

Sustainable Rare Earth Extraction from Phytomining by Ultrafast Electrothermal Activation

Bing Deng

dengbing@tsinghua.edu.cn

Tsinghua University <https://orcid.org/0000-0003-0530-8410>

Mingyue Xu

Tsinghua University

Erkang Feng

Tsinghua University

Teng Wang

Tsinghua University <https://orcid.org/0009-0001-6129-0449>

Ziyu Huang

Tsinghua University

Wen-Shen Liu

Sun Yat-sen University

Lena Q. Ma

Zhejiang university

Jianguo Liu

Tsinghua University

Article

Keywords:

Posted Date: May 6th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-6401377/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Version of Record: A version of this preprint was published at Communications Materials on February 2nd, 2026. See the published version at <https://doi.org/10.1038/s43246-026-01089-x>.

Abstract

Rare earth elements (REEs) are indispensable to clean energy and advanced electronics industries, yet their conventional mining and refining often entail substantial environmental and energy costs. Phytomining, which harnesses the ability of hyperaccumulator plants to concentrate REEs from soil, offers a promising sustainable alternative. However, the downstream recovery of REEs from plant biomass remains inefficient and resource-intensive. In this study, we develop a rapid electrothermal calcination (REC) strategy tailored for REE-enriched biomass, enabling ultrafast thermal activation (e.g., 1000°C for 20 s) that significantly enhances REE extractability using dilute acid leaching (e.g., 0.1 M H₂SO₄), achieving extraction efficiencies exceeding 97%. The REC process is versatile across various organic hyperaccumulator matrices, as demonstrated by *Blechnum Orientale* and *Dicranopteris linearis*. Comparative life-cycle and technoeconomic analyses reveal that REC reduces carbon emissions and operating costs by over 70% relative to conventional furnace-based methods. These results establish REC as a green, scalable, and cross-species-compatible platform for advancing sustainable REE recovery via phytomining.

Introduction

Supplying critical mineral resources that underpin modern technological infrastructure serves as a pivotal facilitator in global endeavors to achieve the United Nations Sustainable Development Goals^{1,2}. Among these mineral resources, rare earth elements (REEs)³ emerge as critical raw materials in modern high-tech industries^{4,5}, with widespread applications in renewable energy systems (e.g., NdFeB magnets in wind turbines), electric vehicles (e.g., Li-ion battery cathodes), and advanced electronics (e.g., phosphors in displays)^{6,7}. Despite the continuous growth in demand for REEs^{8,9}, traditional methods of extraction and separation face numerous challenges¹⁰, including uneven resource distribution, environmental pollution during mining, and high energy consumption^{3,11,12}. As a result, achieving efficient and environmentally sustainable extraction of REEs has become an urgent technological challenge worldwide^{7,13}.

China has dominated the global REE production¹², contributing over 90% of the world supply, primarily from ion-adsorption deposits (IADs) in weathered granitic terrains^{10,14}. With the diminishing availability of high-grade IADs (current ore grades: 0.05–0.2 wt%), there is an urgent need to recover REEs from low-grade soils (< 0.01 wt%) and legacy mine tailings¹⁵. Vegetation naturally colonizing these IADs has revealed a promising solution: certain plant species exhibit exceptional REE hyperaccumulation capabilities¹⁶. For instance, some ferns achieve shoot REE concentrations exceeding 3000 mg kg⁻¹ (dry weight) – a 45-fold enrichment compared to surrounding soils¹⁷. Such hyperaccumulators, defined by their ability to concentrate metals at > 0.1 wt% in aerial tissues¹⁸, not only thrive on marginal lands but also offer scalable biomass production¹⁹. This ecological adaptation positions them as ideal agents for

phytomining – an emerging bioremediation strategy that synergizes metal extraction with ecosystem restoration²⁰.

Phytomining leverages plant uptake to transfer soil-bound REEs into harvestable biomass, followed by target element recovery^{21,22}. Current industrial workflows, however, remain constrained by inefficient post-harvest processing^{23,24}. For example, conventional ash-based methods involve furnace incineration at 550°C for 3 hours, which consumes 8–12 kWh/kg biomass and achieves only 65–85% REE liberation efficiency¹⁵. Subsequent leaching with concentrated acids generates 3–5 L of acidic effluent per kg of biomass, requiring costly neutralization⁷. While recent advances in selective elution (e.g., citric acid at pH 2.5) have improved REE purity to ~ 80%, these methods still suffer from co-dissolution of Fe³⁺ and Al³⁺ (20–30% contamination), necessitating further purification steps¹⁵. Hence, a rapid and energy-efficient pretreatment is imperative for the REE extraction from hyperaccumulators.

To address the limitations of traditional phytomining workflows, recent efforts have explored alternative pretreatment strategies that can more efficiently liberate REEs from plant biomass while minimizing energy and environmental costs. Among them, electrothermal techniques have shown promise due to their rapid heating rates and reduced energy consumption^{25,26,27}. These methods, originally developed for materials synthesis^{28,29,30}, offer a fundamentally different thermal environment compared to conventional furnaces^{31,32,33}. Although prior work has applied flash Joule heating (FJH) to the recovery of critical metals from industrial residues such as coal fly ash or electronic wastes⁷, the application of ultrafast electrothermal techniques to organic biomass – particularly REE-hyperaccumulating plants – remains largely unexplored^{34,35}. Importantly, plant tissues differ significantly from mineral or industrial waste matrices in their morphology, thermal behavior, and REE-hosting mechanisms, demanding distinct optimization approaches³⁶.

Herein, we report a rapid electrothermal calcination (REC) method tailored for phytomining biomass, which enables efficient REE liberation from plant tissues under ultrashort treatment times (~ 20 seconds at ~ 1000°C). Unlike previous studies that focused on REE recovery from inorganic materials, this work pioneers the application of REC to plant-derived matrices, leveraging their unique structural and compositional characteristics. Through systematic comparison with conventional furnace-based calcination (typically operated for hours)¹⁹, we demonstrate that REC significantly enhances REE extractability using only dilute acid (e.g., 0.1–1.0 M H₂SO₄), achieving > 97% recovery efficiency while substantially reducing energy consumption by > 70% as well as acid usage. Furthermore, we show the generalizability of this approach across multiple hyperaccumulator species, including both REE- and heavy-metal-adapted plants. By integrating a plant-based resource with an electrothermal activation pathway, our study advances the development of a scalable, eco-efficient phytomining technology – bridging sustainable agriculture, clean energy, and circular economy goals.

Results

REE extraction from *Blechnum Orientale* by electrothermal activation.

The process of extracting REEs from REE-enriched plants is illustrated in Fig. 1a. *Blechnum Orientale* (BO), a representative REE-enriched plant grown in ion-adsorption-type rare earth deposits in China³⁷, was used as the feedstock material (Fig. 1b). Scanning electron microscopy (SEM) images reveal that the overall structure of BO is tightly encapsulated (Fig. 1c). REEs store both within the cells and adsorbed on the cell walls or precipitated in the intercellular spaces³⁸, exhibiting two distinct compartmentalization effects. X-ray fluorescence (XRF) and elemental analysis results indicate that the major constituents of the raw BO material (Raw BO) are C (39.4%), O (33.7%), Si (6.7%), Ca (6.4%), and H (5.6%) (Supplementary Table 1). Thermogravimetric analysis (TGA) results (Fig. 1d) show that most of the organic matter in Raw BO decomposes below 600 °C, with a total mass loss of 89%. The decomposition process was observed in three stages: (i) evaporation of adsorbed water, (ii) combustion of cellulose, and (iii) combustion of hemicellulose and lignin¹⁹, corresponding to the three peaks of the first derivative plot (Fig. 1d)

In a typical electrothermal activation process, naturally air-dried Raw BO was ground into a powder and then loaded on a carbon paper heater (Fig. 1e). High-voltage discharges from the power source heat the carbon heater to elevated temperatures. With a carbon heater resistance of $\sim 1 \Omega$, different temperature and time gradients are applied. The Raw BO was directly heated up instantly by contact heat conduction. In a typical discharge process, the corresponding real-time temperature curve shows a rapid heating rate ($200 \text{ }^{\circ}\text{C s}^{-1}$) followed by stable heating at $\sim 1000 \text{ }^{\circ}\text{C}$ for 20 s (Fig. 1f). During electrothermal activation, the temperature distribution of the sample is uniform, with no significant gradient (Fig. 1g). The electrical current induces structural reorganization within the plant tissue, thereby loosening tightly bound organic structures into more separable states, which facilitates subsequent extraction and separation processes. The solid generated following electrothermal activation treatment is designated as Activated BO.

