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Biogeochemical cycles of nutrients, rare earth elements (REEs) and Al in soil-plant system in ion-adsorption REE mine tailings remediated with amendment and ramie (*Boehmeria nivea* L.)

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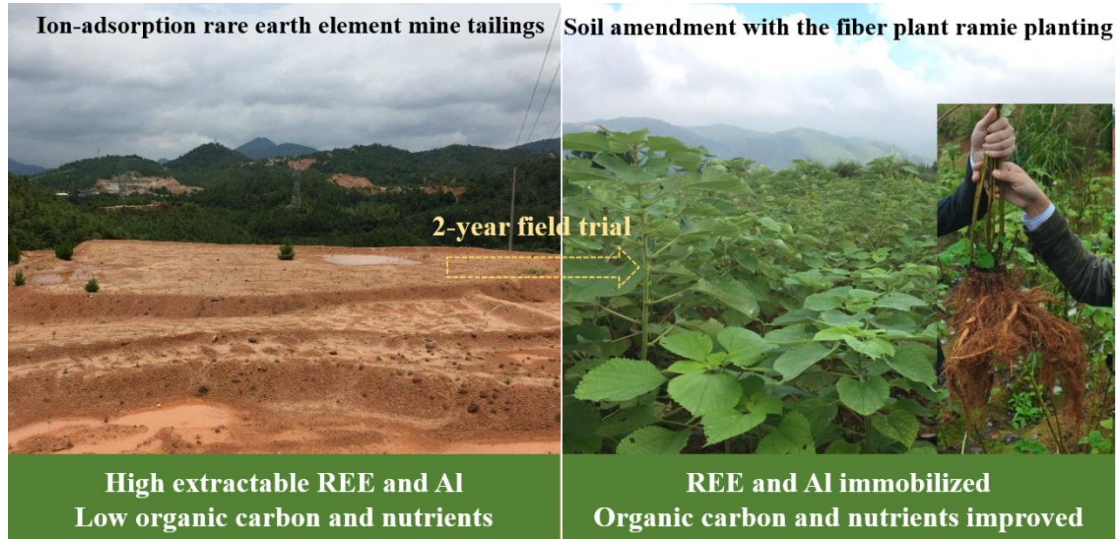
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Graphical abstract



Highlights

- REE mine tailings are characterized by REE and Al excess and nutrient deficiency
- Phytostabilization practices decrease soil extractable REE and Al concentrations
- Phytostabilization practices improve physico-chemical properties of mine tailings
- Ramie root activity increases soil extractable nutrient but not REE and Al contents
- Ramie stores most of the plant REEs and Al in the thick roots

1

2 Biogeochemical cycles of nutrients, rare earth elements (REEs) and Al in
3 soil-plant system in ion-adsorption REE mine tailings remediated with
4 amendment and ramie (*Boehmeria nivea* L.)

5

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29 **Abstract**

30 The exploitation of ion-adsorption rare earth element (REE) deposits in South China
31 has left large areas of mine tailings. However, limited remediation practices on these
32 tailings have been reported, and how the remediation strategies and economic plants
33 cultivation affect the biogeochemical cycles of nutrients, REEs and Al remains unclear.
34 The aim of the present study was to investigate the effects of the combination of the
35 addition of soil amendment and the root development and activity of a fiber plant ramie
36 (*Boehmeria nivea* L.) on the availability and distribution of nutrients, as well as of REEs
37 and other potentially toxic elements (*e.g.* Al) in the soil-plant system. The results
38 showed that the application of organic amendment and ramie planting induced a
39 significant increase in soil pH, total carbon (C), nitrogen (N), and other nutrient (*e.g.* P
40 and Ca) concentrations, while led to a decrease of 80–90% and 60–90% in soil
41 extractable REE and Al concentrations respectively. Matrices of correlation showed
42 that soil pH, total C, N, and P concentrations were among the most important factors
43 controlling the availability of soil REEs and Al, and root characteristics (*e.g.* fine root
44 length). The total C, N, P and extractable nutrient concentrations, and electrical
45 conductivity were higher in the rhizosphere soils of ramie than those in the bulk soils.
46 Moreover, more than 60% of the quantity of REE and Al in the whole ramie plant were
47 stored within the thick roots. These results showed that, in addition to amendment, the
48 effects induced by the roots of ramie could further improve soil properties through C
49 input, nutrient mobilization and toxic element stabilization. Our study concludes that

50 ramie planting with organic amendment is a promising phytostabilization strategy for
51 the remediation of REE mine tailings in South China.

