starting mixtures rare-earth ion tokko competing ions 1,000 hundaaf qabu turan. Gabaafame selectivity gatiiwwan naannoo **1,200** sodium against, **6,500** calcium against, fi **1,700** magnesium against turan.

Kun baramaa ions laaboraatoorii haalawwan kana keessatti separation automatically overwhelm hin goone ragaa faayidaa qabu dha. Guutuu ore-derived liquid metals, acidity fi contaminants hunda qabu qormaata miti.

Enrichment, separation, purity, depletion fi recovery bu'aawwan adda adda

raawwii measures hedduun barruu keessatti mul'atu, wal bakka bu'uu hin danda'an.

Enrichment faaktara reeshiyoo ions lama booda separation, reeshiyoo dura separation waliin walbira qaba. Gatii 5.4 captured maateriyaalii member pair tokko starting mixture irratti ture caalaa 5.4 yeroowwan strongly caalatti filatu jechuu dha.

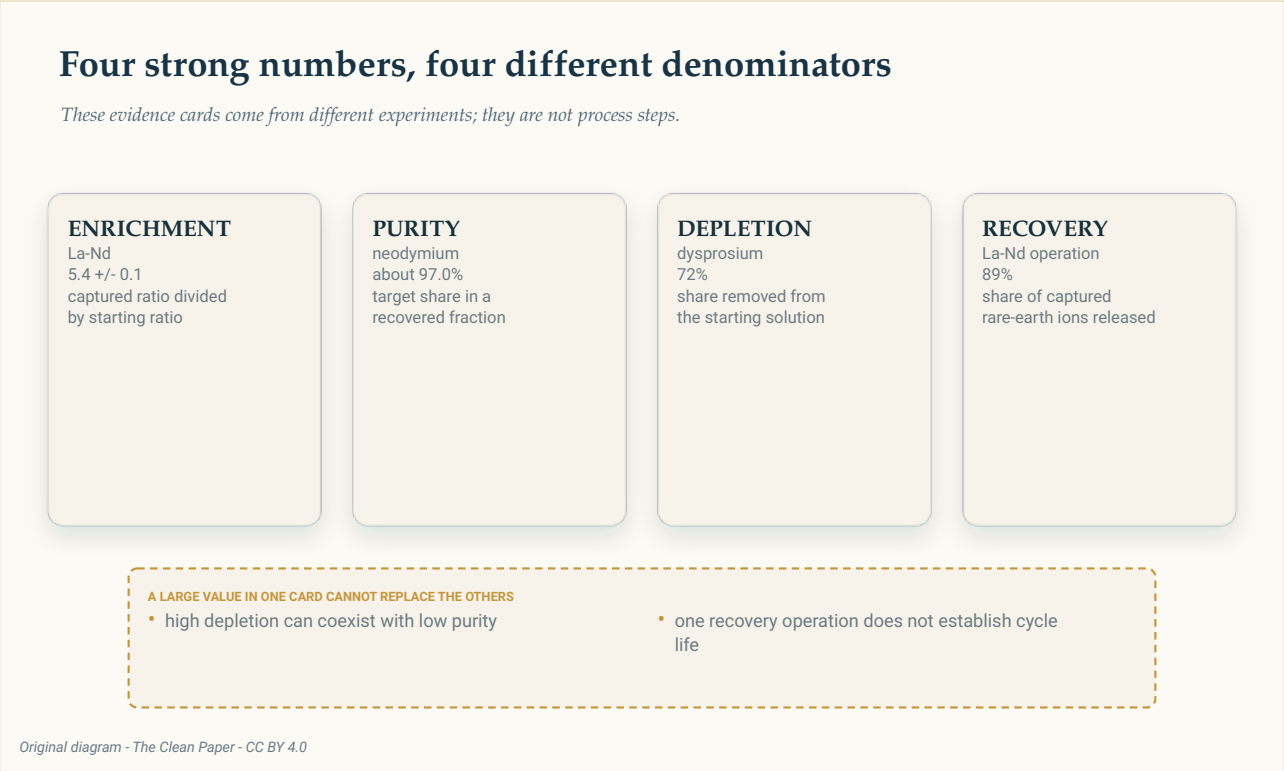
Separation faaktara liquid keessatti maal hafe illee account godha: ion tokko tokko captured amount fi uncaptured amount walbira qabee, balances lamaan sana walbira qaba. Kanaaf caalaa maateriyaalii removed yeroo ta'u separation faaktara rise gochuu danda'a, enrichment faaktara adda akkaataa follow godhus.

Purity recovered fraction keessatti chosen ion share dha. Two-stage demonstrations paths specified keessatti waa'ee **97.0% neodymium purity** fi **92.3% dysprosium purity** ga'an.