REE leaching from the activated biomass by REC.

After the REC reaction, we conducted acid leaching of REEs from the residue. First, to establish baseline concentrations, Raw BO was digested with concentrated nitric acid in a microwave digestion system. The concentrations of REEs were measured using inductively coupled plasma optical emission spectroscopy (ICP-OES). The total concentration of REEs was quantified to be 3753 ppm, with La, Nd, Ce, and Pr concentrations of 1570 ppm, 830 ppm, 542 ppm, and 260 ppm, respectively, which accounting for 85.3% of the total REE content (Fig. 2a).

Then, we conducted acid leaching of the Activated BO. As comparison, Raw BO, as well as the calcinated BO in a muffle furnace at 550 °C for 3 hours (referred to as Calcinated BO), were used. The leachable REEs content in all samples was determined via H_2SO_4 leaching. In previous studies, the effect of acid concentration at $> 1 \text{ M}$ on the leaching of REEs was found to be limited⁷. Therefore, in this work, we adopted 1 M H_2SO_4 leaching as the standard protocol, as it is more cost-effective. Leaching of Raw BO

resulted in a total REE extraction of 82.7%, with extraction rates of 81.5%, 84.8%, 83%, and 84.6% for La, Nd, Ce, and Pr, respectively (Fig. 2b). The Calcinated BO showed a total REE extraction yield of 89.7%, and extraction rates of 87.8%, 88.7%, 97.1%, and 92.8% for La, Nd, Ce, and Pr. In contrast, a total REE extraction yield of 97.2% was obtained for Activated BO, with the extraction rates for La, Nd, Ce, and Pr in Activated BO reaching 96.1%, 97.3%, 104.7%, and 91.5%, respectively (Fig. 2b). Hence, it is evidenced that the REE extraction yield can be improved by up to ~ 22% with the REC activation.

The pH-dependent leaching dynamics of REEs from Raw BO, Activated BO, and Calcinated BO were also investigated (Fig. 2c). In general, the extraction yield decreases as the pH increases. At pH 0.7, the rare earth extraction from Activated BO reached ~ 87%, which is higher than that of Calcinated BO (~ 78%) and Raw BO (~ 54%), and even higher than the extraction rate of Raw BO at higher acid concentrations (e.g., ~ 83% at pH = 0.3). The rapid REC process contributes to a higher REE extraction yield than the lengthy calcination process. We presume that extended thermal treatment during the calcination process could lead to the evaporative loss of rare earths with the ash residue.

Deviations between different REEs were observed, which may be attributed to the uneven distribution of REEs in Raw BO and varying degrees of activation among the REEs. REC experiments were conducted at temperatures of 700 °C, 800 °C, 900 °C, and 1000 °C, with REE extraction rates exceeding 90% at 900 °C and 1000 °C (Fig. 2d). Further optimization of the reaction time revealed that the extraction rate increased initially and then decreased with prolonged reaction time. The highest extraction rate, 97.2%, was achieved at 1000 °C with a reaction time of 20 s. However, when the reaction time was extended to 60 s, the extraction rate slightly decreased, presumably due to the volatilization of ash (Fig. 2e).

Mechanism of the enhanced leaching of REE by REC.

We then studied the mechanism underlying the enhanced REE extraction by REC. First, we used X-ray diffraction (XRD) to reveal the crystallinity and chemical forms. The XRD patterns show substantial differences in the diffraction peaks of Raw BO, Activated BO, and Calcinated BO (Fig. 3a). The diffraction peaks of Raw BO are broad, indicating an amorphous structure. In contrast, the diffraction peaks of Calcinated BO and Activated BO are sharper and more intense, suggesting that furnace calcination improved the crystallinity, due to the recrystallization process of minerals at high temperatures³⁹. The SEM images of Activated BO (Fig. 3b) reveal pivotal changes in the surface microstructure of the sample. The surface of Raw BO, was relatively smooth (Fig. 1c), while after REC treatment, the surface of Activated BO became rougher and more porous. The explosive release of volatiles and thermally-induced microcracking collaboratively establish a hierarchical porous architecture (Fig. 3b and Supplementary Fig. 1), contributing to the acid leaching process.

Next, elemental analysis of the REEs was performed using energy dispersive X-ray spectroscopy (EDS) (Fig. 3c) and X-ray photoelectron spectroscopy (XPS) (Fig. 3d). The EDS and XPS full spectrum of Activated BO showed similar peaks to Calcinated BO, including peaks for oxygen, neodymium, carbon, and silicon. Both are distinct with that of the Raw BO, demonstrating the efficient removal of organics. Compared to Activated BO, the carbon peak in Calcinated BO is lower, and some REEs may escape in

gaseous form along with carbon during the heating process. This could lead to a decrease in the relative contents of REEs, and consequently, the lower REE extraction efficiency from Calcinated BO compared to Activated BO. The EDS maps show a uniform distribution of REEs in all samples (Supplementary Figs. 2–4). According to the XPS fine spectra (Fig. 3e), no La signal was detected in Raw BO, indicating either an extremely low concentration of La. In contrast, Activated BO exhibited La signatures in XPS spectra (Fig. 3e). The observed La^{3+} peaks at 834.9 eV demonstrate the predominant formation of lanthanum metal oxide following REC treatment⁷. In addition, the Nd main peak in Raw BO was located at 980.50 eV, with a satellite peak at 977.55 eV and an O KLL peak at 974.10 eV (Fig. 3f)⁴⁰. In Activated BO, the Nd^{3+} main peak was located at 981.32 eV, the satellite peak at 978.44 eV, indicating changes in chemical bonds or electronic structure. The thermal treatment process involves the breaking and reformation of chemical bonds, which in turn affects the chemical state of REEs in the samples. The XPS spectra of REE in the Calcinated BO were similar to these of Activated BO (Supplementary Figs. 5–6).

Lastly, the speciation and phase-partitioning of REEs were quantitatively assessed through standardized sequential extraction protocols coupled with ICP-OES analysis (see details in Methods section, Figs. 3g–h, Supplementary Figs. 7–10)^{41,42}. In the plant, the primary forms of rare earths were humic acid-bound (60.3%), residue-bound (16.8%), and strongly organic-bound (15.9%). After REC treatment, the proportions shifted to residue-bound (56.0%) and humic acid-bound (41.8%) (Figs. 3g–h), while the strongly organic-bound part was almost eliminated. Similarly, after muffle furnace calcination, the REE distribution was changed to humic acid-bound (66.0%) and residue-bound (33.0%). In natural environments, humic acid-bound rare earths may exhibit higher bioavailability^{43,39}. The REC treatment disrupted the chemical bonds between organics and REEs, leading to the elimination of strongly organic-bound REE (Fig. 3i). Hence, the REE in the Activated BO can be completely extracted using a mild acid leaching condition.