52

53 **Keywords:** fiber plant; mobilization; rhizosphere; root characteristic

54

55 **1. Introduction**

56 Rare earth elements (REEs) are a group of metallic elements comprised of fifteen
57 lanthanide elements plus yttrium. The lanthanides are typically split into two sub-
58 groups, light REEs (LREEs, La to Eu) and heavy REEs (HREEs, Gd to Lu) (Tyler 2004).
59 As the demand of REEs increases globally, the mining of REE deposits has rapidly
60 grown (Yang et al. 2013). Ion-adsorption REE deposits, resulting from the weathering
61 of granite under (sub)tropical climate, are mainly located in South China, and later
62 found in Vietnam, Myanmar and Madagascar (Borst et al. 2020). In these deposits, most
63 REEs exist as trivalent ions and are adsorbed onto the clay minerals (*e.g.* kaolinite) and
64 Fe/Mn oxides originated from the granite. Thus, the REEs can be easily leached out
65 through a simple ion-exchange process using a salt solution: $2(\text{Kaolin})^{3-}\text{RE}^{3+} +$
66 $3(\text{NH}_4)_2\text{SO}_4 \rightarrow 2(\text{Kaolin})^{3-}(\text{NH}_4)_3^+ + \text{RE}_2^{3+}(\text{SO}_4)_3^{2-}$. The heap leaching technology used
67 for decades in South China has consisted of: i) removing the vegetation and the topsoil;
68 ii) excavating the REE-rich clays (ores) from the (semi)weathered layers at a depth of
69 5–20 m; iii) piling up the ores into a heap on a plastic sheet and leaching them with
70 ammonium sulfate solution; iv) recovering REEs from the leachates (Xiao et al. 2015).
71 This mining technology has induced many environmental damages, such as water and
72 soil erosion, vegetation destruction and mine tailings generation (Yang et al. 2013). For
73 instance, it was reported that the area of REE mine tailings in Ganzhou city in the
74 Jiangxi province exceeded 100 km² (Liu et al. 2015).

75

76 Though some pioneer plants have begun to settle after several years of abandonment,
77 the revegetation of these mine tailings under natural succession is quite slow (Liu et al.
78 2015). The poor physical conditions with soil compaction, low pH (4–5), low contents
79 of nutrients (especially P) and organic matter (~0.1%), and low microbial activities are
80 considered as the main obstacles for plant colonization on these mine tailings (Liu et al.
81 2015). Moreover, these tailings still contain high residual REE concentrations (Chao et
82 al. 2016), which are highly exchangeable even after 10 years of abandonment (>20%
83 of the total REEs extracted with 1.0 mol/L MgCl₂) (Wen et al. 2013). This part of REEs
84 may leach out and enter into the surrounding rivers and farmland soils, posing potential
85 risks to local living organisms (Li et al. 2013). Besides, the exchangeable Al³⁺
86 concentration in the tailings soil is high and accounts for 80% of total cation exchange
87 capacity (CEC) (Liu et al. 2020a), which may also inhibit plant colonization. Up to now,
88 the phytoremediation field trials at these mine tailings have mainly focused on the
89 restoration of soil fertility and microbial communities (Zhou et al. 2015; Liu et al. 2016;
90 Wei et al. 2019; Liu et al. 2020b), whilst the control of REE and Al availabilities and
91 the cycling of REE and Al are largely ignored.

