Electronic Supplementary Material (ESI) for Chemical Communications.

Supporting Information for

Learning from Nature: Recovery of rare earth elements by the extremophilic bacterium *Methylacidiphilum fumariolicum*

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1. Materials and Methods

1.1 Description of all tested REE sources

Königstein water

Königstein flooding water was provided by the Wismut GmbH. The former uranium mine of the WISMUT GmbH near Königstein (Saxony, Germany) was one of the biggest uranium mines in Eastern-Germany. Here, uranium was leached from sandstone by using sulfuric acid. Since 2001, controlled flooding of the mine has been implemented for remediation purposes.[1] Due to the leaching process, the flooding water reveals a low pH of 2.9 and high concentrations of uranium (13 mg/L) as well as other heavy metals.[2]

Gessenhalde water

Gessenhalde water was provided by the Applied Geology and Microbiology groups of Friedrich Schiller University Jena as part of the BMBF supported USER2 project. The Gessenhalde is on the ground of a former leaching heap, a legacy of the uranium mining activity, close to Ronneburg and located between the villages Kauern and Grobsdorf (eastern Thuringia). Similar to the Königstein site, uranium was leached with sulfuric acid from waste rocks with low uranium amount, as well as with acid mine drainage. Seepage water samples were collected at the research test site Gessenwiese (in cooperation with Applied Geology and Microbiology groups of Friedrich Schiller University Jena, BMBF supported USER2 project). A more detailed description of the history, composition and speciation of the Gessenhalde water is available in the listed literature.[3]

Post-mining waters

The post mining-waters, including water of an old gold mine; leaching zincblende, Lithium mica, water of ore leaching and quartz leaching (Wendelscheider Schwergut) were available from ore and quartz industries. Various mining degradation products were digested in acid by the company G.E.O.S. We used the extraction supernatants for our recovery experiment. Wastewater of an old gold mine and ore leaching, leaching zincblende, Lithium mica were provided by G.E.O.S. GmbH, samples of quartz leaching (Wendelscheider Schwergut) by Amberger Kaolinwerke GmbH.

Bastnaesite samples

The rock sample was delivered from Thor Lake in Canada as a lump of rock, and was prepared by various crushing steps until a particle size of 45 µm was reached to perform the extraction for rare earth element (REE) chlorides based on Kruesi.[4] Both bastnaesite samples 1 and 2 are from the same extraction, but with sample 2 an additional step was performed to remove Pb.

Artificial WasteMix

Based on the measured inductively coupled plasma mass spectrometry (ICP-MS) analysis of all the tested post-mining waters, it was recognized that all of the sources included Mg, Al, Ca, Fe, Cu and Zn in high concentration. Thereof, this artificial WasteMix was prepared, with the following concentration: 1 mM $FeCl_3 \cdot 5\ H_2O$ and $CuCl_2$; 100 µM $MgCl_2 \cdot 6\ H_2O$, $AlCl_3 \cdot 6\ H_2O$, $CaCl_2 \cdot 2\ H_2O$, $ScCl_3 \cdot 6\ H_2O$, $ZnCl_2$, $BaCl_2 \cdot 2\ H_2O$, $YCl_3 \cdot 6\ H_2O$, 10 µM of all $LnCl_3 \cdot x\ H_2O$ (Lanthanides, Ln) except Pm.

1.2 Cultivation of *Methylacidiphilum fumariolic*um SolV

The bacterial methanotrophic strain SolV was originally isolated from a volcanic mudpot within the Solfatara crater in Italy.[5] Cultivation was performed with a slightly modified procedure as described by Pol and coworkers[6] and is similar for the small-scale experiments with a procedure described already by our group.[7] All experiments of Step I to Step III were performed in polypropylene plastic flasks (100 mL for Step I and II, 500 mL for Step III) sealed with bromobutyl rubber stoppers, while for Step IV a self-constructed 3.7 L bioreactor made out of glass was used.

For the cultivation experiments shown in Step I (small-scale), 10 mL of autoclaved medium (exact composition in Tab. S2) were mixed with the sterile filtered REE sources (detailed amount in the figure captions). A pre-culture grown with 100 nM La^{3+} was added for inoculation to an OD_{600} of 0.06 at t = 0 h. Incubation was performed in 100 mL plastic flasks under a gas atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2 (added with a canula, Ø 0.40 mm, and a syringe) at 55 °C with a shaking speed of 200 rpm for three days. In addition, samples with Bastnaesite 1 were prepared, without the addition of strain SolV and additional gases (no SolV, no CH_4 and CO_2), with biomass but without gases (SolV, no CH_4 and CO_2), and with strain SolV and gases (SolV, + CH_4 and CO_2).

For the different medium compositions used for screening (Step II, Tab. 1), all individual components were added, including the different REE sources, and the volume was filled up to 10 mL with MilliQ water for each sample. pH was adjusted to 2.7 with 1 M H_2SO_4. Inoculation and incubation were performed as described in Step I for 64 hours.

For the scaling-up cyclic experiments (Step III), 50 mL medium including the REE sources were added to 500 mL plastic flasks. Inoculation and incubation were done as already mentioned, and after 3 days of incubation, the bottles were opened, and the biomass was removed by centrifugation for 30 min at 7200 x g. The plastic flasks including the stoppers were rinsed three times with MilliQ water, and then the supernatant was added, including fresh bacterial cells (OD_{600} = 0.06; pre-grown with 100 nM La^{3+}). The bottles were crimped again, gas was inserted, and incubation was performed again. In total, 6 cycles were carried out. A similar procedure was also performed for the control samples without biomass including the centrifugation step to check for a possible precipitate formation due to versatile medium composition.

The large-scale experiment (Step IV) with Königstein water was performed in the self-constructed bioreactor (Fig. S16, S17). To remove remaining REE traces from prior cultivations, the bioreactor was stirred at 55 °C with 2 M HCl for 3 days while air supply was still connected to the system. After disposal of the acid, the system was flushed once with MilliQ water, and then again run for one day with EtOH and connected air supply for elimination of unwanted biological material. Then, all parts (with direct contact to biomass) were autoclaved except of the cultivation vessel itself. For inoculation 300 mL of pre-grown SolV cells with 100 nM La^{3+} with an OD_{600} = 0.77 were used, but to transfer mainly the biomass without the medium, the cell pellet was collected by centrifugation for 20 min at 4000 x g and resuspended in the lowest possible volume. 3.7 L of autoclaved and sterile filtered medium including the Königstein water were poured in the bioreactor, and biomass was added until an OD_{600} of 0.07 was reached. Constant temperature of 55 °C during the cultivation was controlled with an external heating system in combination with an inbuilt heating jacket in the bioreactor itself. Mixing of the solution was enabled with a dumbbell-shaped magnetic

stirring bar to reduce shear stress to the cells, and speed of 500 rpm was set. Gas flow of air was adjusted to 1000 mL/min, while for CH_4 750 mL/min and CO_2 600 mL/min were regulated with needle valves. The gas and the air supply were connected with tygon tubing from pressure regulators (installed directly to the gas bottles) to the bioreactor inlets, and to ensure sterility of incoming gases, syringe filter units (PES membrane, 0.2 µm) were installed. Inside the bioreactor, the gas inlets were connected with silicon tubing (autoclavable) and gas diffusion stones to ensure the formation of small bubbles for a better solubility of the gases in the growth medium. To prevent the evaporation of medium at such a high gas flows in combination with a temperature of 55 °C, inverted reflux condensers were installed in the gas outlet (outcoming gas connected in spiral, ascending turns, while the outer part was constantly cooled), and temperature of the cooling water was set to 5 °C. To visibly check if any evaporation occurred, an impinger was additionally added to the gas outlet, however no liquid was poured into the bottle. The cultivation was performed for 250 hours, and samples of biomass were collected in regular time intervals via the sampling port.

1.3 Optical density measurements

For collection of the samples during the growth studies (Step II), biomass was collected with a syringe and canula through the butyl stoppers. For Step I & III samples, bottles were opened at the end of the cultivation. Samples of Step IV were collected at regular time intervals via the sampling port. Optical density at 600 nM (OD_{600}) was measured with a cell density meter (Fisherbrand™ cell density meter model 40, Fisher Scientific, Waltham, USA) in combination with PMMA semi-micro cuvettes. When necessary, samples were diluted 1:10 – 1:40 to enable a precise measurement. The OD_{600} value shown for all measurements is the mean value over 5 measurements of one sample.

1.4 Preparation for ICP-MS analysis

To separate biomass and supernatant, the samples were centrifuged for 30 min at 14 000 x g. 500 µL of the supernatant were acidified with 5 µL 65 % HNO_3. For Ln concentration determination in the cell pellets in Step III, the biomass of all cycles was collected after each cycle and collected in a tube at RT. After the last cycle was finished, the remaining supernatant was removed by centrifugation at 7100 x g for 15 min, and the biomass was washed three times with 5 mL MilliQ water. The wash fractions were also collected and analyzed. The cell pellet was transferred, and lyophilized (alpha 1-2 LDplus lyophilizer, Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany). Final mass after lyophilization: Königstein water 81.3 mg, Gessenhalde water 78.1 mg, Bastnaesite 1 70.6 mg, Bastnaesite 2 68.0 mg, Artificial WasteMix 61.7 mg, EOL waste 59.4 mg. For the microwave-assisted acid digestion, 10 mg of the cell pellet was transferred to a microwave vessel and mixed with 1000 µL 65 % HNO_3. The digestion was performed in an Anton Paar Microwave 5000 (Graz, Austria) with the following steps: 5 min 180°C, 10 min 200°C, 15 min 220°C. After the procedure, the disrupted cell pellet solution was filled up to 15 mL with MilliQ water. No further acidification was necessary for the ICP-MS analysis. For the analysis of the biomass after the large-scale cultivation, similar procedure as described for Step III was carried out. 10 mL of the final biomass with OD_{600} = 20.0 were used, and after the washing procedure and lyophilization, 53.7 mg of dry cells were obtained.

All samples were measured with ICP-MS (iCAP RQ, Thermo Fisher Scientific, Waltham, USA and NexION 350X ICP-MS, Perkin Elmar, Waltham, USA) to determine the concentration of the selected elements in the samples.

1.5 ICP-OES analysis

For inductively coupled plasma-optical emission spectroscopy (ICP-OES) an Agilent ICP-OES 5800 instrument linked to an Agilent SPS4 autosampler was used (Agilent Technologies, Santa Clara, USA). The elemental composition of the different water samples was estimated by using the IntelliQuant mode with the following settings: pump speed: 12 rpm, uptake delay: 25 s, rinse time: 60 s, RF power: 1.2 kW, stabilisation time: 20 s, viewing mode: axial, nebuliser flow 0.7 L/min, plasma flow: 12 L/min, aux flow 1 L/min. All samples were sterile filtered (0.2 µM PES), and all REE sources were measured directly. Only samples of bastnaesite and EOL were diluted 1:5 with MilliQ water. Values were obtained in mg/L.