Generality of the REC electrothermal activation process.

The electrothermal activation process can be extended to other REE-enriched plants, such as *Dicranopteris linearis* (DL). DL is a pioneering plant in REE mine tailings, known for its strong reproductive capability and fast growth, making it an ideal plant for phytomining¹⁶. Using DL as the precursor (Supplementary Figs. 11–12), REC induced a distinct color transition from green to dark gray (Fig. 4a). SEM revealed a densely encapsulated architecture of DL (Fig. 4b). The solid generated following REC treatment is designated as Activated DL. Activated DL exhibited a porous structural morphology (Supplementary Fig. 13). TGA demonstrated that 95.6% of organic constituents in DL underwent near-complete decomposition below 600°C (Fig. 4c).

The total REE content in DL was determined to be 754 ppm (Fig. 4d), with other major components including C, O, N, Si, Ca, and others (Supplementary Table 2). The extraction of REEs from DL was carried out via a direct leaching process using 1 M H_2SO_4 (as detailed in the Materials and Methods section). Similar to BO, the extractability of REEs from DL after REC electrothermal activation also depends on the REC temperature and duration (Fig. 4e). At the optimized REC temperature and time, the sulfuric acid-

extractable REE content increased to ~ 727 ppm, higher than the ~ 603 ppm obtained by furnace calcination for 3 hours (Fig. 4e). REC experiments were conducted at temperatures of 700 °C, 800 °C, 900 °C, and 1000 °C, with rare earth extraction rate exceeding 90% at 1000 °C (Fig. 4f). Further optimization of the reaction time revealed that the extraction rate increased initially and then decreased with prolonged reaction time (Fig. 4g). The highest extraction rate, 96.5%, was achieved at 1000 °C with a reaction time of 20 s.

The mechanism for improving REE extraction from DL via the REC process is also studied, which is likely similar to that of BO. The XRD diffractograms of Activated DL and Calcinated DL exhibited analogous crystalline signatures, with prominent diffraction peaks corresponding to calcite-phase CaCO_3 (PDF #51-1524) and C (PDF #50-0927), suggesting conserved mineralogical frameworks despite divergent thermal activation mechanisms (Fig. 4h, Supplementary Fig. 14). Elemental characterization using EDS (Supplementary Fig. 15) and XPS (Supplementary Fig. 16) revealed comparable spectral signatures between Activated DL and Calcinated DL, exhibiting characteristic peaks of C, O, and Si. The EDS maps show a uniform distribution of REEs in all samples (Supplementary Figs. 17–19). XPS fine spectra (Supplementary Figs. 20–21) further confirmed analogous chemical interaction patterns in both DL and BO systems. REC process can expose the REEs by breaking down the matrix, accelerating the leaching rate and extraction efficiency of the REEs.

Life-cycle assessment and technoeconomic analysis.

The environmental impacts were evaluated via life cycle assessment (LCA) (Supplementary Note 1, Supplementary Fig. 22). Two scenarios were considered in this study: rapid electrothermal calcination (REC) and furnace calcination (FC) (Fig. 5a). The system boundary was defined as the input of BO and the output of leachate. The extraction of REEs from 1 tonne of BO was analyzed within this boundary. Life-cycle inventory (LCI) data for inputs was obtained from our lab and the literature (Supplementary Table 3)⁴⁴. The LCI entries were converted into environmental impacts using the ReCiPe 2016 methodology²⁸. Monte Carlo simulations were implemented for sensitivity analyses (Supplementary Fig. 23). The energy efficiency of REC was quantitatively compared with conventional furnace calcination under optimized operational parameters. The REC system achieved rapid thermal activation through resistive heating, operating at a low power at 0.37 kWh per batch. In contrast, the muffle furnace process required prolonged thermal exposure and consumed 1.44 kWh per cycle. Four midpoint indicators were analyzed, namely, global warming potential (GWP), terrestrial acidification, human toxicity, and water depletion (Figs. 5b-e, Supplementary Tables 4–7). The GWP of REC and furnace calcination were estimated to be ~ 66 and ~ 254 tonnes of CO_2 equivalents, respectively (Fig. 5b and Supplementary Fig. 24). Notably, REC exhibits a reduction of ~ 74% in GWP compared to furnace calcination (Fig. 5b). Other environmental impacts (Figs. 5c-e) exhibit a similar trend.

The economic feasibility of the REC process was evaluated via technoeconomic analysis (TEA). The required chemical reagents were sourced based on domestic market prices in China, with specific prices for relevant items detailed in Supplementary Table 3. The industrial electricity consumption rate was

estimated at \$0.11 per kWh. We note that the evaluation in this work does not account for labor cost. The operating cost was calculated by projecting energy consumption and materials usage. The process cost associated with REC is significantly lower, representing only ~ 26% of that associated with furnace calcination (Fig. 5f and Supplementary Fig. 24). The REC approach demonstrates significant advantages over conventional furnace calcination across multiple environmental and economic metrics, as evidenced by radar plot analysis (Fig. 5g).

Discussion

The integration of REC with phytomining establishes a paradigm shift for sustainable REE extraction, addressing two critical bottlenecks in conventional biomass processing: energy-intensive thermal degradation, and reliance on environmentally hazardous chemical treatments. Our findings demonstrate that REC-driven ultrafast pyrolysis (1000 °C for 20 s) achieves near-complete REE liberation (~ 97%) from hyperaccumulator ferns while drastically reducing acid consumption and carbon footprint compared to traditional furnace-based methods.

The REC process reduces energy consumption, attributable to its direct Joule heating mechanism (> 95% energy efficiency) and sub-minute processing. LCA quantifies a 74% reduction in CO₂ emissions compared to conventional calcination, while TEA highlights the operational cost saving from reduced acid consumption and waste treatment. These metrics align with global net-zero targets, positioning REC as a scalable solution for sustainable REE extraction from hyperaccumulator biomass.

By integrating ultrafast electrothermal processing with plant-based REE enrichment, this work bridges materials science, environmental engineering, and industrial ecology. Integrating renewable electricity and low-grade biomass (0.1–0.3 wt% REE) could decentralize supply chains, mitigating geopolitical risks of REE. Future studies should explore REC optimization for non-hyperaccumulator waste streams, potentially transforming agricultural residues into urban mines.

Materials and Methods

Materials. The chemicals used were HCl [36 to 38 wt%, ≥ 99%, Macklin], HNO₃ (65 to 68 wt %, ≥ 99%, Macklin), H₂SO₄ [98 wt %, ≥ 99%, Sinopharm Chemical Reagent Co., Ltd.], HClO₄ (70 to 72 wt%, ≥ 99%, Sinopharm Chemical Reagent Co., Ltd.), HF (48 wt %, ≥ 99%, Sinopharm Chemical Reagent Co., Ltd.), MgCl₂ (99%, Acme), CH₃COONa (99%, Amethyst), Na₄P₂O₇ (99%, Macklin), NH₂OH (50 wt %, Acme). The *Blechnum orientale* samples and *Dicranopteris linearis* samples were collected from Guangdong province, China and provided to our laboratory [see Acknowledgments]. The *Blechnum orientale* samples and *Dicranopteris linearis* samples were ground into powders using a grinder (Dade, DF-15). The carbon paper was purchased from Fuel Cell Store (Toray Carbon Paper 060). Carbon paper is chosen as the heater because it has appropriate resistance for heating, it is highly graphitized material that is stable up to 3,000 °C.