92

93 Phytostabilization, one strategy of phytoremediation, aims to establish a plant cover on
94 the surface of contaminated soils, hence retaining contaminants within the vadose zone
95 through root accumulation or precipitation of contaminants within the rhizosphere. This
96 strategy can also reduce contamination dispersion by wind, water, and direct contact

97 with humans or animals (Bolan et al. 2011). Addition of organic amendments is a
98 common practice in phytostabilization, which can improve soil structure, alleviate soil
99 nutrient deficiency, and effectively stabilize contaminants in mine tailings (Meeinkuirt
100 et al. 2016). A recent pot experiment showed that organic amendments are effective in
101 increasing the soil pH and organic matter concentration, thus reducing the REE
102 concentrations in tailing soil solution (Liu et al. 2020a). However, organic amendment
103 would induce an enrichment of dissolved organic carbon (DOC) in soil solution. As a
104 result, heavy metals that are adsorbed on soil particles can be complexed by DOC and
105 solubilized into the soil solution. For example, it was found that manure amendment
106 was less efficient to stabilize heavy metals (*e.g.* Cd and Zn) (Houben et al. 2012).
107 Nevertheless, the effectiveness of phytostabilization practice with organic amendment
108 in stabilizing REE and Al on the mine tailings needs further examination in the field.

109

110 Root development and activities are critical for the growth of plant and the cycling of
111 nutrients and pollutants in the soil-plant system since roots are the interface between
112 the plant and the soil environment (Abe 2001). Plants can adapt to harsh soil condition
113 through the manipulation of root morphology and metabolites (Sasse et al. 2019). Root
114 morphological architectures and physiological adaptations are easily altered by
115 nutritional stress (Lambers and Colmer 2005). A number of studies found that the
116 changes of root morphology (*e.g.* fine root length) are critical for plant nutrient
117 acquisition (Hill et al. 2006; Christopher and Jonathan 2020). Plant root exudates,

118 consisting of a complex mixture of metabolites, play a fundamental role in regulation
119 of soil nutrient availability and detoxification of undesirable metal pollutants for plants
120 (Dakora and Phillips 2002; Chen et al. 2017). Under conditions of nutrient deficiency
121 (*e.g.* P), plant roots would release carboxylates and lower soil pH, thus solubilizing P,
122 and Mn (or heavy metals) accidentally (Lambers et al. 2015). Although the availability
123 of heavy metals can be largely reduced in the early stage of phytostabilization practices,
124 a subsequent re-mobilization of heavy metals may happen as a result of root secretion
125 (Pierzynski et al. 2002; Cui 2011). However, there are no detailed studies reporting the
126 *in situ* effects of root activities on soil properties and on the change of REE and Al
127 availabilities in mine tailings.

128

129 The cultivation of economic crops in the mine tailings can produce biomass of industrial
130 interest (*e.g.* fibers and bioenergy) and contribute to the socio-economic redevelopment
131 of these mining areas (Ding et al. 2018). However, most studies focused on native or
132 pioneer plants (Wang et al. 2017), and the potential use of the economic crops for the
133 remediation of mine sites is largely ignored. The fiber plant ramie (*Boehmeria nivea* L.)
134 is a perennial herb, with a complex underground system composed of fine fibrous roots,
135 radish roots and rhizome. In previous studies, ramie is regarded as a multi-metal tolerant
136 plant, with strong tolerance to Pb, Zn, Cd, As, and has strong adaptability to harsh
137 environment such as drought (Yang et al. 2010). Ramie has also been found to have
138 great REE tolerance and retain most of the REEs in roots under hydroponic culture (Liu

139 et al. 2021a). Therefore, it could be a potential candidate for the phytoremediation of
140 ion-adsorption REE mine tailings and for the production of fibers of economic value.

141

142 In this work, a field trial of phytostabilization combining addition of soil amendment
143 and cultivation of the fiber plant ramie were conducted on ion-adsorption REE mine
144 tailings in South China with the aim of investigating: (i) the effects of phytostabilization
145 practice on the changes of soil physico-chemical properties, including nutrients, REE
146 and Al availabilities; (ii) the root development and the role of root activities in the
147 changes of nutrients, REE and Al availabilities; (iii) the distribution, transfer and
148 fractionation of REEs in the soil-plant system.