2. Figures

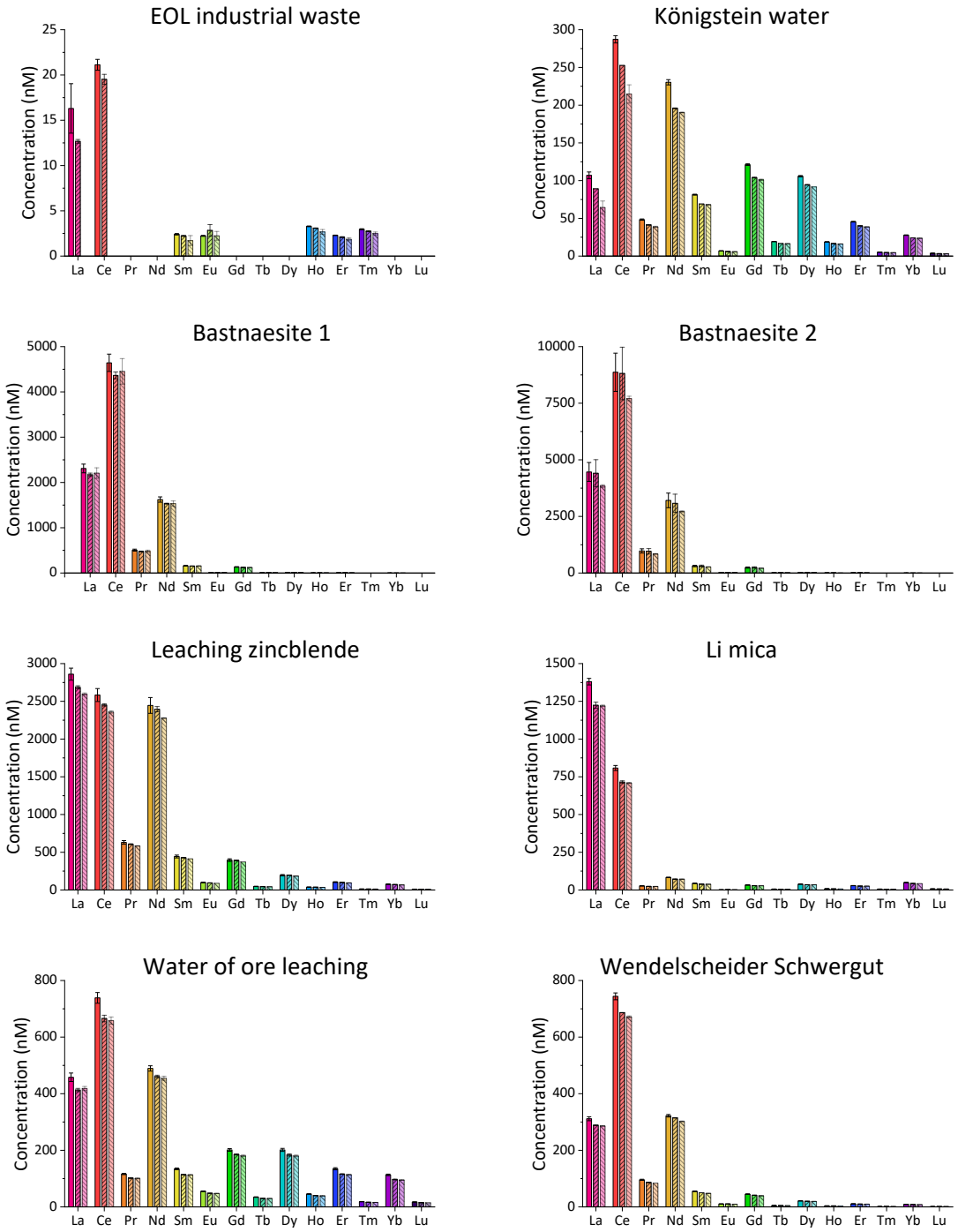


Fig. S1. Screening of concentration of Ln in different REE-containing sources. All potential REE-containing solutions before (left bar, no pattern) and after (right bar, left up to right down diagonal lines) cultivation with strain SolV, a control without inoculation with strain SolV (middle bar, left down to right up diagonal lines) was also analyzed with ICP-MS. Starting OD_{600} was set to 0.06, and cultivation was performed for 3 days at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. 10 mL of minimal medium as described in Tab. S1 was used, and REE-containing solutions (sterile filtered with 0.2 µM PES) were added (1 µL EOL industrial water, 2000 µl Königstein water, 1 µL Bastnaesite 1 and 2, 3000 µL Leaching zincblende, 1000 µL Lithium mica, 1500 µL water of ore leaching, 200 µL Wendelscheider Schwergut). In control samples (without strain SolV) of water of an old gold mine, Lithium mica, and leaching zincblende, precipitate formation was visible. Königstein and Gessenhalde water (Fig. 1a) showed only a slight precipitate formation, which was only visible after 1 hour of centrifugation at 14 000 x g.

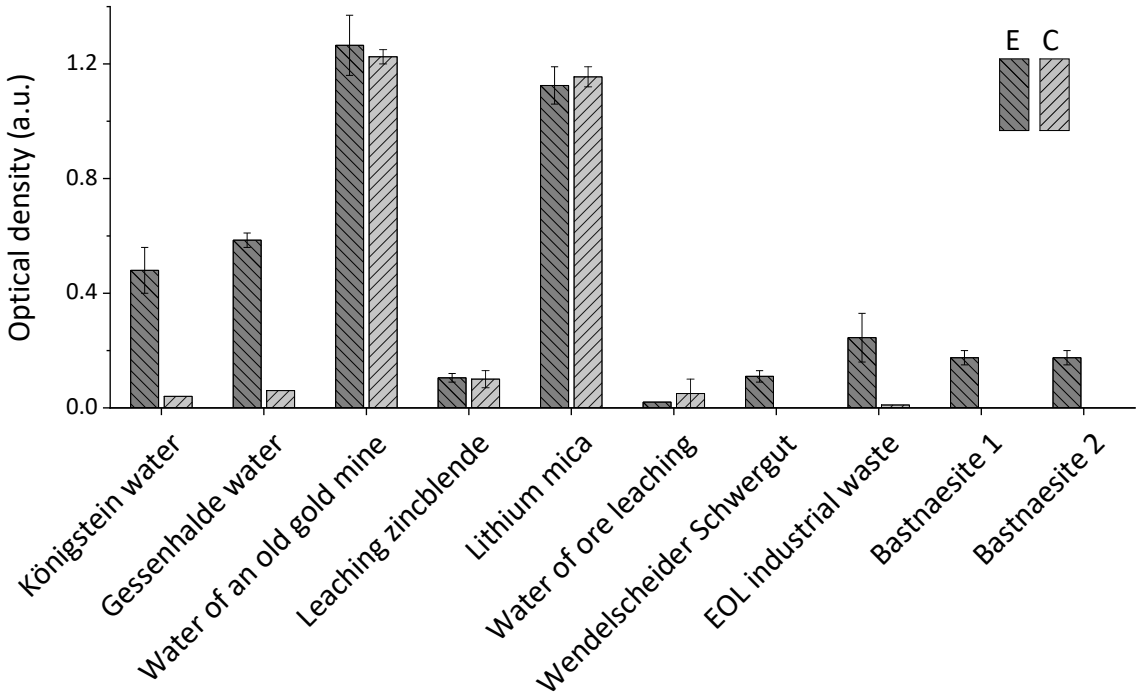


Fig. S2. Optical density at 600 nm for the different REE-containing sources of samples described in Fig. S1 when strain SolV was added (E) and without added bacterial strain (C) after 3 days of cultivation. The high OD in the controls for certain sources (e.g. water of an old gold mine, Lithium mica, and leaching zincblende) is due to precipitate formation.

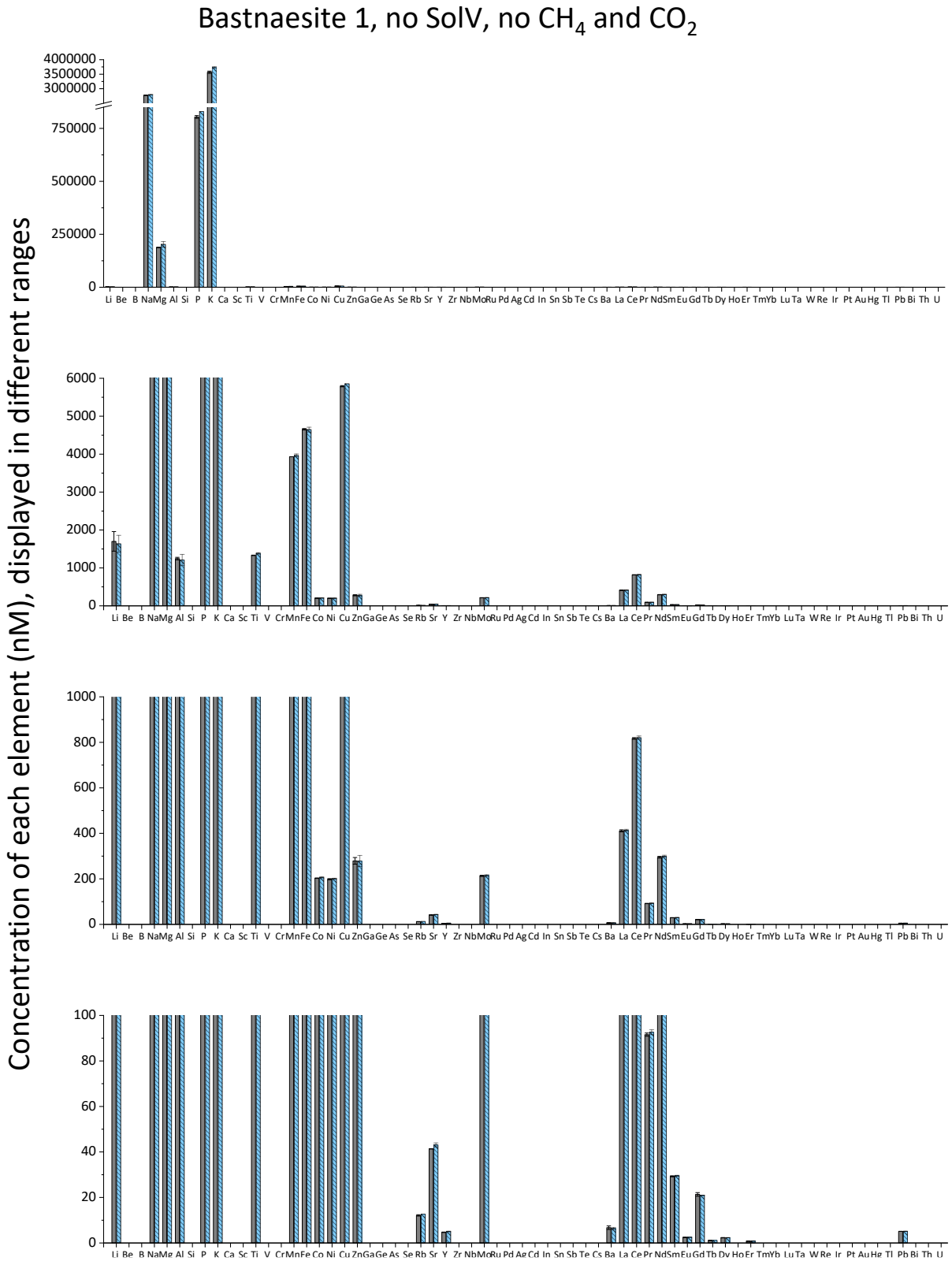


Fig. S3. Screening of concentration of all elements (detectable with ICP-MS) in Bastnaesite 1 samples, with no addition of strain SolV or CH_4 and CO_2. The solutions before (grey left bar, no pattern) and after (blue right bar, left up to right down diagonal lines) the experiment were analyzed with ICP-MS. Cultivation was performed for 87 hours at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks and no CH_4 and CO_2 was added. 10 mL of minimal medium as described in Tab. S1 was used, and 0.2 µL of Bastnaesite 1 (sterile filtered with 0.2 µM PES) was added.

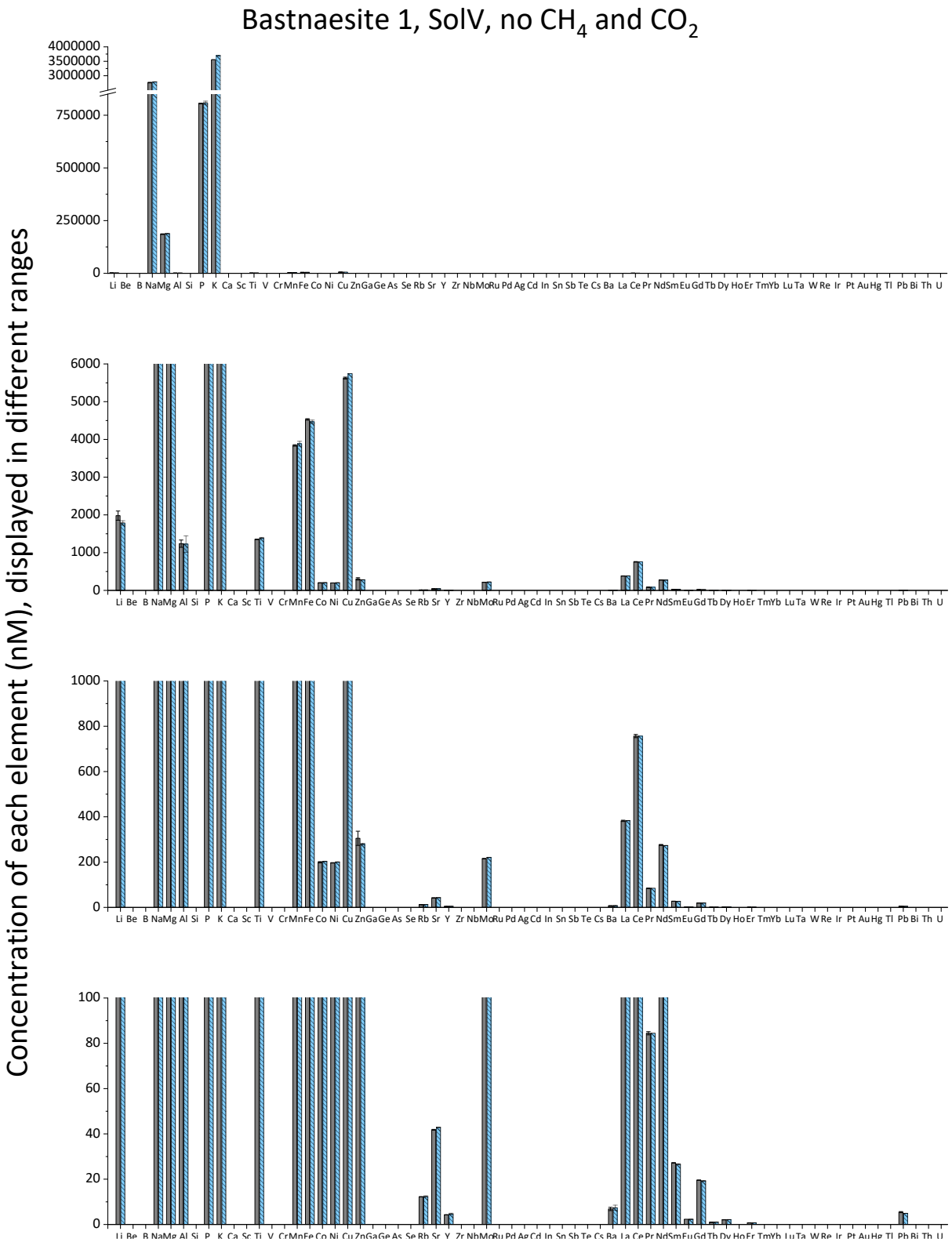


Fig. S4. Screening of concentration of all elements (detectable with ICP-MS) in Bastnaesite 1 samples, with addition of strain SolV but no additional CH_4 and CO_2. The solutions before (grey left bar, no pattern) and after (blue right bar, left up to right down diagonal lines) the experiment were analyzed with ICP-MS. Starting OD_{600} was set to 0.06, and cultivation was performed for 87 hours at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks and no CH_4 and CO_2 was added. 10 mL of minimal medium as described in Tab. S1 was used, and 0.2 µL of Bastnaesite 1 (sterile filtered with 0.2 µM PES) was added.