REC system and process. In preparation for REC treatment, *Blechnum orientale* and *Dicranopteris linearis* biomass samples were mechanically pulverized using a commercial grinder (Dade, DF-15). For controlled thermal processing, precisely measured 500 mg aliquots of plant material were uniformly distributed on carbon paper substrates ($5 \times 4 \text{ cm}^2$ dimensions). The substrate assembly was integrated with a capacitive discharge system, where controlled pulse current inputs induced rapid resistive heating of the carbon paper. As demonstrated in Fig. 1f, real-time thermal monitoring revealed synchronous temperature profiles between the carbon paper heater and sample matrix during the millisecond-scale heating phase. The REC process (Fig. 1g) initiated rapid oxidative combustion of organic constituents in ambient atmosphere, achieving peak combustion temperatures sufficient for complete volatile organic compound (VOC) decomposition. This combustion process selectively preserved REEs through differential thermal stability mechanisms: (1) organic cellular matrices binding REEs underwent complete pyrolysis, while (2) target REEs with elevated boiling points remained thermally stabilized on the carbon substrate. Post-treatment analysis confirmed efficient extraction of REE-enriched residues through simple mechanical detachment from the carbon paper interface.

Sample digestion, leaching, ICP-OES measurement, and various forms of REE content measurement. For the *Blechnum orientale* samples and *Dicranopteris linearis* samples, acid-extractable REE content measurement and total REE quantification were conducted. For total quantification, ~ 250 mg samples were digested in 10 ml concentrated HNO_3 (15 M) at 120°C for one hour of digestion under microwave. The sample was filtered using a sand core funnel (class F) and diluted using ultrapure water for ICP-OES measurement. For H_2SO_4 leaching, ~ 1 g samples (Raw BO, Raw DL, Activated BO, Activated DL, Calcinated BO, and Calcinated DL) were digested in ~ 10 ml H_2SO_4 (0.1 M) at 90°C for 1 hour. After digestion, the sample was filtered using a sand core funnel (class F) and diluted to ~ 100 ml using ultrapure water for ICP-OES measurement. The pH-dependent leaching dynamics were investigated by using 1, 0.1, 0.01, and 0.001 M H_2SO_4 at pH 0.3, 0.7, 1.8, and 2.5 respectively, as the leaching agents.

The ICP-OES measurement was conducted using a ThermoFisher iCAP 6300 system. The detection limits for REE are in the level of 0.5 to 5 parts per trillion (ppt). The REE mixture standard was used (Macklin; 16 elements; 10 mg L^{-1} each; Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu in 5 wt % nitric acid). In our analyses, the standards were in the concentration range of 1 to 1000 parts per billion. All the analyzed samples were carefully diluted into the concentration range, which is at least two orders of magnitude higher than the detection limit of quantification. All the samples were measured three times to afford the SDs.

A sequential extraction routine was used to evaluate the REE fractions in Raw BO, Activated BO, and Calcinated BO^{41,42}. The ion-exchangeable fraction (step I) was extracted using MgCl_2 solution ($\text{pH} = 7 \pm 0.2$), the carbonate binding fraction (step II) was extracted using CH_3COONa solution ($\text{pH} = 5 \pm 0.2$), the humic acid binding fraction (step III) was extracted using $\text{Na}_4\text{P}_2\text{O}_7$ solution ($\text{pH} = 10 \pm 0.2$), the Fe-(hydr)oxide fraction (step IV) was extracted using $\text{NH}_2\text{OH}-\text{HCl}$ solution ($\text{pH} = 2 \pm 0.2$), the strong organic

binding fraction (step V) was extracted using $\text{H}_2\text{O}_2 + \text{HNO}_3$, and finally the residual fraction (step VI) was extracted using $\text{HNO}_3\text{--HF--HClO}_4$ solution.

Characterization. The SEM images were obtained by using a Czech TESCAN MIRA LMS SEM system at 5 kV. XRD was collected by using a Bruker D8 Discover system. XPS spectra were taken using a Thermofisher Nexsa XPS system under the base pressure of 5×10^{-9} Torr. Elemental XPS spectra were collected using a step size of 0.1 eV with a pass energy of 26 eV. All of the XPS spectra were calibrated by using the standard C 1s peak at 284.8 eV. TGA was conducted in N_2 at a heating rate of $10^\circ\text{C min}^{-1}$ up to 800°C by using a Q5000IR Simultaneous TGA/DSC from TA instruments. Calcination was conducted using the Mafu furnace in the air (SA2-6-12TP).

Life-cycle assessment. The environmental impacts were evaluated via life cycle assessment (Supplementary Note 1). Two scenarios were considered in this study: furnace calcination and rapid electrothermal calcination (Fig. 5a). The LCI entries were converted into environmental impacts using the ReCiPe 2016 methodology²⁸. According to the experimental results, treating 5g of rare earth-enriched plants would consume 4.9 g sulphuric acid and 45.1 ml water. The energy efficiency of REC was quantitatively compared with conventional muffle furnace processing under optimized operational parameters. The REC system achieved rapid thermal activation through resistive Joule heating, operating at a peak temperature of $3,600^\circ\text{C}$ with a rated power of 3 kW. It demonstrated an ultrahigh heating rate of 100°C s^{-1} , reaching the target temperature of $1,000^\circ\text{C}$ within 10 seconds, followed by a 20-second isothermal phase, amounting to 0.37 kWh per batch. In contrast, the muffle furnace process required prolonged thermal exposure: heating from ambient to 550°C at $10^\circ\text{C min}^{-1}$ (equivalent to $0.167^\circ\text{C s}^{-1}$) over 55 minutes, followed by a 3-hour isothermal retention at 550°C . With a rated power of 2.5 kW, this protocol consumed 1.44 kWh per cycle. Monte Carlo simulations were implemented for sensitivity analyses. It is important to note that the LCA conducted in this study is preliminary; in actual production, the water requirement for separation and current efficiency may vary due to optimization efforts. These factors could introduce uncertainty into the LCA analysis.

Techno-economic analysis. The economic feasibility of the ECD process was evaluated via technoeconomic analysis (Supplementary Note 1). The required chemical reagents were sourced based on domestic market prices in China, with specific prices for relevant items detailed in Supplementary Table 3. The industrial electricity consumption rate in China was estimated at \$0.11 per kWh. The evaluation in this work does not account for the price of spent materials or the labor cost. The overall process cost was calculated by projecting energy consumption and potential benefits under the proposed operating conditions. Economic performance indicators such as net present value (NPV), internal rate of return (IRR), and payback period (PBP) were not included in this preliminary analysis but could be incorporated into future studies for a more comprehensive evaluation. It is also acknowledged that scaling the laboratory-based process to an industrial level may introduce additional technical and economic challenges, which could affect the overall feasibility and profitability of the proposed process.

Declarations

Acknowledgments

We express our gratitude to the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences for providing the *Blechnum orientale*. The funding of the research was provided by the National Natural Science Foundation of China (No. 92475112, 51978375), the National Key R&D program of China (No. 2024YFC3907000), the Beijing Natural Science Foundation (No. F251042), and the Central Leading Local Science and Technology Development Fund (YDZJSX2024D002).

Author contributions

B.D. and M.X. conceived the idea. M.X. conducted most of the experiments and characterization. T.W., E.F., and Z.H. assisted with the experiments. M.X. conducted the LCA and TEA with the help of T.W. Q.M. and W.L. provided hyperaccumulators and offered useful suggestions to the experimental design. M.X., B.D., and J.L. wrote the manuscript. This work is supervised by B.D. and J.L. All authors revised and commented on the final version of this article.

Competing interests

Authors declare that they have no competing interests.

Data availability

The data supporting the findings of this study are available within the article and its Supplementary Information. Other relevant data are available from the corresponding author upon reasonable request.