Depletion starting furmaata irraa fraction removed dha. Sequential additions eight, powder 10 milligrams tokko tokko, neodymium-dysprosium qormaata keessatti **72% dysprosium** keessaa baasuu, accumulated separation faaktara 10.8 uuman.

Recovery captured ion keessaa hammam boodaa gadhiifame ta'uu danda'a gaafata. Reverse ion exchange neodymium-dysprosium operation tokko keessatti **80%** rehammate. Electrochemical removal lanthanum-neodymium operation tokko keessatti **89%** rehammate.

Recovery reversibility agarsiisa. Electrode raawwii preserve gochuun yeroo meeqa refayyadamamuu danda'a hin mirkaneessu.



Gabaafame safartuuwwan afur denominators adda adda fayyadamu fi yaaliiwwan adda adda irraa dhufu. Isaan ragaa cards dha; adeemsa tokko sequential stages miti.

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> **Percentages nama ajaa'iban lama maaliif hiika adda qabu?**
>
> Adeemsa tokko starting liquid irraa ion tokko 90% keessaa baasuu yaadi. Kun ol-aanaa depletion dha. Yoo unwanted ions hedduun waliin dhufan, recovered maateriyaalii ammallee gadi-aanaa purity qabaachuu danda'a. Faallaa kanaan, very pure xiqqaa fraction poor recovery bakka bu'uu danda'a, yoo galma keessaa baay'een hafe. Adeemsa assessment balances kana hunda barbaada, isa guddaa lakkoofsa qofa miti.

Demonstrated apparatus ammallee beaker yaalii dha

Scale-oriented electrochemical qormaatawwan **5 millilitres** furmaata, tokkoon tokkoon ion 25 millimoles liitira tokko keessatti qabu irraa jalqaban. Electrodes gara **25 hanga 40 milligrams** socho'aa maateriyaalii baatan.

Electrode tokko neodymium waa'ee 40% keessaa baasuu. Electrodes sadii series keessatti fayyadamuun waa'ee **90% depletion** fi accumulated separation faaktara **16.6 +/- 0.4** ga'e. Operating saffisa irratti hundaa'uun reactions **daqiiqaa 200 hanga sa'aatii 13** fudhatan.

Dimensions fi yeroowwan kun ijoo seenaa keessa jiraachuu qabu, sababni demonstrated maal akka ta'e define godhaniif.

Supplement mass-transfer daangaa tokko illee adda baasa. Higher-concentration beaker galmaaf 50% total depletion ga'uuf tilmaamame **266-milligram electrode**, ykn **532 milligrams socho'aa maateriyaalii tokkoon tokkoon square centimetre** barbaachisa. Maateriyaalii hammanaa xiqqaa electrode irratti pack gochuun dissolved ions hundumaa bira ga'u rakkisa. Barreessitoonni kanaaf caalaa dilute furmaata beaker yaalii'f itti jijjiiran.

Hypothetical flow seelii projection qofa keessatti mul'ata. Assumed 1.25-millilitre seelii waliin 5 × 5 centimetre electrode'f, supplement waa'ee **1C irratti daqiiqaa 20** ykn **0.5C irratti daqiiqaa 40** for waa'ee 90% depletion tilmaama godha. Flow-cell yaalii gosa kanaa hin gabaasa godhamne.

Ladder daangaa irratti xumura: binary fi staged laaboraatoorii ragaa jira; flow timing fi environmental raawwii projected ykn scenario-based qofa, plant safartuu irratti hin agarsiifamne.

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Environmental walbira qabuu scenario dha, plant bu'aa miti

Supplementary life-cycle assessment separation tarkaanfiiwwan rare-earth oxides irratti xumuraman walbira qaba, galteewwan tokkoon tokkoon **1 kilogram neodymium oxide** gabaasa godha.

Albuuda baasuun, ore pretreatment ykn guutuu commercial refining chain hin dabalatu. Laaboraatoorii adeemsa yaadota bu'uuraa maddoota hedduu irraa assembled ta'een represented. Electrode lifetimes **10, 20 fi 100 cycles** scenario fi sensitivity gatiiwwan dha, durability qorannoo kana keessatti safarame miti. Moodeela magnesium recovery furmaata concentration isaa 10% jijjiirama hanga refayyadamamuu danda'a assume godha, **95% water recycling** assume godha, fi calcination 450-600

degrees Celsius lama hours dabalata, vaikka calcination as experimentally demonstrated hin taane.

Life-cycle assessment environmental burdens stated sirna daangaa keessatti account godha. Deebii isaa daangaa sun hammam broad ta'e fi inventory/safartuu yaadota bu'uuraa hammam reliable ta'an irratti hunda'a.