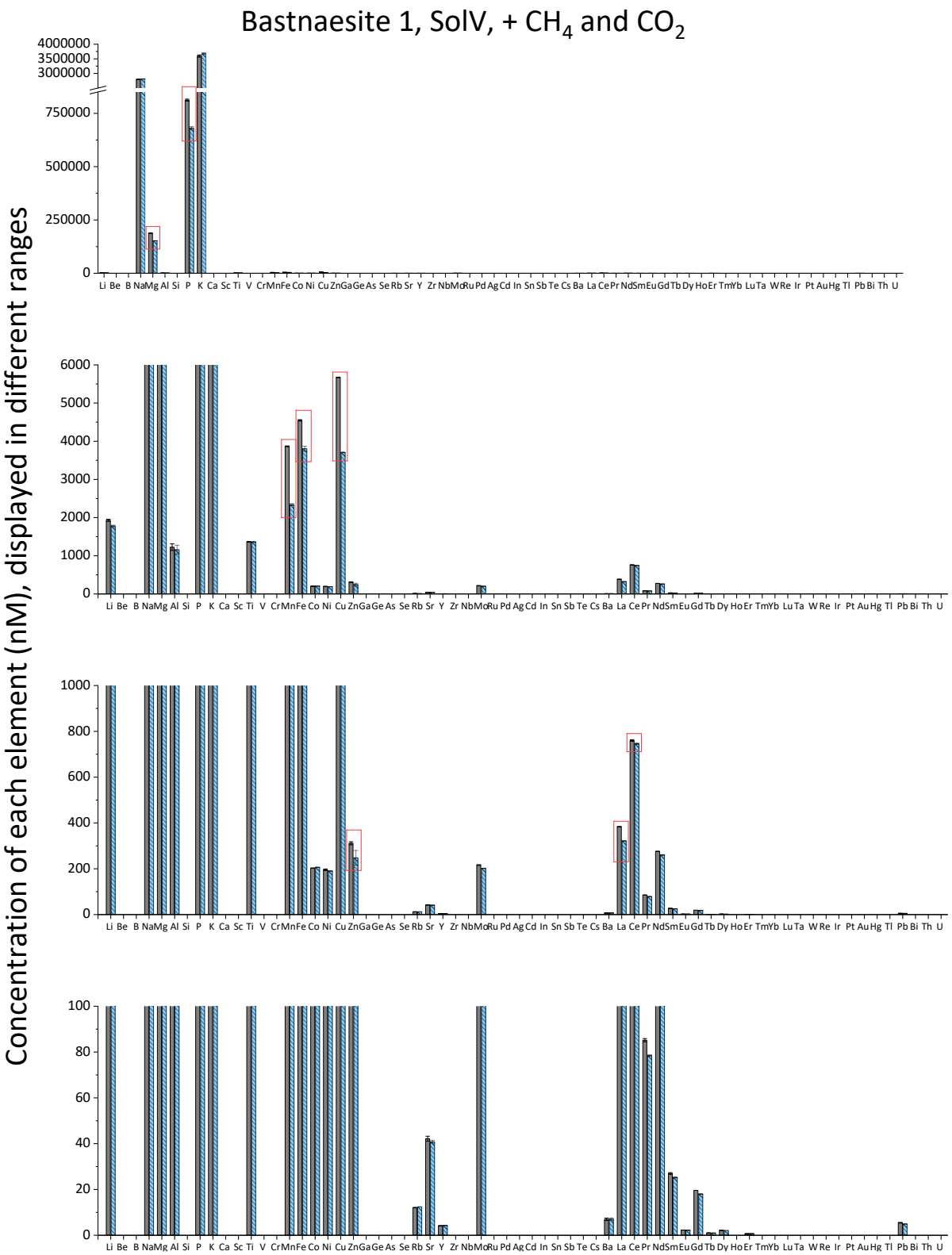


Fig. S5. Screening of concentration of all elements (detectable with ICP-MS) in Bastnaesite 1 samples, with addition of strain SolV, CH_4 and CO_2. The solutions before (grey left bar, no pattern) and after (blue right bar, left up to right down diagonal lines) the experiment was analyzed with ICP-MS. Starting OD_{600} was set to 0.06, and cultivation was performed for 87 hours at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. 10 mL of minimal medium as described in Tab. S1 was used, and 0.2 µL of Bastnaesite 1 (sterile filtered with 0.2 µM PES) were added.

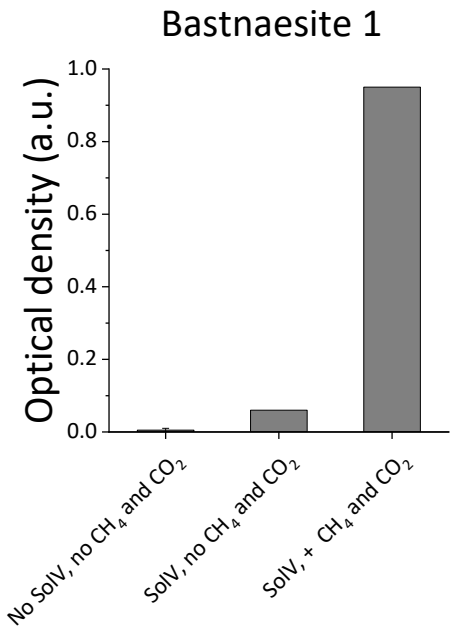


Fig. S6. Optical densities at 600 nm for the experiments regarding Bastnaesite 1 samples described in Fig. S3 – S5 under the different conditions. OD_{600} was collected after 87 hours incubation at 55 °C (200 rpm).

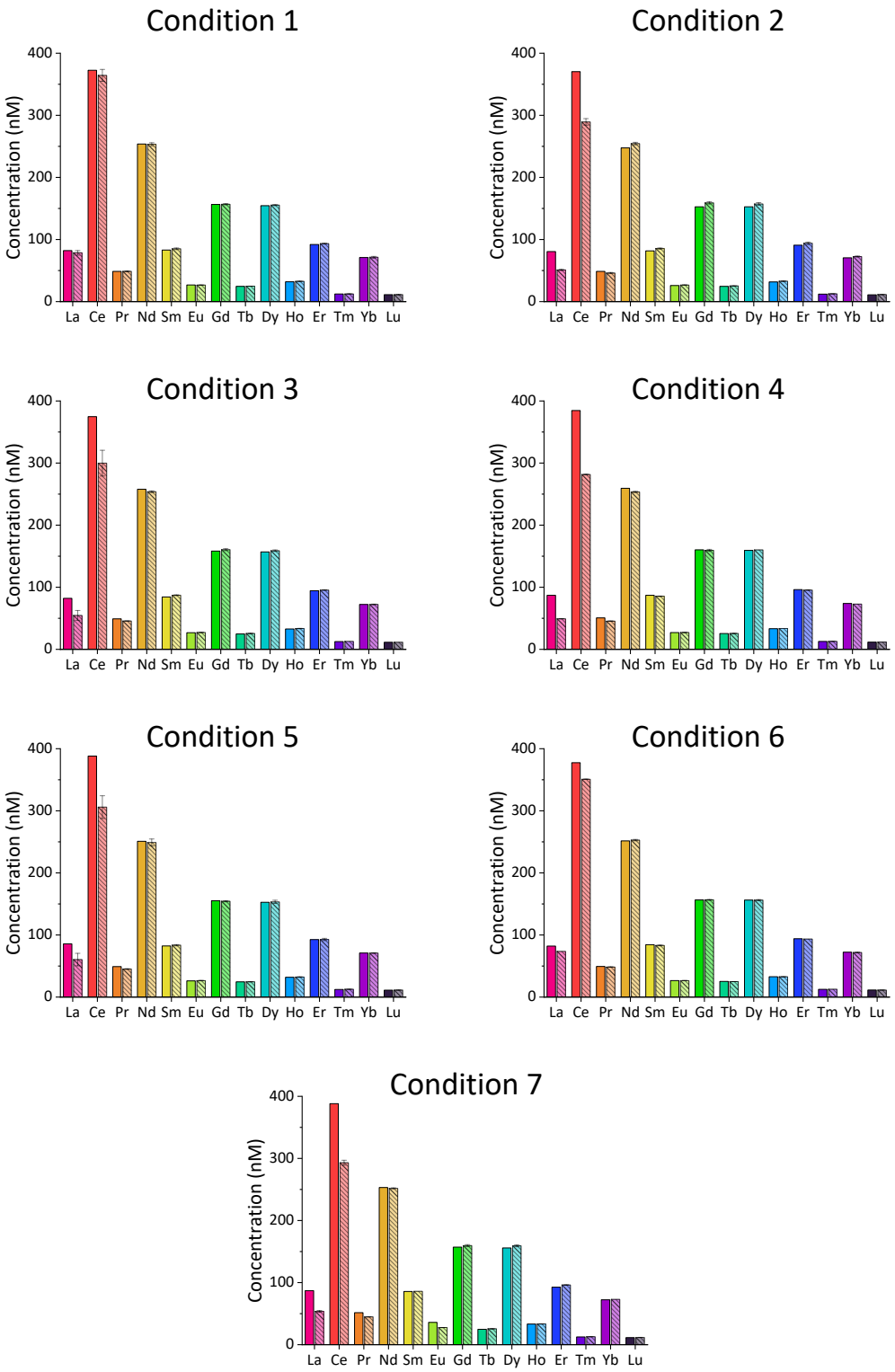


Fig. S7. Concentration of Ln in Gessenhalde water before (left bar, no pattern) and after cultivation (right bar, left up to right down diagonal lines) with strain SolV under different conditions determined with ICP-MS analysis. A detailed description of the different conditions can be found in the main manuscript (Tab. 1). For each sample, 10 mL of medium including 1 mL Gessenhalde water were prepared, and unless otherwise stated not autoclaved. Starting OD_{600} was set to 0.06, and cultivation was performed for 70 h at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2.