References

1. Dethier, E. N. *et al.* A global rise in alluvial mining increases sediment load in tropical rivers. *Nature* **620**, 787–793 (2023).
2. Jowitt, S. M., Mudd, G. M. & Thompson, J. F. H. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Commun. Earth Environ.* **1**, 1–8 (2020).
3. Wang, P. *et al.* Regional rare-earth element supply and demand balanced with circular economy strategies. *Nat. Geosci.* **17**, 94–102 (2024).
4. Cheisson, T. & Schelter, E. J. Rare earth elements: Mendeleev's bane, modern marvels. *Science* (80-.). **363**, 489–493 (2019).
5. Fu, R. *et al.* Tracing metal footprints via global renewable power value chains. *Nat. Commun.* **14**, 3703 (2023).
6. Balaram, V. Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geosci. Front.* **10**, 1285–1303 (2019).

7. Deng, B. *et al.* Rare earth elements from waste. *Sci. Adv.* **8**, 1–9 (2022).
8. Elshkaki, A. Sustainability of emerging energy and transportation technologies is impacted by the coexistence of minerals in nature. *Commun. Earth Environ.* **2**, 186, (2021).
9. Barbera, M. *et al.* Accumulation of rare earth elements in common vine leaves is achieved through extraction from soil and transport in the xylem sap. *Commun. Earth Environ.* **4**, 1–8 (2023).
10. Prommer, H. Towards sustainable rare-earth-element mining. *Nat. Sustain.* **6**, 13–14 (2023).
11. Wang, G. *et al.* Industrial-scale sustainable rare earth mining enabled by electrokinetics. *Nat. Sustain.* **8**, 182–189 (2025).
12. Lee, J. C. K. & Wen, Z. Pathways for greening the supply of rare earth elements in China. *Nat. Sustain.* **1**, 598–605 (2018).
13. Dance, A. Microbial miners take on rare-earth metals. *Nature* **623**, 876–878 (2023).
14. Wang, G. *et al.* A green and efficient technology to recover rare earth elements from weathering crusts. *Nat. Sustain.* **6**, 81–92 (2023).
15. Chour, Z. *et al.* Basis for a new process for producing REE oxides from *Dicranopteris linearis*. *J. Environ. Chem. Eng.* **8**, 103961 (2020).
16. Zheng, H. X. *et al.* Plasma-Membrane-Localized Transporter NREET1 is Responsible for Rare Earth Element Uptake in Hyperaccumulator *Dicranopteris linearis*. *Environ. Sci. Technol.* **57**, 6922–6933 (2023).
17. Rabbani, M., Taqi Rabbani, M., Muthoni, F., Sun, Y. & Vahidi, E. Advancing phytomining: Harnessing plant potential for sustainable rare earth element extraction. *Bioresour. Technol.* **401**, 130751 (2024).
18. van der Ent, A. *et al.* *Exceptional Uptake and Accumulation of Chemical Elements in Plants: Extending the Hyperaccumulation Paradigm.* (2021).
19. Jally, B. *et al.* A new method for recovering rare earth elements from the hyperaccumulating fern *Dicranopteris linearis* from China. *Miner. Eng.* **166**, 106879 (2021).
20. Dang, P. & Li, C. A mini-review of phytomining. *Int. J. Environ. Sci. Technol.* **19**, 12825–12838 (2022).
21. Christopher W. N. Anderson*, Robert R. Brooks*, Robert B. Stewart* & Robyn Simcock. Harvesting a crop of gold in plants . *Nature* **395**, 553 (1998).
22. Wang, L. *et al.* Field trials of phytomining and phytoremediation: A critical review of influencing factors and effects of additives. *Crit. Rev. Environ. Sci. Technol.* **50**, 2724–2774 (2020).
23. Qin, B. *et al.* Vacuum pyrolysis method for reclamation of rare earth elements from hyperaccumulator *Dicranopteris dichotoma* grown in contaminated soil. *J. Clean. Prod.* **229**, 480–488 (2019).
24. Jalali, J., Gaudin, P., Ammar, E. & Lebeau, T. Bioaugmentation coupled with phytoextraction for the treatment of Cd and Sr, and reuse opportunities for phosphogypsum rare earth elements. *J. Hazard. Mater.* **399**, 122821 (2020).
25. Luong, D. X. *et al.* Gram-scale bottom-up flash graphene synthesis. *Nature* **577**, 647–651 (2020).

26. Liu, Q. & Chen, S. W. Ultrafast synthesis of electrocatalysts. *Trends Chem.* **4**, 918–934 (2022).
27. Deng, B. *et al.* Urban mining by flash Joule heating. *Nat. Commun.* **12**, 5794 (2021).
28. Zhu, X. *et al.* Continuous and low-carbon production of biomass flash graphene. *Nat. Commun.* **15**, 3128 (2024).
29. Jia, C. *et al.* Graphene environmental footprint greatly reduced when derived from biomass waste via flash Joule heating. *One Earth* **5**, 1394–1403 (2022).
30. Deng, B. *et al.* High-temperature electrothermal remediation of multi-pollutants in soil. *Nat. Commun.* **14**, 6371 (2023).
31. Choi, C. H. ‘William’ *et al.* Flash-within-flash synthesis of gram-scale solid-state materials. *Nat. Chem.* **16**, 1831–1837 (2024).
32. Deng, B. *et al.* High-surface-area corundum nanoparticles by resistive hotspot-induced phase transformation. *Nat. Commun.* **13**, 5027 (2022).
33. Brown, R. M., Mirkouei, A., Reed, D. & Thompson, V. Current nature-based biological practices for rare earth elements extraction and recovery: Bioleaching and biosorption. *Renew. Sustain. Energy Rev.* **173**, 113099 (2023).
34. Deng, B., Eddy, L., Wyss, K. M., Tiwary, C. S. & Tour, J. M. Flash Joule heating for synthesis , upcycling and remediation. *Nat. Rev. Clean Technol.* **1**, 32–54 (2025).
35. Cheng, Y. *et al.* Electrothermal mineralization of per- and polyfluoroalkyl substances for soil remediation. *Nat. Commun.* **15**, 6117 (2024).
36. Hong, C., Tang, Q., Liu, S., Kim, H. & Liu, D. A two-step bioleaching process enhanced the recovery of rare earth elements from phosphogypsum. *Hydrometallurgy* **221**, 106140 (2023).
37. Grosjean, N. *et al.* Accumulation and fractionation of rare earth elements are conserved traits in the *Phytolacca* genus. *Sci. Rep.* **9**, 18458 (2019).
38. Wang, H. *et al.* Uptake and transport mechanisms of rare earth hyperaccumulators: A review. *J. Environ. Manage.* **351**, 119998 (2024).
39. Chen, Y., Fabbicino, M., Benedetti, M. F. & Korshin, G. V. Spectroscopic in situ examination of interactions of rare earth ions with humic substances. *Water Res.* **68**, 273–281 (2015).
40. Talik, E. *et al.* XPS characterisation of neodymium gallate wafers. *J. Alloys Compd.* **377**, 259–267 (2004).
41. Huang, J. *et al.* Groundwater controls REE mineralisation in the regolith of South China. *Chem. Geol.* **577**, 120295 (2021).
42. Denys, A. *et al.* Evaluation of selectivity of sequential extraction procedure applied to REE speciation in laterite. *Chem. Geol.* **559**, 119954 (2021).
43. Liu, W. S. *et al.* Phytoextraction of rare earth elements from ion-adsorption mine tailings by *Phytolacca americana*: Effects of organic material and biochar amendment. *J. Clean. Prod.* **275**, 122959 (2020).