Xiinxala anniisaa, maateriyaalota fi reuse eessa barbaachisaa akka godhan adda baasu danda'a. Commercial gosa industrial solvent extraction caalaa gadi-aanaa environmental rukuttaa qaba mirkaneessuu hin godhu.

Adeemsa hojii tokko, platform tokko, fi engineering road dheeraa

Barruu spacing fi chemical environment hydrated layered jajjabaa deliberately to'annoo gochuun selected lanthanide separations improve godhamuu danda'u mirkaneessa. Magnesium pinning chemical binding site biraa dabaluu caalaa godhe: caasaa water-wrapped ions keessa darban constrain godhe.

Bu'aa kun hojiirra oolu gaaffilee bana. raawwii dhugaa ore-derived mixtures keessatti survive godhaa? Electrodes workable maassaa loading'n manufacture godhamuu danda'aa? Manganese oxide insertion/gadhiisuu cycles hedduu keessatti hammam tasgabbaa'aa? Continuous seelii selectivity, throughput fi water balance maintain godhuu danda'aa? Environmental walbira qabuu safarame pilot-scale inventories waliin maal fakkaata?

Yaalii gaaffilee kana hin deebisu. Isaan caalaa ifa ta'e godha.

Achievement finished rare-earth refinery miti. Angstroms muraasa to'atame water-filled space difficult separation jijjiiruu danda'u ragaa dha.

Cuunfaa gabaabaa

Researchers hydrated layered manganese oxide fayyadamuun selected lanthanide-ion pairs bishaan keessatti addaan baasan. Maateriyaalii free gap waa'ee 6.8-6.9 angstroms ture, gabaafame jalqabaa hydration shells ions 6.6-7.1-angstrom diameter waliin dhihoo. Retained magnesium channel pin gochuuf gargaare, pair-specific enrichment fooyyesse, lanthanum-neodymium 1.6 irraa 5.4 fi lanthanum-praseodymium 1.5 irraa 4.2 dabalatee. Qorannoo abundant-ion qormaatawwan, staged purity, sequential depletion fi recovery operations illee gabaase. Demonstrated safartuu 5-millilitre beaker qormaatawwan 25-40 milligrams socho'aa maateriyaalii fi reaction yeroowwan daqiiqaa 200 hanga sa'aatii 13 irratti hafe. Flow-cell timing projected, reuse hedduu cycles hin tested, life-cycle walbira qabuu laboratory-scale yaadota bu'uuraa irratti hunda'e. Barruu confinement adeemsa hojii fi laaboraatoorii platform deeggara; industrial replacement solvent extraction miti.

Sakatta'a ifaa

Wanti barruu agarsiisu: Hydrated manganese-oxide gap near 6.8-6.9 angstroms retained magnesium'n qabachuun selected lanthanide pairs separation jijjiire. Structural safartuuwwan, electrochemistry fi shallaggiiwwan adeemsa hojii confinement, dehydration, coordination fi binding qabu deeggaaru.

Wanti isa gaarii perform godhe: Specified haalawwan jalatti lanthanum-neodymium enrichment **5.4 +/- 0.1**, lanthanum-praseodymium **4.2 +/- 0.1** ga'e. Biraa pair gatiiwwan adda turan. Adda yaaliiwwan purity, depletion fi recovery bu'aawwan denominators adda adda fayyadaman gabaasan.

Wanti hin agarsiifne: Universal separator hunda muraasa earths; guutuu ore stream irratti operation; demonstrated continuous flow seelii; durable many-cycle electrodes; solvent extraction replacement; ykn mirkanaa'e commercial environmental superiority.

Ijoo safartuu daangaalee: Demonstrated qormaatawwan 5 millilitres furmaata, gara 25-40 milligrams socho'aa maateriyaalii fi daqiiqaa 200 hanga sa'aatii 13 fayyadaman. Higher-concentration galma 532-milligram-per-square-centimetre loading rakkoo imply godhe. Flow yeroowwan extrapolated. Electrode lifetime fi guddaa recycling galteewwan life-cycle assessment keessatti yaadota bu'uuraa turan.

Dubbisaan waliigalaa hammam amantaa qabaachuu qaba? Named pairs fi haalawwan irratti gabaafame laaboraatoorii safartuuwwan'f amantaa guddaa. Proposed molekiyuulii hiika caasaa kallattii fi electrochemistry shallaggiiwwan waliin combine godhu waan ta'eef amantaa giddugaleessaa. Ammaa daataa industrial throughput, lifetime ykn environmental raawwii tilmaamu irratti amantaa gadi-aanaa.

Maddoota

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