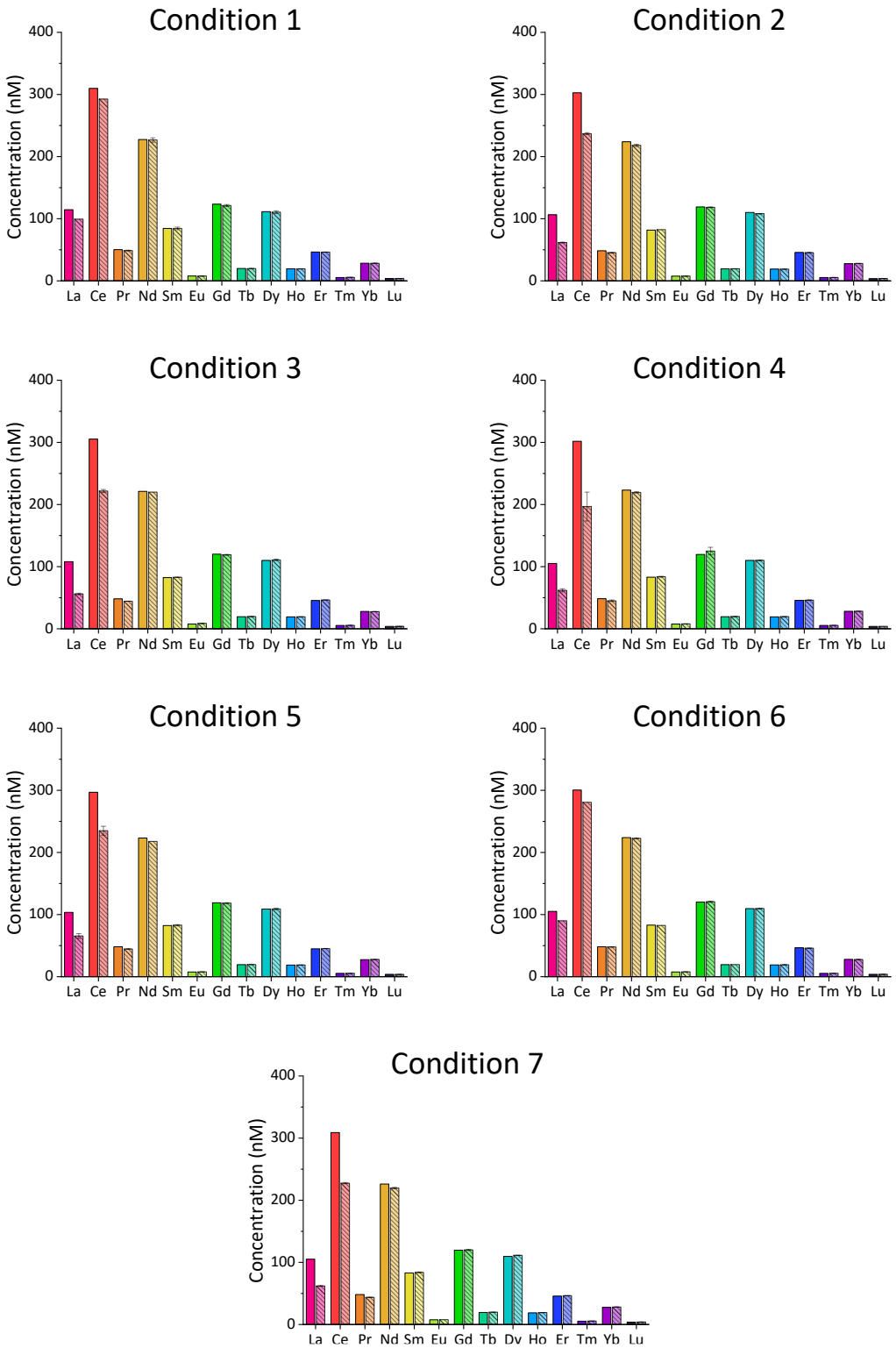


Fig. S8. Concentration of Ln in Königstein water before (left bar, no pattern) and after cultivation (right bar, left up to right down diagonal lines) with strain SolV under different conditions determined with ICP-MS analysis. A detailed description of the different conditions can be found in the main manuscript (Tab. 1). For each sample, 10 mL of medium including 2 mL Königstein water were prepared, and unless otherwise stated not autoclaved. Starting OD_{600} was set to 0.06, and cultivation was performed for 70 h at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2.

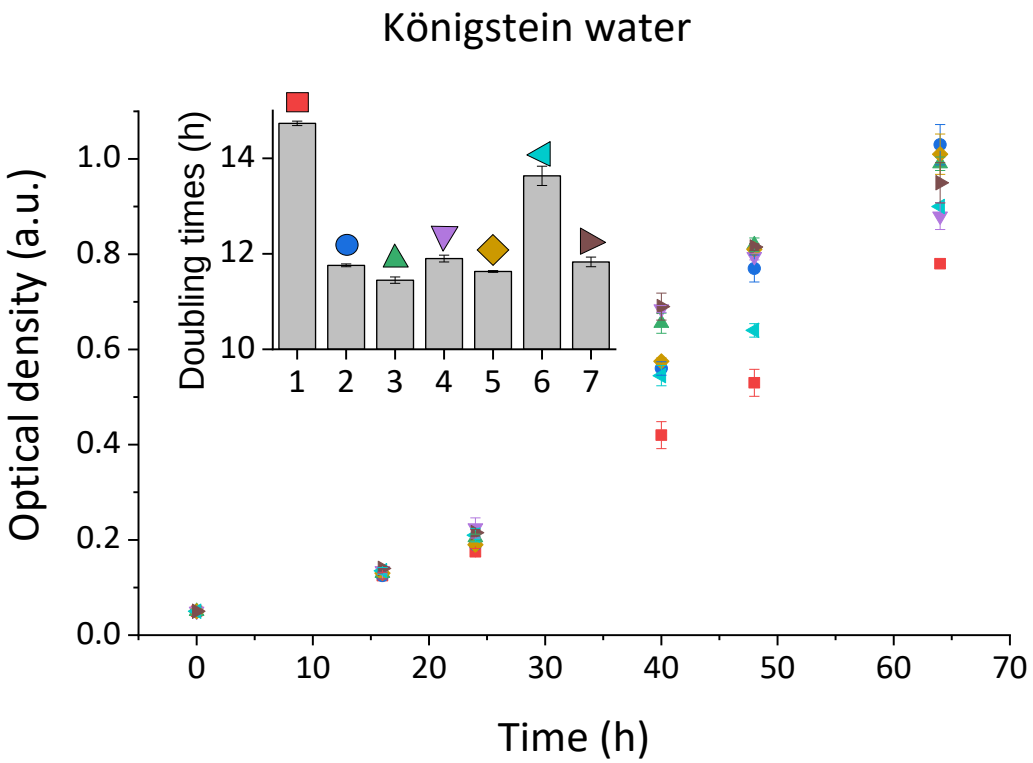


Fig. S9. Growth curves and rates of Königstein water under condition 1 to 7, indicated by different color and shape. Conditions were already described in Fig. S8. Samples were collected at regular time intervals with a syringe to maintain the gas atmosphere and OD_{600} was measured.

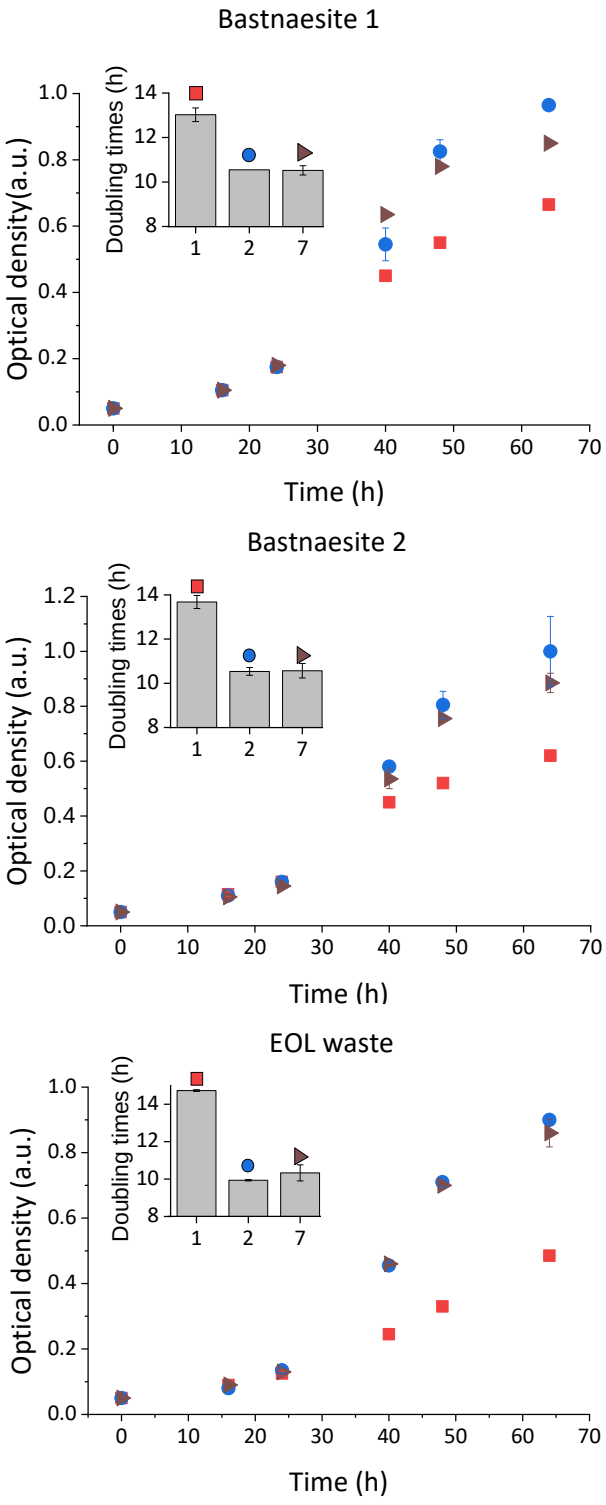


Fig. S10. Growth curves and rates of Bastnaesite 1 &2 and EOL waste under condition 1,2 and 7. A detailed description of the different conditions can be found in the main manuscript (Tab. 1). For each sample, 10 mL of medium including 0.2 µL bastnaesite or 20 µL EOL waste were prepared, and unless otherwise stated not autoclaved. Starting OD_{600} was set to 0.06, and cultivation was performed for 70 h at 55 °C with a shaking speed of 200 rpm in 100 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. Samples were collected in regular time intervals with a syringe to maintain the gas atmosphere and OD_{600} was measured.

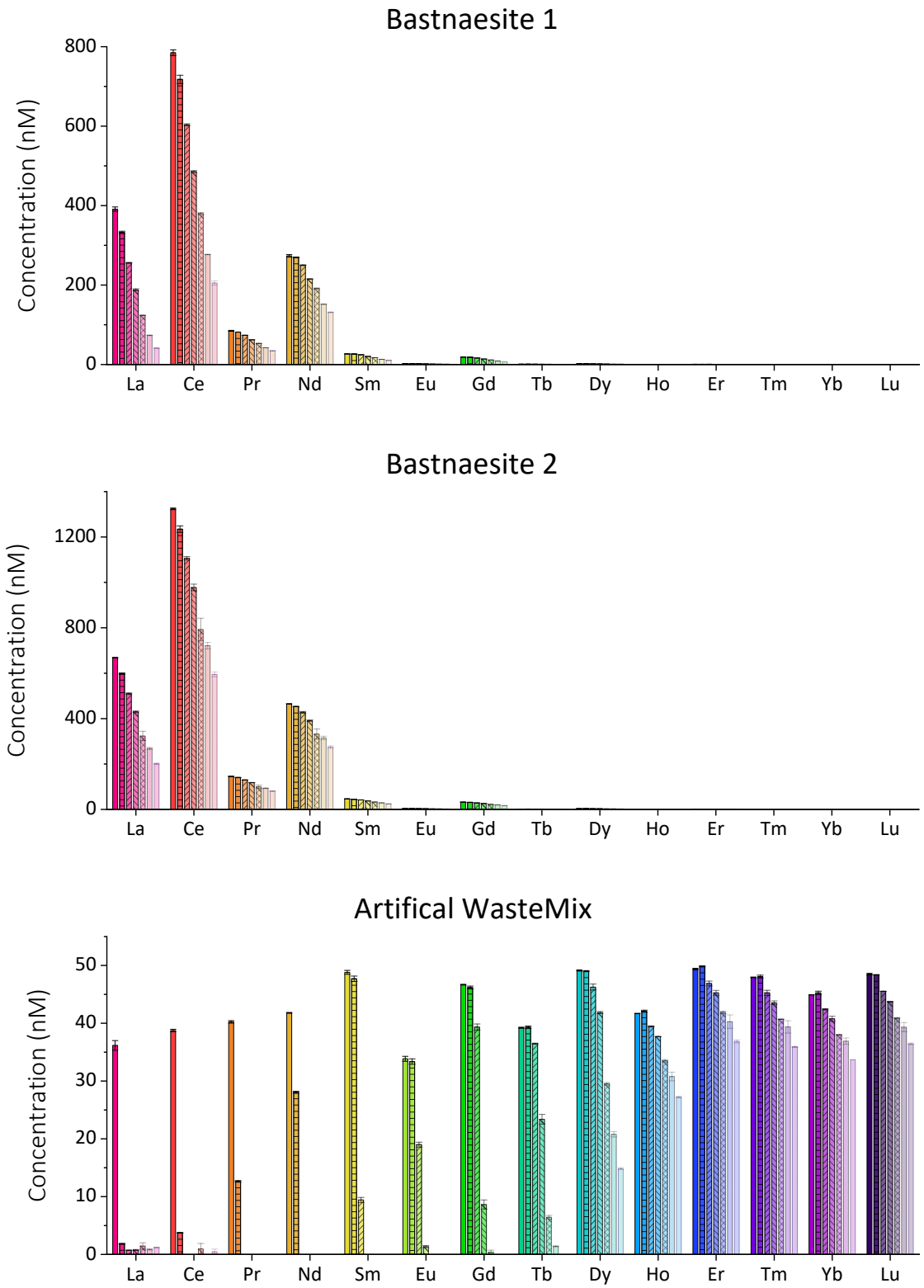


Fig. S11. Up-scaling approach of strain SolV with bastnaesite and artificial WasteMix up to 6 cycles. Concentration was determined with ICP-MS. The bar with no pattern shows the starting concentration, while the bars with pattern show from left to right the ongoing cycles. For each sample, 50 mL of medium including 1 µL bastnaesite or 500 µL artificial WasteMix were prepared. Starting OD_{600} was set to 0.06, and cultivation was performed for 3 days at 55 °C with a shaking speed of 200 rpm in 500 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. After the biomass was removed via centrifugation, fresh biomass was added and the cultivation was continued.