44. Deng, B. *et al.* Flash Separation of Metals by Electrothermal Chlorination. *Nat. Chem. Eng.* **1**, 1–26 (2024).

Figures

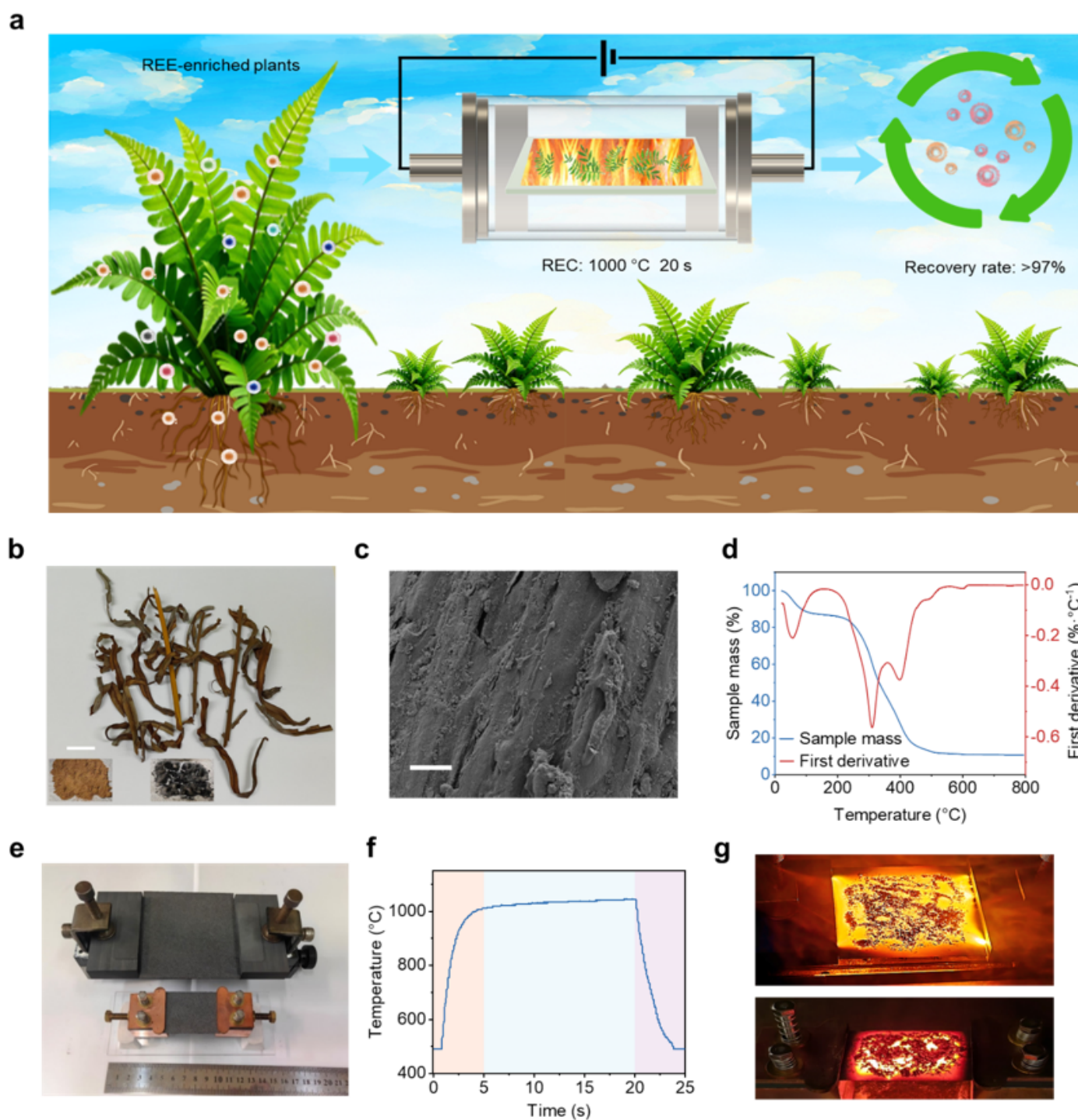


Figure 1

Extraction of REEs by flash Joule heating.(a) Conceptual schematic of REE extraction from phytomining by REC. (b) Picture of dried *Blechnum Orientale* (BO). Scale bar, 3 cm. Inset, the mixture of crushed BO

before and after REC. (c) SEM image of dried raw BO materials. Scale bar, 10 μm . (d) Thermogravimetric analysis of BO and the first derivative. (e) Picture of the reactor and enlarged reactor during the REC process. (f) Real-time temperature curve measured during the REC reaction. (g) Pictures of intense light emission during the REC process.