149

150 **2. Materials and Methods**

151 *2.1 Site description*

152 The study area is located in the Dingnan county of Ganzhou city, Jiangxi province,
153 China (latitude: 24.99°, longitude: 115.05°). The terrain is hilly with an altitude ranging
154 between 200 and 1200 m. It is situated in the subtropical monsoon humid climate zone
155 with an average annual temperature of 18.9 °C and annual rainfall of 1620 mm (Shi et
156 al. 2020). Dingnan is famous for its abundant reserve of ion-adsorption REE deposits,
157 which have been mined since the 1980s. The studied REE mine tailings were resulted
158 from the exploitation of REE deposits by heap leaching technology until 2008. The
159 tailings were further terraced to protect them from landslides in 2012 (Fig. 1a).

160

161 The studied mine tailings covered a surface area of about 0.53 km², some parts of which
162 were featured with steep slopes (> 45°) and subjected to strong erosion (Fig. 1). In 2015,
163 the vegetation coverage was limited (< 5%) and composed mainly of pioneer species
164 (*e.g. Miscanthus sinensis, Pinus massoniana*). Since 2015, this site has been used as a
165 demonstration base to implement remediation projects using amendments and different
166 plants.

167

168 2.2 Field plot description and samplings

169

170 *Remediation practices*

171 Two field plots (zones A and B) were set at the demonstration base in July 2015 to test
172 the feasibility of cultivating fiber plants on ion-adsorption mine tailings (Fig. 1).
173 Different remediation practices in terms of fertilization, tillage and planting have been
174 applied in both plots (about 2000 m² for each). Before planting, organic amendment
175 (pig manure and sawdust with a ratio of 2:1, v/v) was added at a rate of 5–6 kg/m² and
176 mixed with the first 10–12 cm of the tailings by tillage. Based on laboratory
177 experiments, this organic amendment was shown to be efficient in supporting the
178 growth of fiber plants in these mine tailings. Compared to manure, the mixture of
179 manure and sawdust showed a slower release of DOC and nutrients (Chen et al. 2018).
180 Plant resources (seeds and seedlings) for cultivation were brought from the Institute of

181 Bast Fiber Crops (Changsha, Chinese Academy of Agricultural Sciences).

182

183 In the zone A, an annual fiber plant was sown with a density of 3 g/m² in July 2015. In
184 June 2016, plants were removed, and organic amendment was further added at a rate of
185 5–6 kg/m² and mixed in the first 10–12 cm. And then, one-year ramie seedlings of about
186 35 cm in height (cultivar Zhongzhu No.1), were planted in rows (3–5 plants per m²). In
187 the zone B, ramie seedlings (one-year plants, about 35 cm in height) were planted in
188 rows (3–5 plants per m²) in July 2015. In June 2016, the aboveground parts of ramie
189 plants were cut and granules of inorganic fertilizers (N/P/K) were introduced at a rate
190 of 30–45 g/m².

191

192 *Soil and plant sampling*

193 The sampling of both field plots was performed in November 2017. For each zone (A
194 and B), five whole ramie plants with soils associated to roots were sampled.
195 Rhizosphere soils were separated into two fractions: (i) the soil loosely adhering to the
196 roots (LAR) which was collected by shaking the roots for 3 min until almost no soil
197 particles dropped and (ii) the remaining soil tightly adhering to the roots (TAR) which
198 was then recovered by brushing the roots (Otero et al. 2012). For comparison, bulk soils
199 were collected between two plants in each zone. In addition, bare tilling samples were
200 collected at three locations situated near the field plots and were considered as controls
201 without amendment and planting (Fig. 1b).