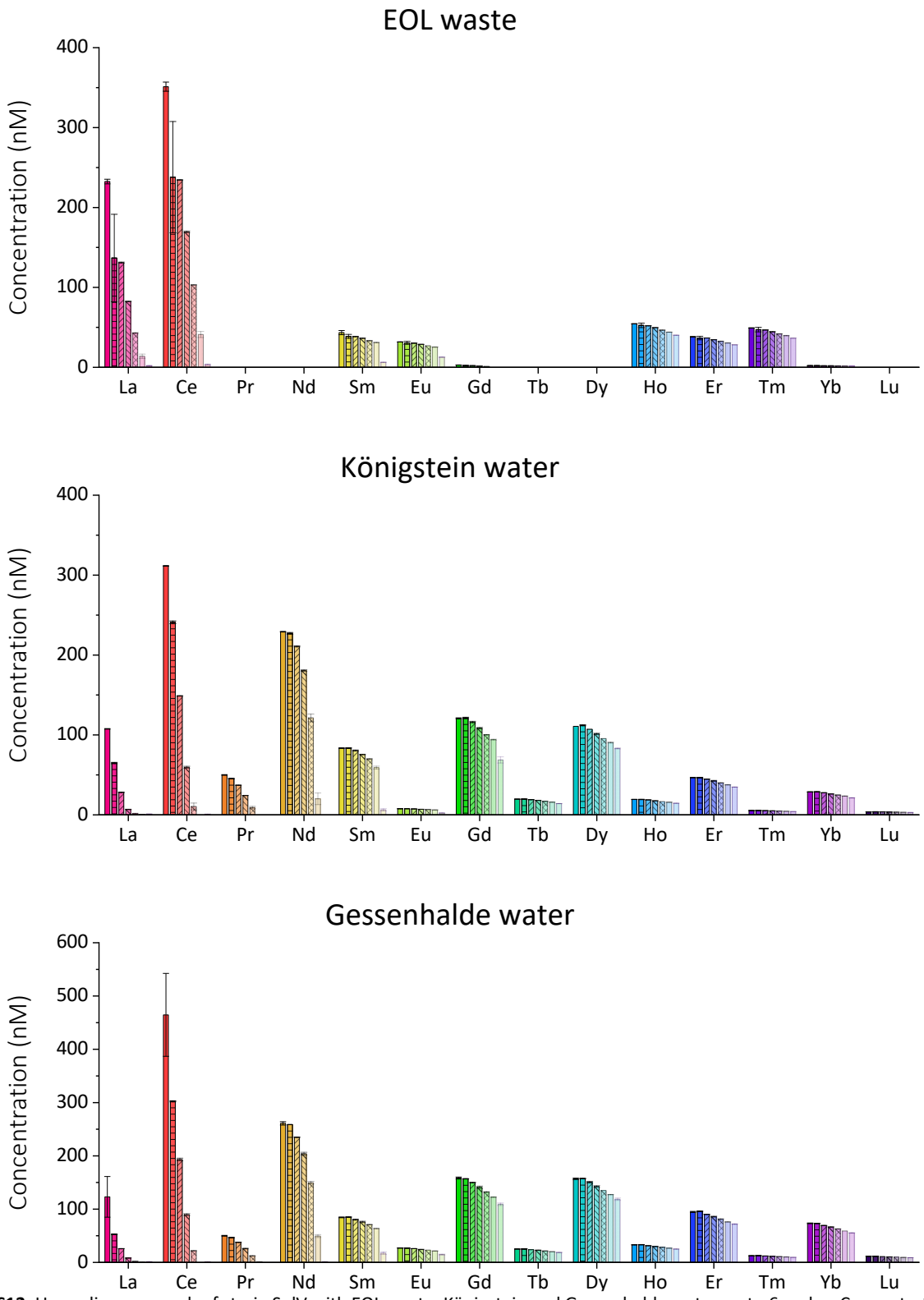


Fig. S12. Up-scaling approach of strain SolV with EOL waste, Königstein and Gessenhalde water up to 6 cycles. Concentration was determined with ICP-MS. The bar with no pattern shows the starting concentration, while the bars with pattern show from left to right the ongoing cycles. For each sample, 50 mL of medium including 100 µL of EOL waste, 10 mL Königstein water or 5 mL Gessenhalde water were prepared. Starting OD_{600} was set to 0.06, and cultivation was performed for 3 days at 55 °C with a shaking speed of 200 rpm in 500 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. After the biomass was removed via centrifugation, fresh biomass was added and the cultivation was continued.

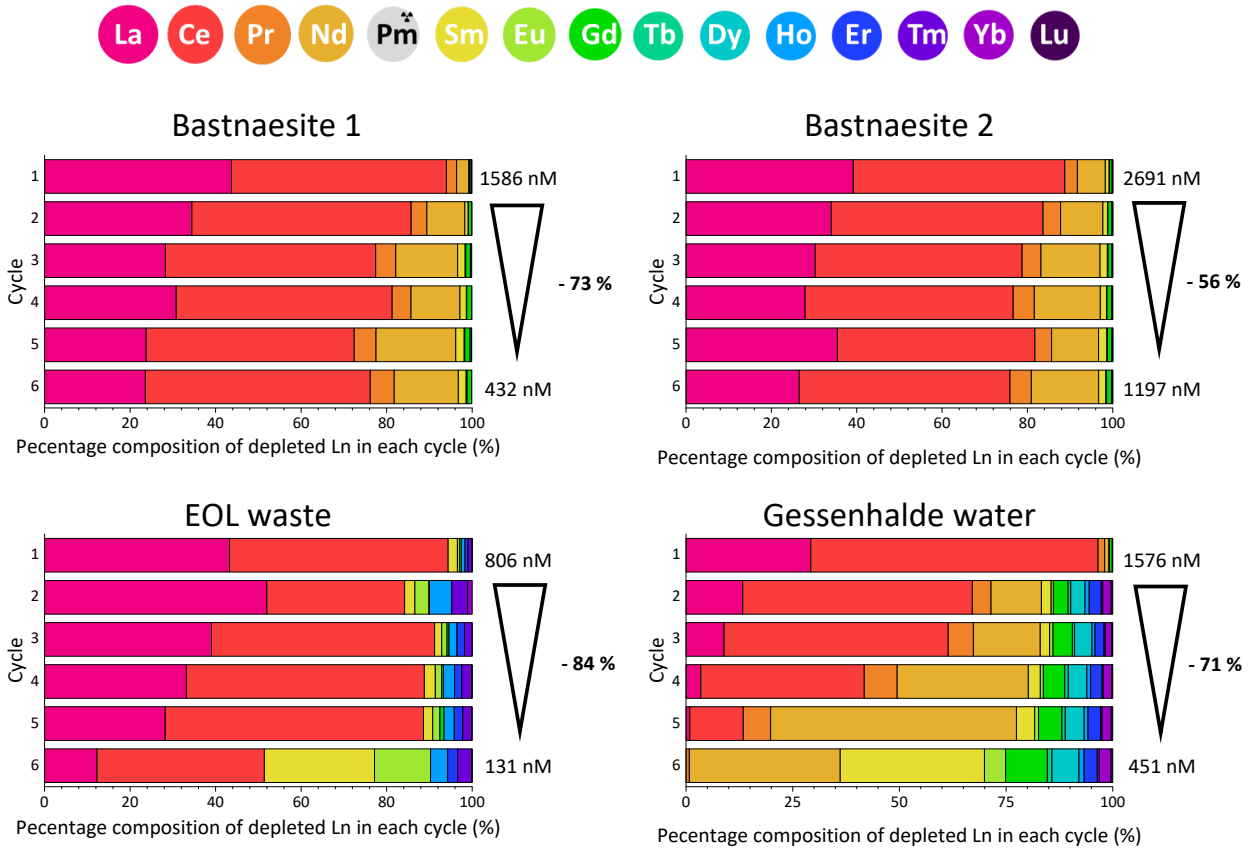


Fig. S13. Percentage Depletion of different Ln by strain SolV over 6 cycles in the different REE sources. Conditions for all samples as described in Fig. S11 and S12. Outline on the right shows the total Ln concentration in the beginning and after the 6 cycles, including total values and percentage. The bars display only the fraction of depleted Ln and their composition in each individual cycle.

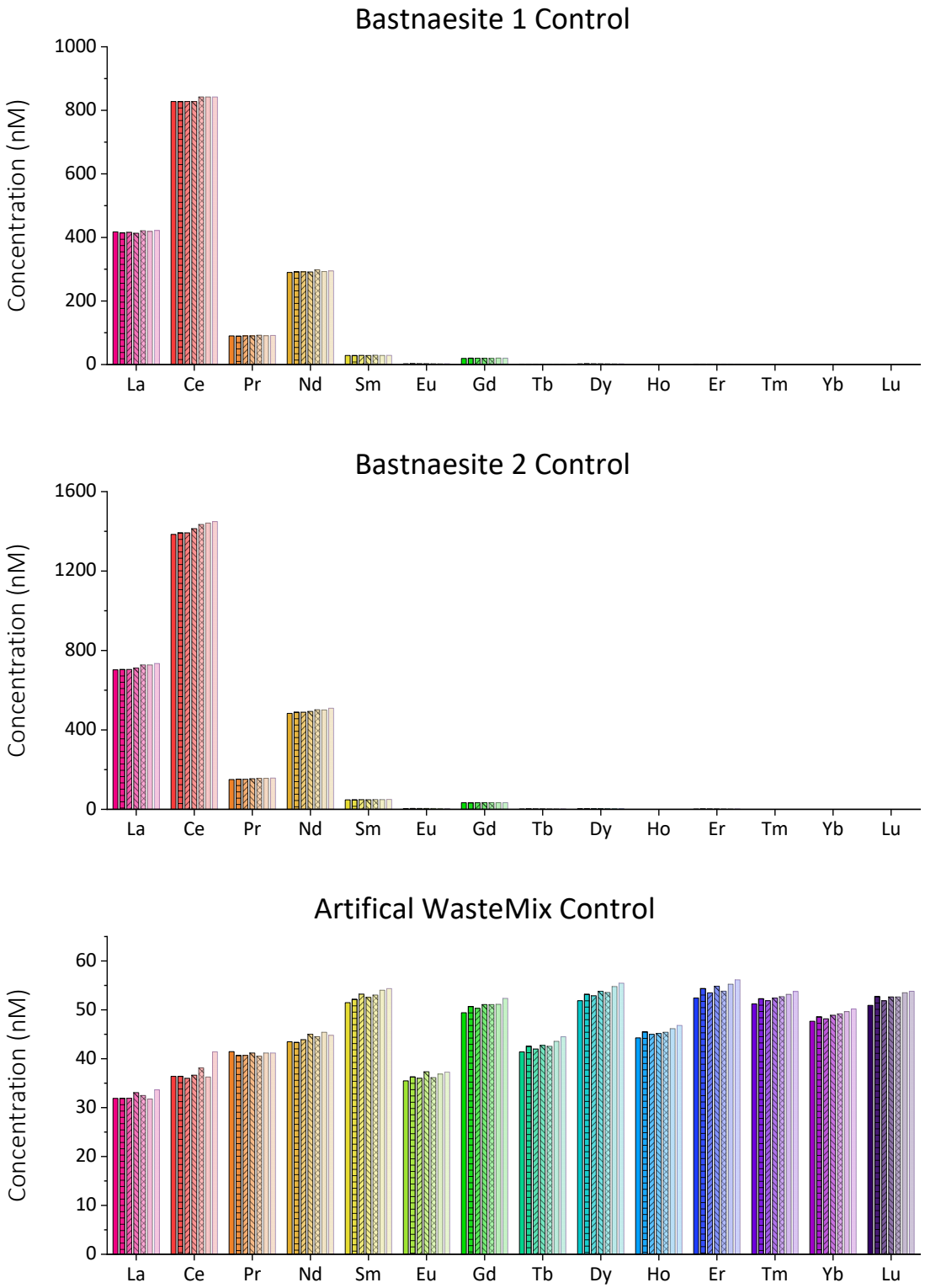


Fig. S14. Control of the up-scaling approach with bastnaesite and artificial WasteMix up to 6 cycles. Concentration was determined with ICP-MS. The bar with no pattern shows the starting concentration, while the bars with pattern show from left to right the ongoing cycles. For each sample, 50 mL of medium including 1 µL bastnaesite or 500 µL artificial WasteMix were prepared. No bacterial cells were added, and the medium with the REE source was incubated for 3 days at 55 °C with a shaking speed of 200 rpm in 500 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. In none of the control samples, precipitate formation could be observed.