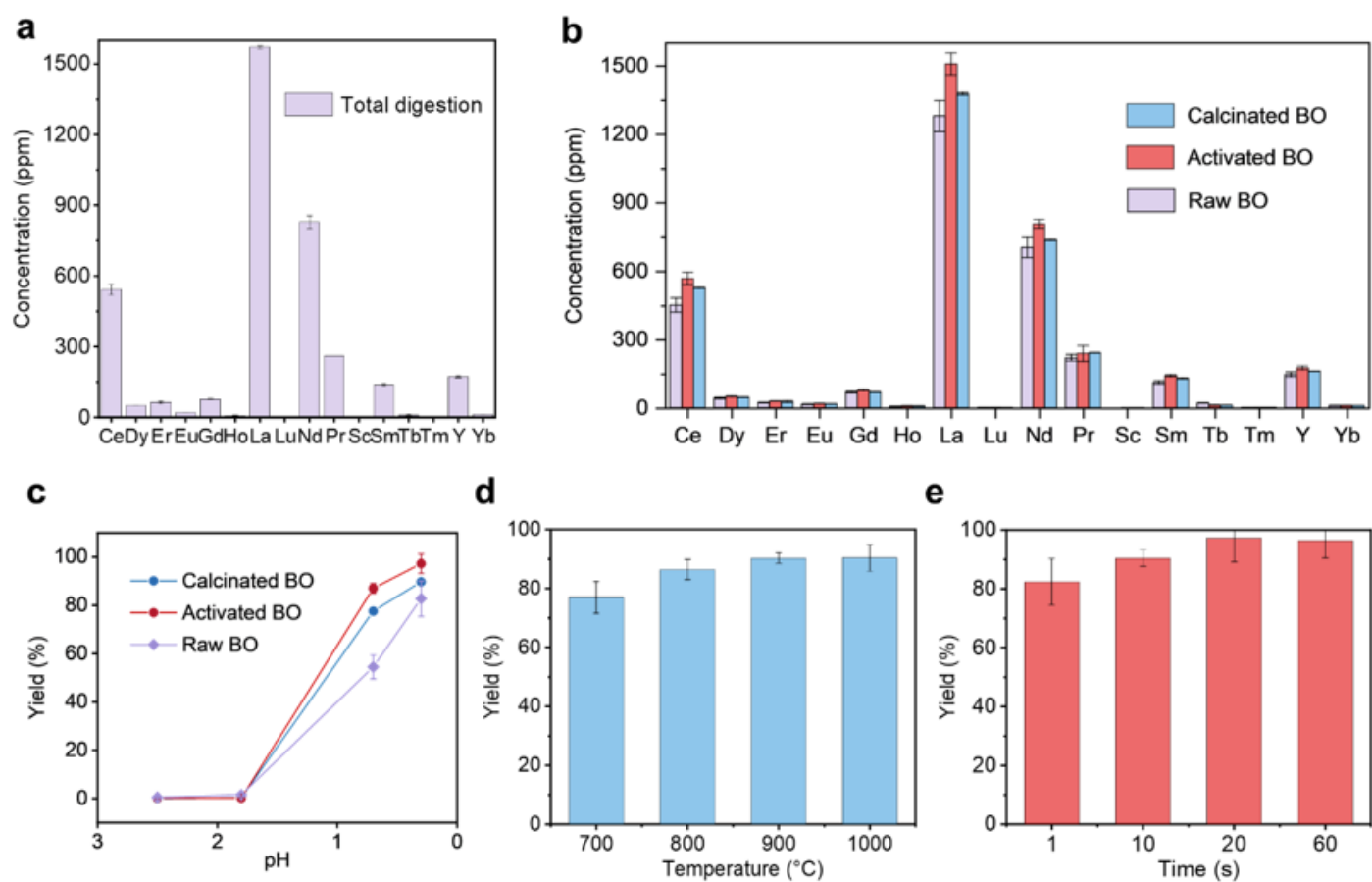


Figure 2

Improved extraction yield of REE from BO by electrothermal activation. (a) Total quantification of REE in Raw BO. (b) H₂SO₄-extractable REE contents (1 M, 90 °C) of REE in Raw BO, Activated BO, and Calcinated BO. (c) pH-dependent REE leaching yield from the Raw BO, Activated BO, and Calcinated BO. (d) Extraction yield of REE at different REC reaction temperatures for 10 seconds. (e) Extraction yield of REE at 1000 °C for different reaction times. All error bars denote standard deviation where *N* = 3.

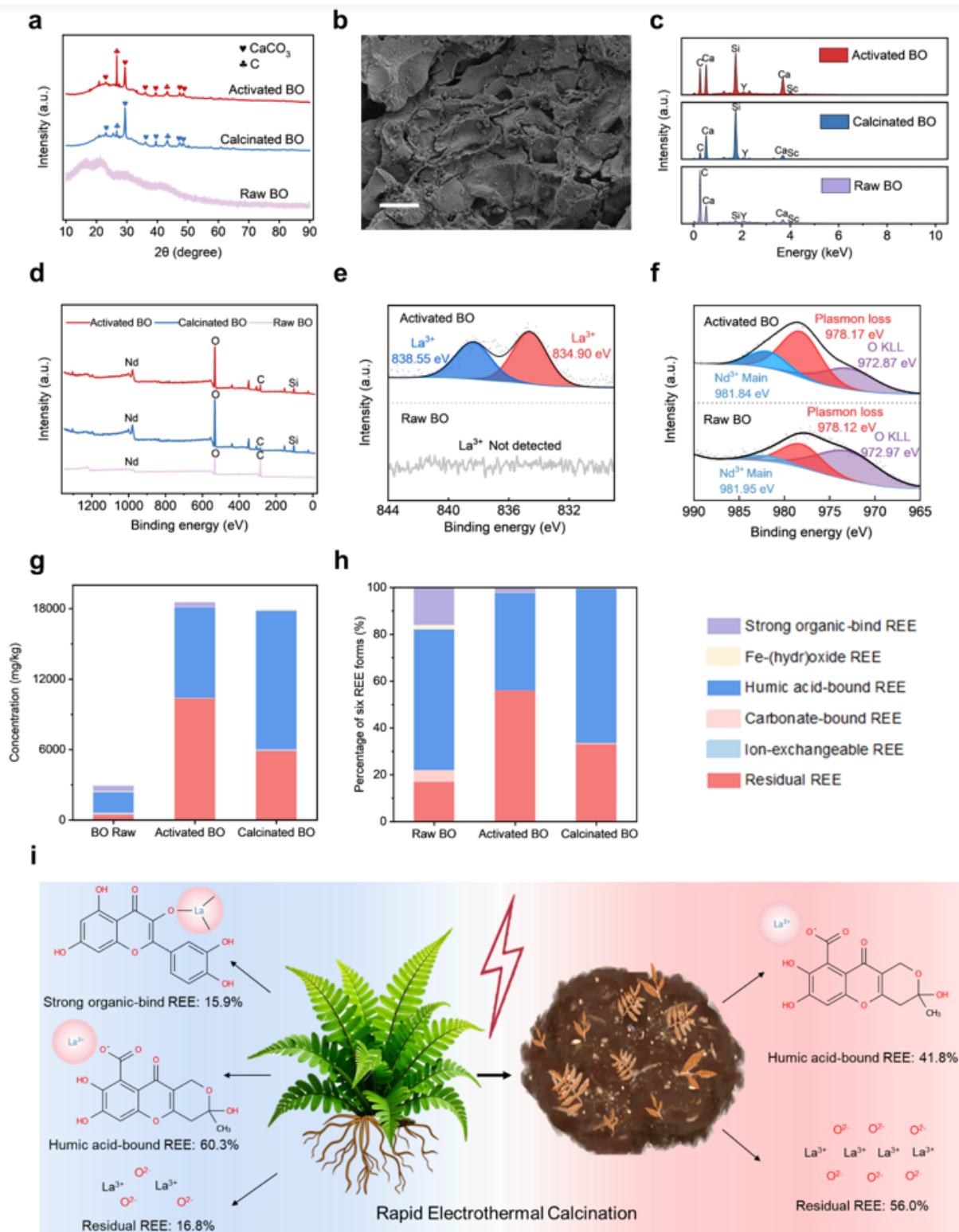


Figure 3

Mechanism of the improved REE extractability by the electrothermal activation. (a) XRD patterns of Raw BO, Activated BO, and Calcinated BO. The CaCO₃ with reference PDF (CaCO₃, #72-1937) and C with reference PDF (C, #26-1080) were shown. (b) SEM image of Activated BO. Scale bar, 10 μ m. (c) EDS of Raw BO, Activated BO, and Calcinated BO. (d) XPS full spectra of Raw BO, Activated BO, and Calcinated BO. (e) XPS fine spectra of La 3d_{5/2} in Raw BO and Activated BO. La was not detected in Raw BO. Note

that the La at 838.55 eV is the shake-up satellite. **(f)** XPS fine spectrum of Nd 3d_{5/2} in Raw BO and Activated BO. The O Auger KLL peak is labeled. **(g)** Content of six REE forms in Raw BO, Activated BO and Calcinated BO. **(h)** Percentage of six REE forms of La in Raw BO, Activated BO and Calcinated BO. **(i)** Changes in the percentage of different forms of REE in Raw BO and Activated BO.