202

203 2.3 Analyses

204

205 *Preparation and analysis of soil samples*

206 Soil samples were air-dried for two weeks and sieved through a mesh of 2 mm. Roots
207 and stones were discarded from soils. An aliquot of 2-mm sieved soil sample was
208 further ground (<0.15 mm) for the elemental analysis. The total carbon (TC) and
209 nitrogen (TN) were analyzed by dry combustion using an elemental analyzer
210 (Elemental, Vario EL, Germany). The concentrations of soil total REEs and other major
211 and trace elements (*e.g.* Al, Fe, Ca, P, Mn) were measured at ALS Chemex (Guangzhou)
212 Co., Ltd. Namely, about 1 g of the air-dried soil was digested by lithium borate fusion
213 method and analyzed by inductively coupled plasma mass spectrometry (ICP-MS)
214 (Agilent VISTA, USA) for REEs and X-ray fluorescence spectrometry (XRF)
215 (PANalytical PW2424, Netherlands) for major elements (Liu et al. 2020a).

216

217 The soil pH was measured at a ratio of 1: 2.5 (soil: deionized water, w/v) (Mettler
218 Toledo, LE438 pH, Germany). An extraction using 0.001 mol/L CaCl₂ solution with a
219 ratio of 1: 2 (soil: CaCl₂ solution, w/v) was performed to mimic the soil solution
220 (Groenenberg et al. 2010). Namely, 20 g of air-dried and < 2 mm soil was mixed with
221 40 mL 0.001 mol/L CaCl₂ solution. The suspensions were shaken horizontally at 80 rpm
222 for 48 h. After centrifugation and filtration through a 0.45- μ m membrane, the extracts

223 were analyzed for the electrical conductivity (EC) using an electrochemical analyzer
224 (INESA DDS-307A, China), for the CaCl₂-extractable concentrations of organic
225 carbon (CaCl₂-EOC) using a TOC analyzer (Elemental, Vario TOC, Germany) and for
226 the CaCl₂-extractable concentrations of major and trace elements at ALS Chemex
227 (Guangzhou) Co., Ltd using ICP-MS and inductively coupled plasma optical emission
228 spectrometry (ICP-OES) (Agilent VISTA, USA).

229

230 *Preparation and analysis of plant samples*

231 For plant sample analyses, each plant was separated into leaves, stems, fine roots (0–5
232 mm in diameter) and thick roots (>5 mm, including radish roots and rhizomes) (Fig. 1d)
233 (Boehm 1979; Bai et al. 2016). In order to eliminate the dust from the surface of the
234 plants, and the soil particles adhering to the roots, each plant part was carefully washed
235 with tap water and deionized water. After cleaning, the fine roots were scanned (Epson
236 perfection, V700 photo, Indonesia) and analyzed using a WinRHIZO software to
237 measure the fine root total length (TL), surface area (SA), average diameter (AD), root
238 volume (RV), root length depending on the diameter classes (0–0.2 mm, 0.2–1 mm, 1–
239 2 mm, 2–3 mm, 3–4 mm, 4–5 mm). The small fine root (<1 mm) and fine root (<5 mm)
240 morphological parameters are defined as follows:

$$241 \quad \textit{specific root length (SRL, cm/g)} = \frac{\textit{fine root length (cm)}}{\textit{fine root biomass (g)}}$$

$$242 \quad \textit{specific root surface area (SRA, cm/g)} = \frac{\textit{fine root surface area (cm}^2\text{)}}{\textit{fine root biomass (g)}}$$

$$243 \quad \textit{small fine root percentage (SFRP, \%)} = \frac{\textit{small fine root length (cm)}}{\textit{fine root length (cm)}} \times 100$$

$$244 \quad \text{root tissue density (RTD, g/cm}^3\text{)} = \frac{\text{fine root biomass (g)}}{\text{fine root volume (cm}^3\text{)}}$$

245

246 Plant materials were dried at 105 °C for 30 min and 60 °C for 48 h and then ground to
 247 <1 mm and preserved in polyethylene bags. The plant samples were digested by HNO₃
 248 (65%, 6 ml) and HCl (37%, 2 ml). Afterwards, the trace and major elements in the
 249 digested solutions were analyzed by ICP-MS and ICP-OES at ALS Chemex
 250 (Guangzhou) Co., Ltd as described above.