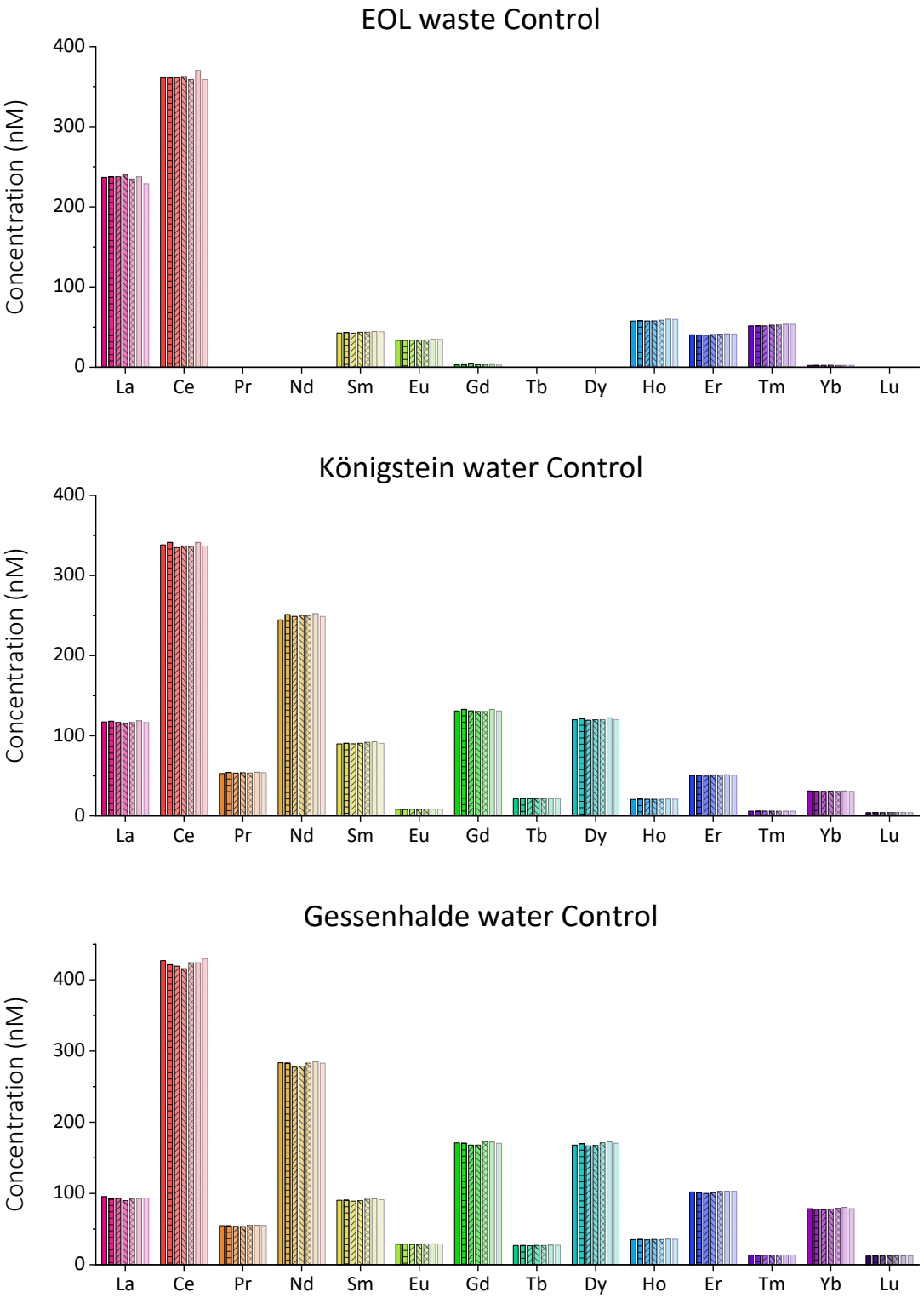


Fig. S15. Control of the up-scaling approach with EOL waste, Königstein water and Gessenhalde water up to 6 cycles. Concentration was determined with ICP-MS. The bar with no pattern shows the starting concentration, while the bars with pattern show from left to right the ongoing cycles. For each sample, 50 mL of medium including 100 µL of EOL waste, 10 mL Königstein water or 5 mL Gessenhalde water were prepared. No bacterial cells were added, and the medium with the REE source was incubated for 3 days at 55 °C with a shaking speed of 200 rpm in 500 mL plastic serum flasks with an atmosphere of 85 % air, 10 % CH_4 and 5 % CO_2. No precipitate formation was observed in EOL samples, in Königstein and Gessenhalde water only during the first cycle minimal precipitation was observed (no discernible turbidity, only visible after 1 hour of centrifugation at 14 000 x g)

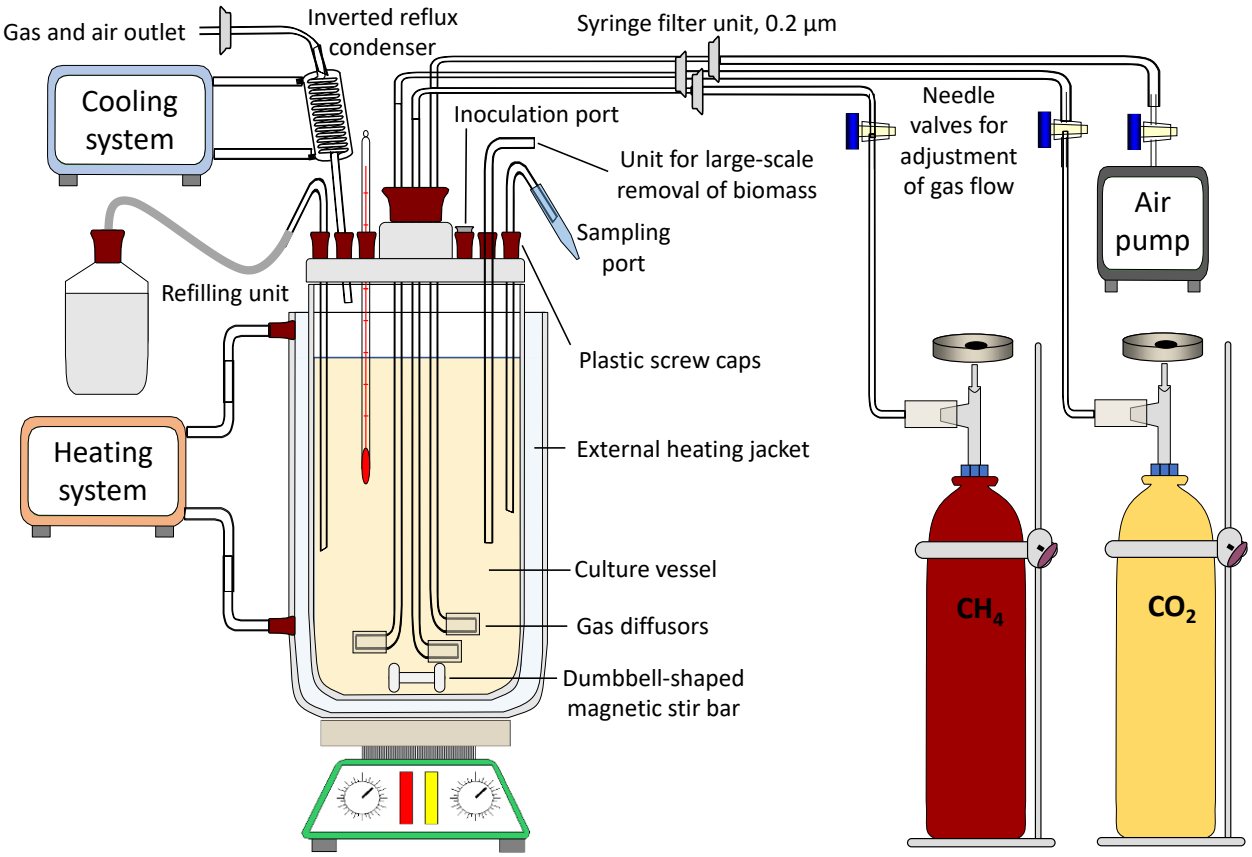


Fig. S16. Scheme of the constructed bioreactor for large-scale cultivation of strain SolV. Heating and cooling system is based on a refrigerated circulator (Haake F6 C40) and a recirculating heated chiller bath (Haake F3 CH). For air supply, a diaphragm vacuum pump (LABOPORT® Mini, N 86 KT.18, 5,5 l/min, 160 mbar) was used. Quality of CH_4 ≥ 99,5 mol %, CO_2 ≥ 99,9 Vol.%. The gas and air supply were connected with Tygon tubing while for the autoclavable connections (syringe filter to bioreactor, gas diffusors) a silicon tubing was used.

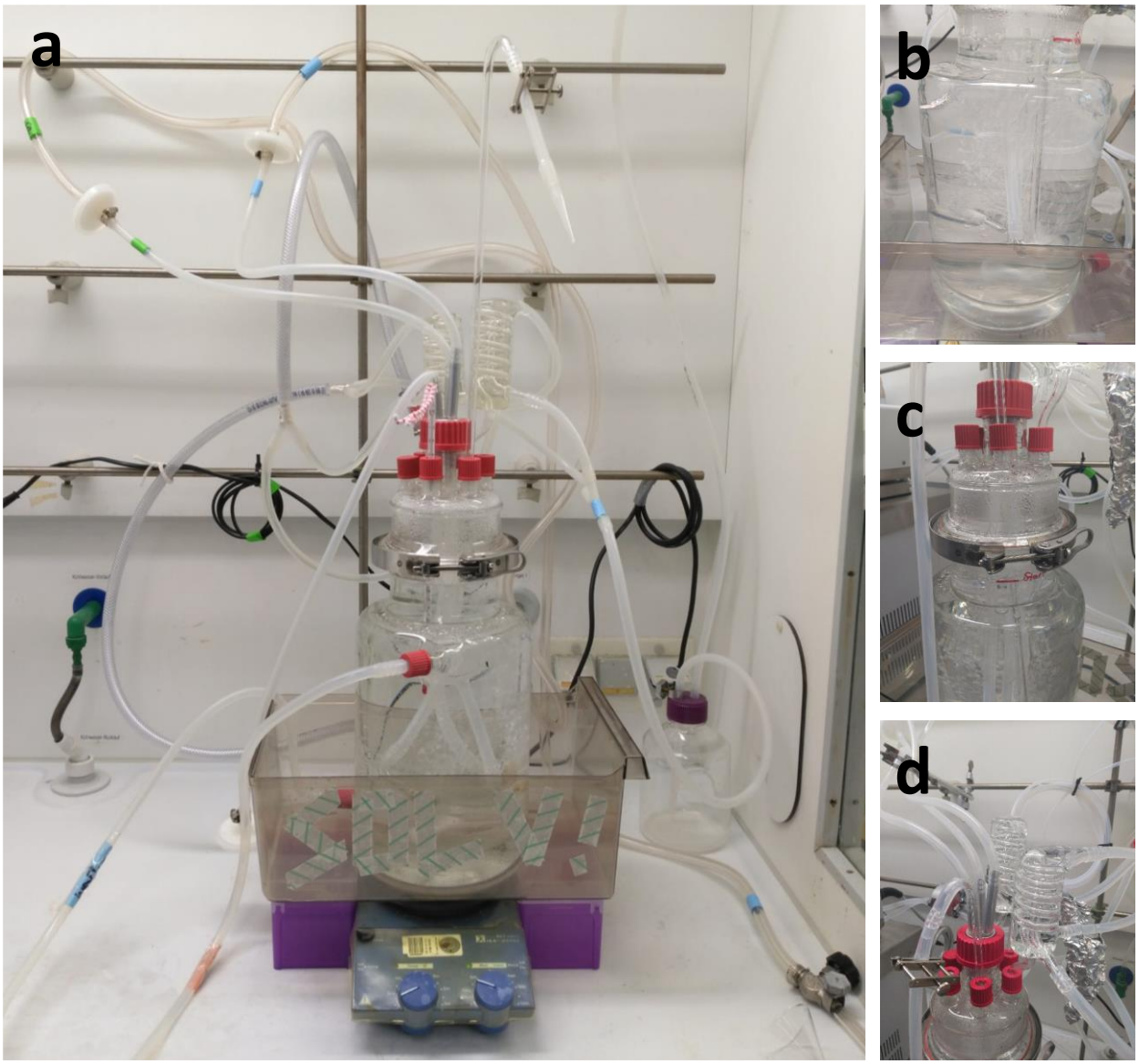


Fig. S17. Pictures of the constructed bioreactor for large-scale cultivation of strain SolV. (a) shows the bioreactor without cooling/heating system, as well as gas bottles and vacuum pump. (b) displays the culture vessel of the bioreactor, with gas inlets connected to silicon tubing and diffusion stones. (c) Removable cap of the bioreactor, sealed with a silicon ring and a clamp. (d) Upper part of the cap with all the different connectors (GL 32 screw caps, can be modified as required to closed and with hole) and the cooled, inverted reflux condensers to minimize the evaporation during the cultivation.