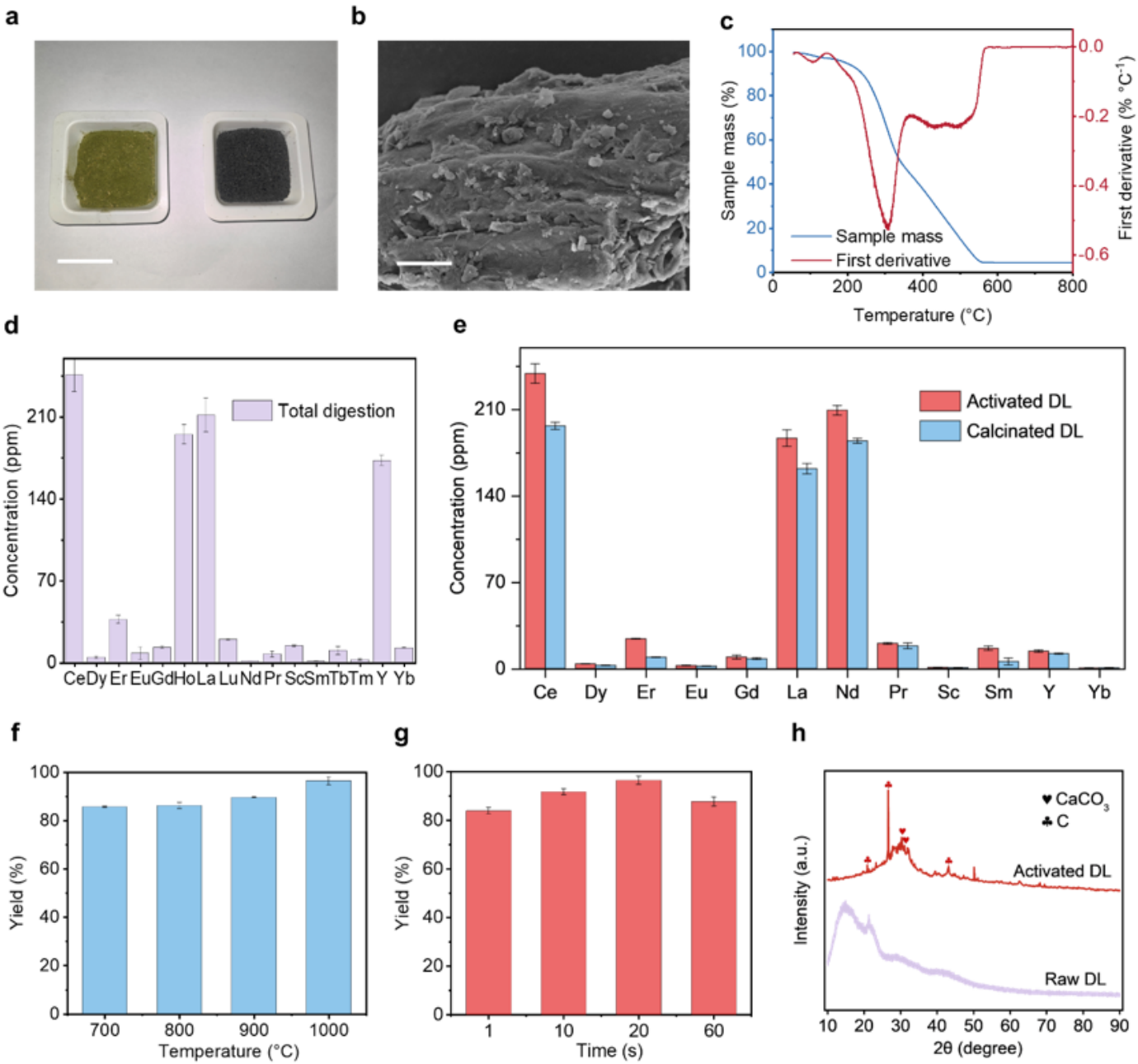


Figure 4

Extraction of REE from DL. **(a)** Picture of dried *Dicranopteris linearis* (DL). Scale bar, 2 cm. **(b)** SEM image of dried DL Raw materials. Scale bar, 5 μm. **(c)** Thermogravimetric analysis of DL and the first derivative. **(d)** Total quantification of REE in Raw DL. **(e)** H₂SO₄-extractable REE contents (1 M, 90°C) of REE in Raw DL, Calcinated DL, and Activated DL. **(f)** Extraction yield of REE for 10 seconds at different REE reaction temperatures. **(g)** Extraction yield of REE at 1000°C for different reaction times. All error bars denote

standard deviation where N = 3. (h) XRD patterns of Calcinated DL and Activated DL. The CaCO_3 with reference PDF (CaCO_3 , #51-1524) and C with reference PDF (C, #50-0927) were shown.

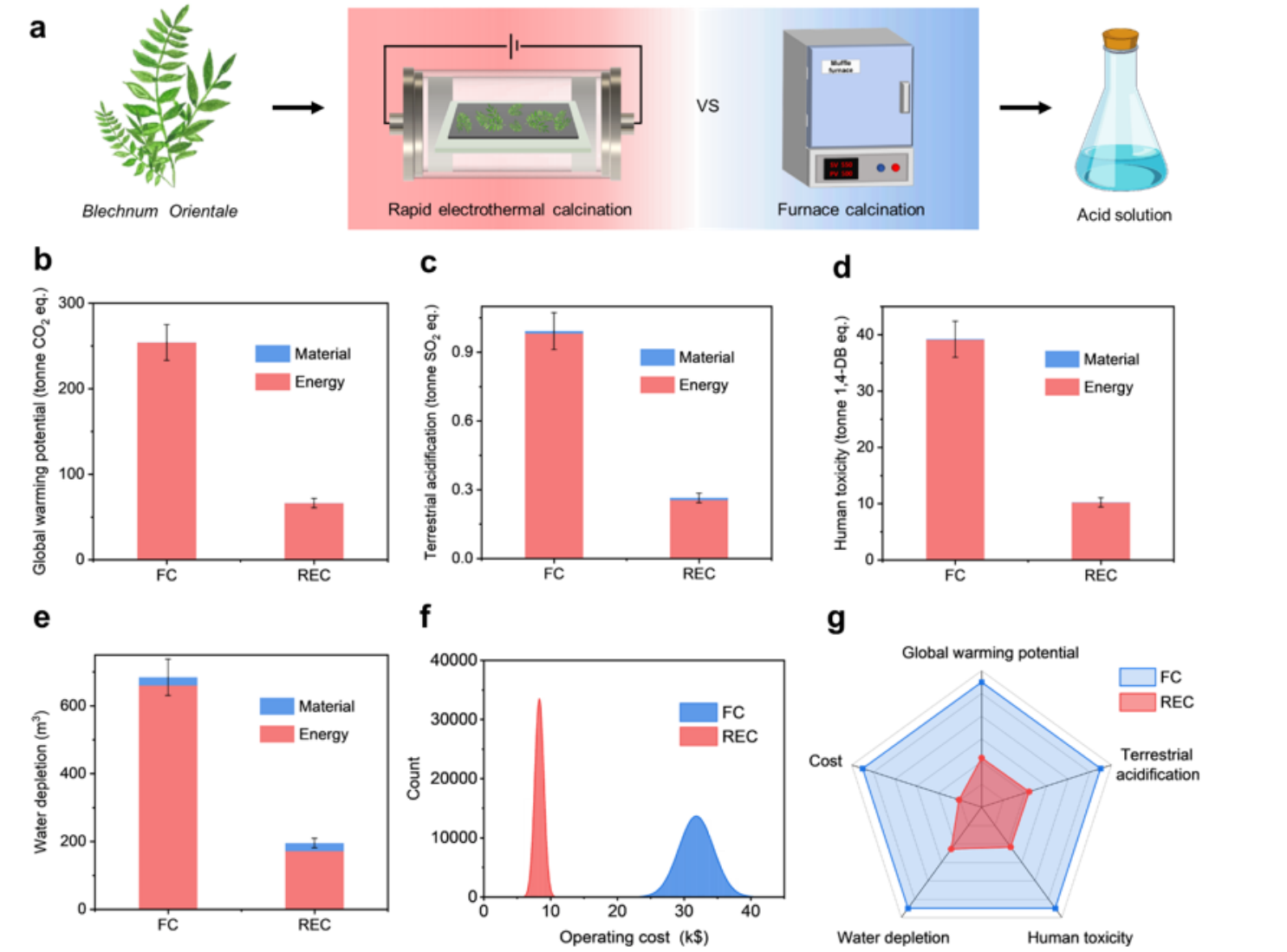


Figure 5

Environmental and economic considerations for REE extraction processes. (a) Process design comparison of REC and FC scenarios for LCA and TEA analysis. (b) Global warming potential comparison. (c) Terrestrial acidification comparison. (d) Human toxicity comparison. (e) Water depletion comparison. (f) Operating cost comparison utilizing Monte Carlo uncertainty analysis with N=50,000 iterations. (g) Comprehensive performance comparison. The scales bars in b-e denote the standard deviation based on Monte Carlo analyses. Functional unit is the leaching of 1 tonne of REE-enriched plants.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Sl.docx](#)