251

252 *REE fractionation analysis*

253 The REE fractionation in the soil-plant system results from the small variations in the
 254 behaviors of individual REEs during soil and plant physiological processes (Tyler
 255 2004). The Ce anomaly and REE fractionation pattern (*i.e.* LREE or HREE enrichment)
 256 are widely used indicators in the soil-plant system. The transfer factors (K_n), which are
 257 defined as the REE concentrations in one compartment divided by the concentrations
 258 in another compartment, were also calculated along the REE transfer route. The REE
 259 transfers in the soil-ramie system can be divided into 5 steps: I, from rhizosphere soil
 260 (TAR) to soil solution; II, from rhizosphere soil solution to fine roots; III, from fine
 261 roots to thick roots; IV, from thick roots to stems; V, from stems to leaves. The transfer
 262 factors of these steps are calculated as follows:

$$263 \quad K_I = \frac{[\text{REE}]_{\text{CaCl}_2\text{-extractable in TAR soil}}}{[\text{REE}]_{\text{total in TAR soil}}}$$

$$264 \quad K_{II} = \frac{[\text{REE}]_{\text{fine roots}}}{[\text{REE}]_{\text{CaCl}_2\text{-extractable in TAR soil}}}$$

265
$$K_{III} = \frac{[REE]_{\text{thick roots}}}{[REE]_{\text{fine roots}}}$$

266
$$K_{IV} = \frac{[REE]_{\text{stems}}}{[REE]_{\text{thick roots}}}$$

267
$$K_V = \frac{[REE]_{\text{leaves}}}{[REE]_{\text{stems}}}$$

268

269 The REE fractionation during each transfer process can be roughly estimated by
 270 (La/Yb), and Ce anomaly.

271
$$K_n(*Ce) = \frac{2 \times K_n(Ce)}{K_n(La) + K_n(Pr)}$$

272
$$K_n(La/Yb) = \frac{K_n(La)}{K_n(Yb)}$$

273

274 The Ce anomaly value (*Ce) >1 and <1 means positive and negative anomaly,
 275 respectively, and the ratio of La to Yb >1 and <1 means a LREE and HREE enrichment
 276 pattern, respectively (Wei et al. 2001; Liu et al. 2021b).

277

278 *2.4 Data analysis*

279 The SPSS 20.0 statistical analysis software was used for data analysis. All results were
 280 presented as arithmetic means with standard deviation calculated on three or five
 281 samples. Soil physico-chemical properties, plant growth characteristics, element
 282 concentrations in plant organs were compared using one-way analysis of variance
 283 (ANOVA) followed by a Duncan test at a significance level of 0.05. For one parameter,
 284 values with different letters refer to significant differences between the different
 285 samples from zones A and B and the controls. For some parameters, if the data were

286 not normally distributed, they were transformed by normal score to follow a normal
287 distribution before being tested. Matrices of correlation were performed on the soil
288 physico-chemical properties and plant elemental composition or root morphological
289 characteristics using a Pearson correlation two-sided test.

290

291 **3. Results**

292

293 *3.1 Bulk and rhizosphere soil properties*

294 The general physico-chemical characteristics of the bare tailings, bulk and rhizosphere
295 (LAR and TAR) soils are shown in Fig. 2. The pH values of the mine tailings after
296 planting and amendments (4.80–6.00) were significantly higher than those of the bare
297 tailings (4.38–4.47). There was no significant difference in pH between the bulk, LAR
298 and TAR soils in both zones A and B. The TC and TN concentrations showed significant
299 differences between different soil fractions, and were in the order of bare tailings < bulk
300 soil < LAR < TAR in both the zones A and B. Whatever the soil fraction, the
301 concentrations of TC and TN were higher in the zone A compared with the zone B. The
302 total P concentrations were higher in the LAR (30–100 mg/kg) and TAR (20–120 mg/kg)
303 soils than in the corresponding bulk soil (20–80 mg/kg), and much higher than that in
304 bare tailings (4.36 mg/kg). The total concentrations of other nutrients (Ca, K) showed
305 similar trends as the total P concentrations (Table S1). Concerning the bulk soils, some
306 chemical properties (pH, EC and total N, P, Ca, K, REE concentrations) were

307 significantly higher in the zone A than in the zone B.