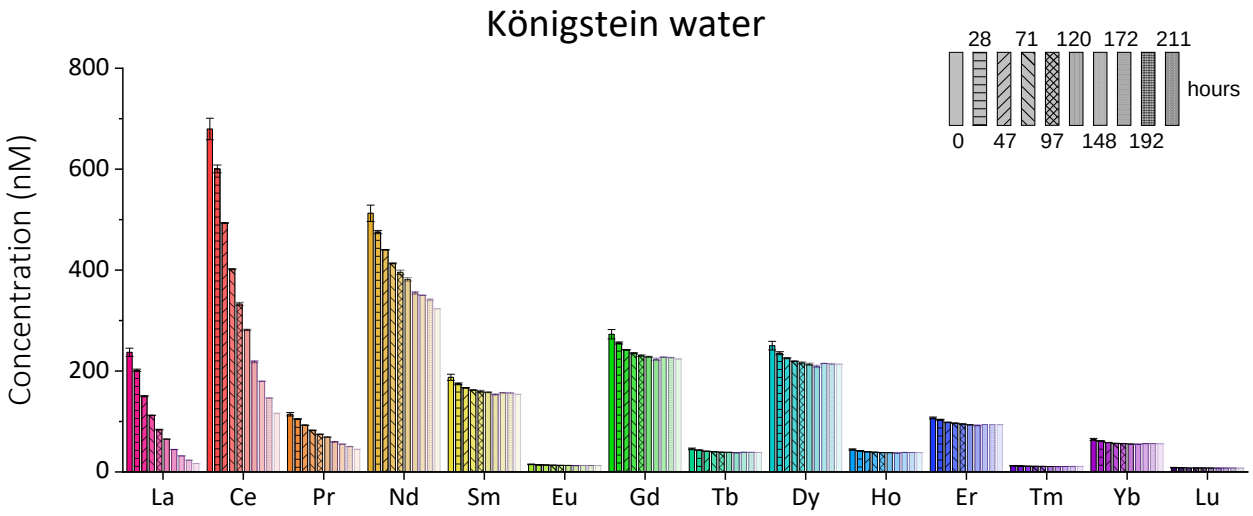


Fig. S18. ICP-MS analysis of the Ln concentration in the supernatant during cultivation of strain SolV with Königstein water. The samples were collected in the indicated time intervals (in the legend label, shown in different patterns). For preparation of medium, 600 mL of autoclaved medium were mixed with 400 mL Königstein water, and together autoclaved and sterile filtered. In total 3.7 L of the prepared medium was used. Cultivation was started by adding biomass to an OD of 0.07. Temperature was set to 55 °C, and gas was regulated (1000 mL/min air, 750 mL/min CH_4, 600 mL/min CO_2), stirring speed of 500 rpm was adjusted. Cultivation was run for 250 hours.

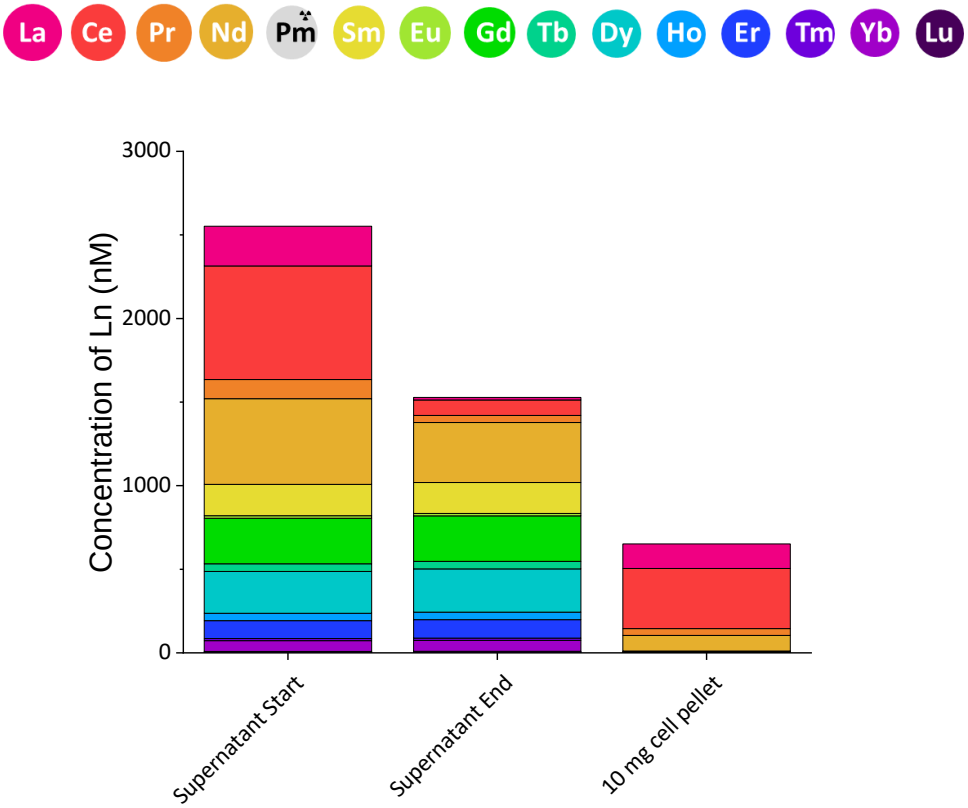
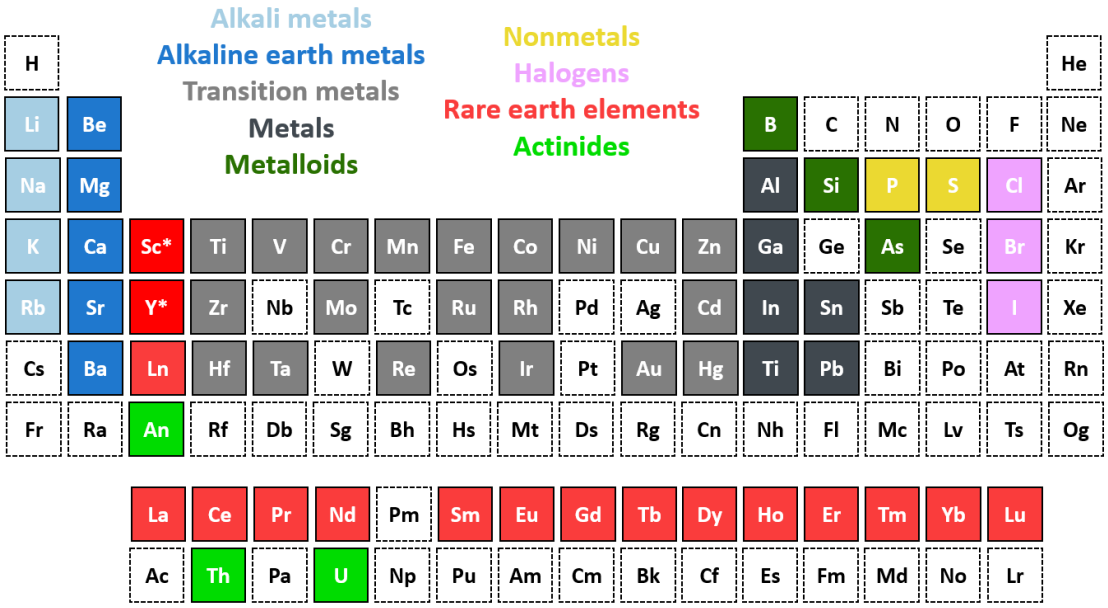
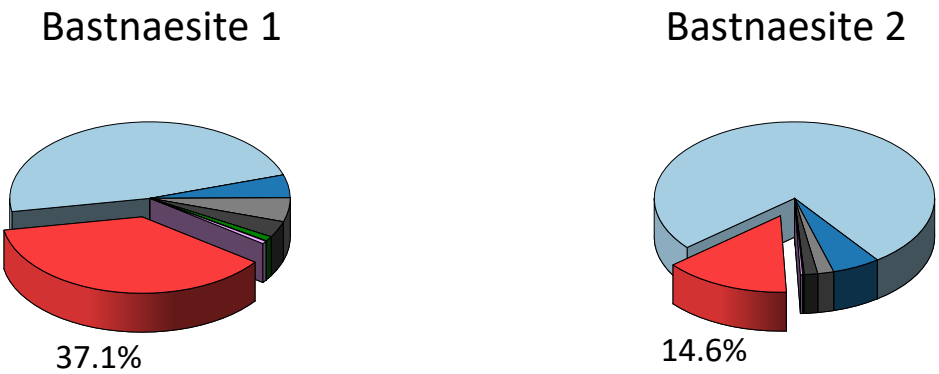


Fig. S19. ICP-MS analysis of the Ln concentration in the supernatant in the beginning, as well as after 250 hours of cultivation with strain SolV and Königstein water, and concentration of Ln in 10 mg of the collected disrupted bacterial cell pellet (lyophilized and acidic microwave disruption) after 250 hours. Conditions for the cultivation as described in Fig. S18.For the collection of the cell pellet, 10 mL of the final biomass were collected, centrifuged and washed three times with MilliQ water. The pellet was lyophilized, and total weight was 53.7 mg. 10 mg of the cell pellet were digested with acid and microwaved for disruption, and afterwards resuspended in 15 mL of MilliQ water, to enable a direct comparison between the different REE biomasses in the same unit (nM).





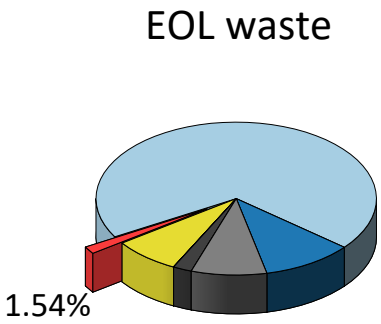


Fig. S20. Percentage of the composition of the different tested REE sources, divided in alkali metals (light blue), alkaline earth metals (dark blue), transition metals (light grey), metals (dark grey), metalloids (dark green), nonmetals (yellow), halogens (pink), rare earth elements including scandium and yttrium and the lanthanides (red), and actinides (light green). The number displayed is the percentage of REE in the REE source. The periodic table shows the measurable elements in colors, including the group where they belong to. Elements with no filling and a dotted box were not measurable with the IntelliQuant mode. Amount in mg/L of each element was detected with ICP-OES. For all samples, the amount of all elements in mg/L was summed up, and the respective amounts of each group were calculated in percentage.