308

309 The reclaimed tailings generally presented higher EC values in soil CaCl₂ extracts
310 (154–693 μS/cm) than the bare tailings (185–200 μS/cm). For each zone, the EC values
311 of rhizosphere soils were higher than the corresponding bulk soils. The concentrations
312 of soil CaCl₂-EOC showed significant differences between the soil fractions and were
313 in the order of bare tailings < bulk soil < LAR < TAR in both the zones A and B. The
314 concentrations of soil CaCl₂-EOC were higher in the zone A compared with the those
315 in the zone B for the corresponding soil fractions. The extractable nutrient
316 concentrations (K, Mg, Mn, Na, S, Zn) were significantly higher in the rhizosphere soils
317 (LAR and TAR fractions) compared with the corresponding bulk soils and the bare
318 tailings (Table S2).

319

320 The total REE concentrations varied in the bare tailings (281–729 mg/kg) and the
321 reclaimed tailings (zone A: 926–3460 mg/kg; zone B: 551–1030 mg/kg), revealing the
322 heterogeneity of the distribution of residual REEs in the tailings. The total Al
323 concentrations were around 8.5% in all the soil samples. The CaCl₂-extractable REE
324 concentrations in the bare tailings (controls) were ten times higher than those in the
325 reclaimed tailings. The proportions of extractable REE concentrations out of the total
326 REE concentrations in the soils followed the order of control (0.11–0.79%) > zone B
327 bulk soil (0.04–0.13%) > zone A bulk soil (0.01–0.06%). Similar to those of REEs, the

328 extractable Al concentrations and the proportions of extractable Al out of the total Al
329 concentrations were both ten times higher in the controls than in the reclaimed tailings.
330 No significant difference in the extractable REE and Al concentrations or proportions
331 was found between bulk and rhizosphere soils in both zones A and B (Fig. 3).

332

333 *3.2 Plant growth and elemental distribution*

334 The biomass and root characteristics of ramie plants are shown in Fig. 4 and Table S3.
335 Among the different ramie organs, the thick roots showed the highest dry biomass both
336 in the zone A (159–406 g per plant) and the zone B (251–1090 g per plant). The thick
337 roots accounted for 85–89% of the total dry biomass of ramie, followed by the stems
338 (9.6–14.4%), fine roots (1.3–3.0%) and leaves (0.02–0.12%). Each ramie plant had an
339 average ramet number of 6 in both zones. The average height of these ramet stems was
340 170 and 163 cm in the zones A and B, respectively.

341

342 The characteristics of the fine roots (< 5 mm in diameter) of ramie plants are presented
343 in Table A3. The root morphological parameter AD was higher in the zone B than the
344 zone A, while the TL, SA, and RV of the fine roots showed no significant difference
345 between the zones A and B. The length of the small fine roots (<1 mm in diameter)
346 represented more than 99% of the total fine root length, including 27 % for the very
347 fine roots with a diameter <0.2 mm. The SRL was significantly higher in the zone A
348 than that in the zone B, while the SRA and RTD were similar in both zones.

349

350 The distribution of nutrients varied greatly between the ramie organs and between the
351 zones A and B (Tables S4 and S5). The major elements accumulated by ramie plants
352 were Ca, K and P, and to a lesser extent Mg and Fe. Phosphorus (P) concentrations in
353 the organs showed the order of leaves \approx stems > thick roots > fine roots in the zone A,
354 and leaves > thick roots > stems > fine roots in the zone B. The amount of P (elemental
355 concentration \times dry biomass) accumulated in the different organs of ramie generally
356 showed the order of thick roots (76.6–91.7%) > stems (7.33–21.3%) > fine roots (0.54–
357 2.60%) > leaves (0.02–0.14%) in both the zones A and B.