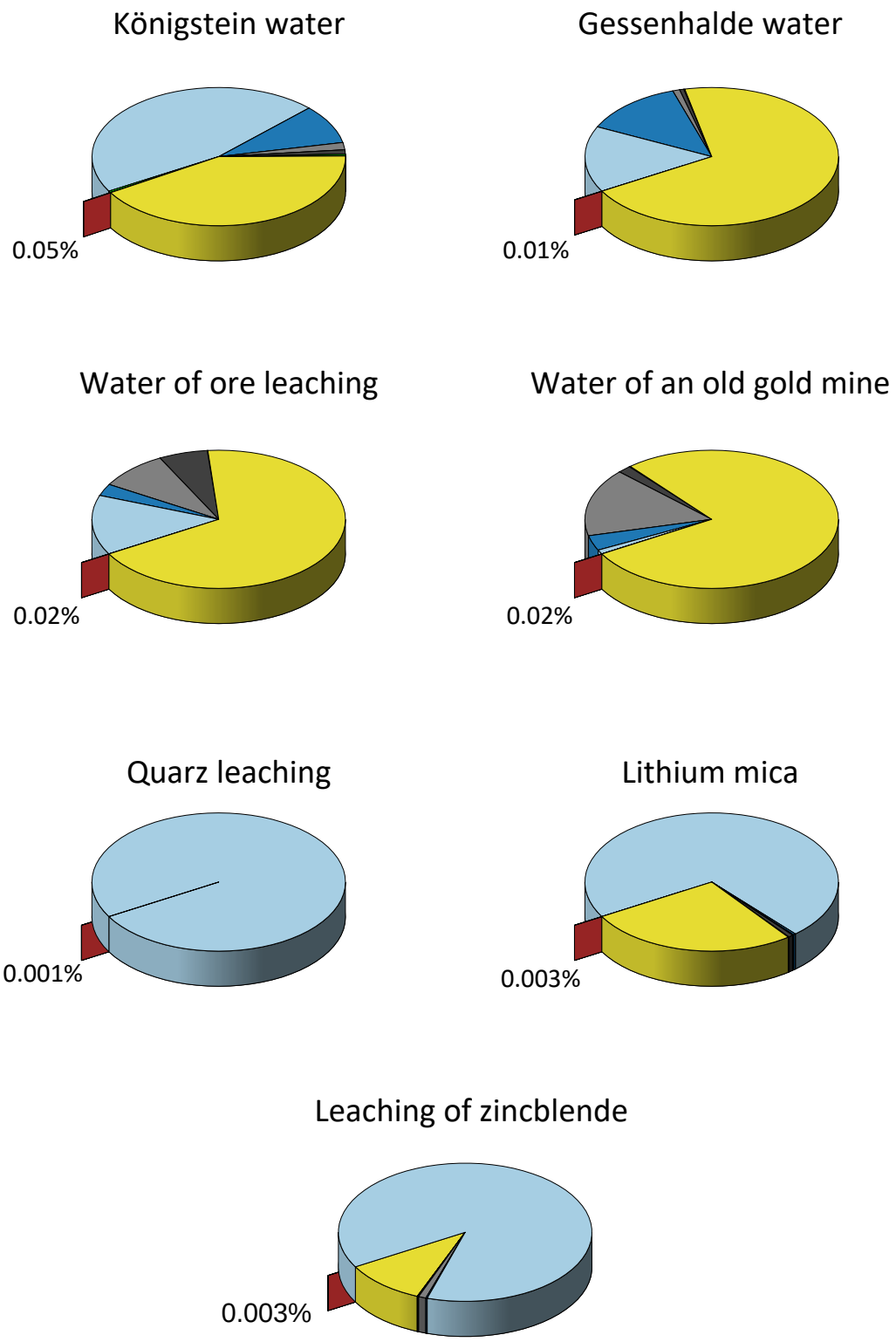
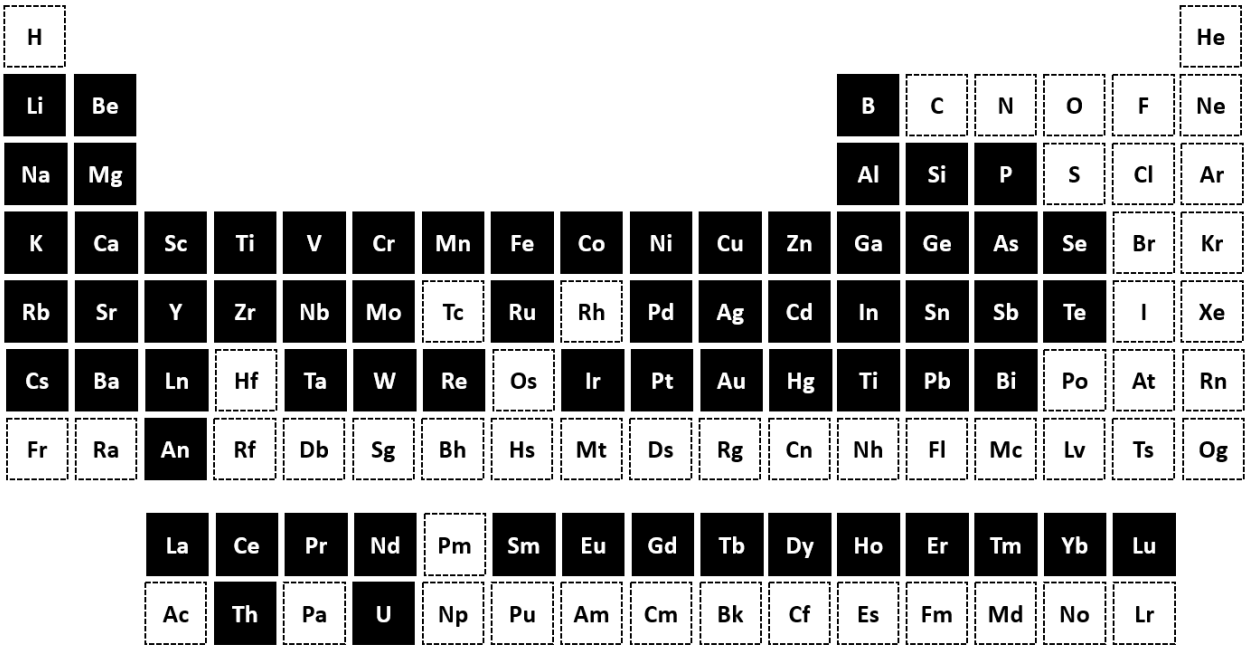


Fig. S21. Percentage of the composition of the different tested REE sources, divided in alkali metals (light blue), alkaline earth metals (dark blue), transition metals (light grey), metals (dark grey), metalloids (dark green), nonmetals (yellow), halogens (pink), rare earth elements including scandium and yttrium and the lanthanides (red), and actinides (light green). A more detailed description of the elements included is shown in Fig. S20. The number displayed is the percentage of REE in the REE source. Amount in mg/L of each element was detected with ICP-OES. For all samples, the amount of all elements in mg/L was summed up, and the respective amounts of each group were calculated in percentage.

3. Tables

Tab. S1. ICP-MS analysis of the different REE sources. Concentration in µg/L; 1: Königstein water; 2: Gessenhalde water; 3: Water of an old gold mine; 4: Leaching zincblende; 5: Lithium mica; 6: Water of ore leaching; 7: Quartz leaching (Wendelscheider Schwergut); 8: EOL industrial waste; 9: Bastnaesite 1; 10: Bastnaesite 2; Periodic table shows in black the elements which can be determined with ICP-MS



Element in µg/L	1	2	3	4	5	6	7	8	9	10
Li	80.9	205.5	6760	1160	187000	5140	10.3	377.5	4035	6540
Be	26.1	13.6	254	148	399	103	12.2	5.665	507	547.5
B	97.8	2.8	3.45	74.75	358	110	15.15	96.25	543	2310
Na	35900	40550	431000	4590000	3790000	420000	3800000	42325	60300	150500
Mg	15200	193500	7240000	679000	121000	3820000	4110	18450	204000	244000
Al	14700	24850	7010000	299000	1070000	5540000	28200	33025	668000	809000
Si	15700	12950	21350	62400	42800	4385	63150	1745	78200	56500
P	<100	<100	323000	<100	175000	253000	5100	54400	5935	12700
K	8380	3900	76700	144	2110000	53800	43600	29800	489500	801000
Ca	181000	515500	20700000	376000	199000	321000	12500	104500	1450000	1690000
Sc	12.8	15.4	1780	136	25.55	1130	188	21.69	<1	61.4
Ti	93.6	892.5	1095	1605	1155	26500	538.5	20000	18100	28450
V	<0.1	1.85	12.3	23.35	92.25	15850	113.5	808	112.5	175
Cr	32.0	<1	7390	815	3660	4110	148	1650	377.5	572.5
Mn	6680	84000	2270000	509000	120000	1220000	895	1477.5	20350	31900
Fe	15800	14350	38600000	976000	294000	7530000	17400	80975	792000	964000
Co	163	6520	129000	5540	284	75600	13.9	710.25	620.5	1260
Ni	350	12400	11300	7070	12100	8110	38	3635	618.5	936
Cu	34.2	7970	2210000	71100	7080	1830000	2600	40225	9385	15400
Zn	7670	11400	1170000	1770000	17000.0	743000	217.0	28675	35550	55650

Ga	1.93	2.105	1700	16.1	99.1	907	84.7	21150	9460	421000
Ge	<0.1	1.635	<0.1	4.31	5.20	16.1	2.32	36.85	22300	37200
As	3.91	<5	156000	17300	458	55800	112	116	57900	95950
Se	58.5	<100	<100	<100	<100	<100	<100	<100	22300	34750
Rb	59.6	5.89	0.8035	1.67	87200	261.5	166.5	376.5	2175	3650
Sr	763	755	69400	22.6	244	8230	372	1210	17200	31250
Y	429	1840	2050	1120	190	981	845	15400	17400	21100
Zr	<5	<5	235	12.5	12.0	657	177.0	6870	1835	4175
Nb	<1	<1	4.78	<1	<1	5.66	<1	<1	3470	5625
Mo	<0.1	2.445	2.345	1.945	3.535	381.5	6.92	20.8	161.5	248
Ru	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Pd	<1	6.08	21.8	<1	0.800	11.1	8.05	585.5	316	495.5
Ag	<1	<1	269	11.7	10.8	9.04	1.04	83.95	95.95	146.5
Cd	46.8	91.35	2260	17400	21.5	1900	4.29	77.85	280	504.5
In	<0.1	<0.1	68.2	38.1	<0.1	35.6	0.679	0.653	22.5	34.4
Sn	<0.1	2.32	111	16.3	1.80	20.1	2.27	3.4	678	1345
Sb	<1	<1	858	136	<1	11.7	1.635	63.8	83.4	111.5
Te	<1	<1	92.6	<1	<1	145	<1	397	73.6	7575
Cs	7.41	<1	738	4.41	2220	428	6.43	26.2	90.65	162
Ba	12.2	12.7	12700	<1	45.0	18.3	3230	41250	89700	1680000
La	75.1	113	1450	1100	1340	244	2120	2545	2570000	3120000
Ce	212	524	3370	2610	711	373	4950	7107.5	4850000	4880000
Pr	35.4	70.9	54.05	326	22.6	83.35	636	0.9995	569000	677000
Nd	163	359	1700	1300	<0.1	242	2280	47	1900000	2360000
Sm	65.6	121	353	59	37	71	404	478	190000	231000
Eu	5.08	41.3	123	307	0.600	28	42	408	15300	19400
Gd	85.1	244	445	365	31	122	384	11	162000	138000
Tb	15.7	41.6	63	47	6	20	29	1	10800	12200
Dy	89.1	239	382	241	39	135	191	0.786	12200	14600
Ho	15.8	57.2	75	41	10	30	24	681	1180	1410
Er	38.8	150	215	108	32	93	106	488	1460	1760
Tm	4.76	22.2	29	14	8	13	10	614	102	133
Yb	25.5	124	182	86	53	89	88	35	1330	1490
Lu	3.46	21.2	28	12	9	14	9	0.111	2570000	167
Ta	<1	<1	<1	<1	2.41	<1	<1	13.55	4.51	7.32
W	<1	<1	<1	<1	<1	701.5	18.3	11.2	319	471.5
Re	<0.1	<0.1	<0.1	0.24	0.3275	<0.1	<0.1	<0.1	0.3235	0.7095
Ir	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Pt	<1	<1	0.269	<1	<1	0.267	<1	<1	18.95	3.43
Au	<10	<10	36.8	<10	<10	1.36	<10	<10	<10	<10
Hg	<1	<1	<1	5.16	5.84	11.35	1.775	4.495	10.8	8.47
Tl	8.90	1.67	<1	<1	328	14.35	4.41	<1	<1	1.275
Pb	685	<1	266000	<1	69.5	2670	352	474	45200	38000
Bi	<1	<1	529	2.25	<1	72.5	3.355	57.7	8.275	14
Th	11.8	<1	134.5	99.7	<1	117.5	1800	17.6	3570	7490
U	6550	262	1990	609	20.6	1870	161	9.94	415.5	601.5

Tab. S2. Medium composition for growth medium of strain SolV.

Solution	Composition
Minimal medium (10x)	2 mM $MgCl_2 \cdot 6\ H_2O$, 10 mM Na_2SO_4, 20 mM K_2SO_4, 10 mM NaH_2PO_4, 2 mM $CaCl_2$ **Note:** All components except $CaCl_2$ were mixed and adjusted to pH 2.7 with 1 M H_2SO_4. $CaCl_2$ was autoclaved separately and added afterwards to prevent the precipitation of calcium phosphates.
Trace element (TE) solution	200 mM $FeSO_4 \cdot 7\ H_2O$, 200 mM $MnCl_2 \cdot 4\ H_2O$, 300 mM $CuSO_4 \cdot 5\ H_2O$, 10 mM $NiCl_2 \cdot 6\ H_2O$, 10 mM $ZnSO_4 \cdot 7\ H_2O$, 10 mM $CoCl_2 \cdot 6\ H_2O$, 10 mM $Na_2MoO_4 \cdot 2\ H_2O$ **Note:** All components were dissolved one after the other in 1.5 % v/v H_2SO_4. Solution will occur blue immediately after preparation but turns green after a few days.
Growth medium for strain SolV	Prepared according to Pol and coworkers[6] 1x Minimal medium, 20 µL/L TE, 8 mM NH_4^+ for cultivation in bottles, for the bioreactor experiments the TE concentration was increased to 80 µL/L and 30 mM NH_4^+. All components were mixed and autoclaved. The different REE sources were sterile filtered with 0.2 µM PES syringe filters and added to the autoclaved medium for bottle cultivation while for the large-scale bioreactor experiments, the prior autoclaved medium was mixed with Königstein water and again together autoclaved. During the sterilization process, precipitate formation occurred which was removed by filtration (0.2 µM, PES membrane). **Note:** NH_4^+ available from a 2 M $(NH_4)_2SO_4$ solution in MilliQ water.

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