358

359 The concentrations and amount of REEs and Al in plants are presented in Fig. 5. The
360 concentrations of REEs in the different organs of ramie were distributed in the order of
361 fine roots (248–590 mg/kg) > leaves (160–312 mg/kg) > stems (36–172 mg/kg) > thick
362 roots (31–59 mg/kg) in both the zones A and B. Despite the high REE concentrations
363 in leaves, the amount of REEs accumulated in leaves was low, being 0.01–0.30 mg per
364 plant for both the zones A and B, and only accounted for about 0.5% of the total amount
365 of REEs accumulated in the whole plant. The amount stored in the thick roots reached
366 12.9–21.3 mg per plant, and represented approximately 67.0% and 80.2% of the total
367 amount of REEs accumulated in the whole plant in the zones A and B, respectively. The
368 concentrations of Al in different organs of ramie showed the order of leaves (2920–
369 10800 mg/kg) > fine roots (1690–6300 mg/kg) > thick roots (495–3140 mg/kg) > stems

370 (641–2050 mg/kg) in the zones A and B. The amount of Al accumulated in the different
371 organs showed similar trends to those of REEs. Namely, most of the Al (67–94%)
372 accumulated by ramie plant was stored in the thick roots in the zones A and B (Fig. 5).

373

374 *3.3 Transfer and fractionation of REEs in the soil-ramie system*

375 The transfer factors in the soil-ramie system are shown in Fig. 6 and Table S6. The
376 results showed that $K_{II} > K_V > K_{IV} > K_{III} > K_I$, indicating a REE accumulation in fine
377 roots compared with the soil extractable REE fraction (step II) and a slight enrichment
378 in the leaves compared with the stems (step V). The slopes of K_I (La/Yb) and K_V (La/Yb)
379 were 0.4–0.5 in the zones A and B, indicating a selective transport of HREEs during
380 soil-solution and stem-leaf transfers. While the slopes of K_{II} (La/Yb) (~4) suggested a
381 selective absorption of LREEs by ramie roots. The Ce anomaly values was <1 for the
382 steps I and IV, and >1 for steps II, III and V. In addition, there were no significant
383 differences of transfer factors and line slopes between the zones A and B.

384

385 *3.4 Relationships between soil properties and plant characteristics*

386 A correlation matrix analysis was performed on selected physico-chemical properties
387 and extractable REEs of the bare tailings, the bulk and rhizosphere soils (Table 1).
388 Results showed that extractable REE concentrations were positively correlated with
389 extractable Al concentrations, and negatively correlated with soil pH and soil total C,
390 N, P and Ca concentrations ($p < 0.05$).

391

392 A correlation matrix analysis was also performed on selected physico-chemical
393 properties of TAR soils and plant parameters (Table 2 and Table S7). In plants, four root
394 characteristics (length for the different diameter classes, TL, SA, RV) were positively
395 correlated with REE, Al and nutrient (Ca, P) concentrations of fine roots ($p < 0.05$). The
396 amount of REEs accumulated in the whole plant was also positively correlated with
397 these four root characteristics. Moreover, these four root characteristics were positively
398 correlated with soil pH, TC, TP, and soil extractable Mg concentration. The SRL was
399 positively correlated with pH, TC, and TP in soils, and the SRA was positively
400 correlated with TC in soils. However, the AD and SFRP were positively and negatively
401 correlated with the extractable REE concentrations in the soil, respectively.

402

403 **4. Discussion**

404 *4.1 Effects of phytostabilization practices on dynamics of REEs, Al and nutrients in soil*

405 In line with previous studies, our results confirmed that the soils of bare tailings exhibit
406 low pH, low concentrations of CaCl_2 -EOC, TC, TN, and nutrients (Ca, Mg, P, S, etc.),
407 but high concentrations of extractable REE and Al (Fig. 3). The REE concentrations in
408 the tailings were higher than the background values in the soils of mainland China (188
409 mg/kg) or Jiangxi province (221 mg/kg) (Wei et al. 1991), and showed high proportions
410 of available REEs. A pot experiment has shown that plants can hardly grow on these
411 tailings without soil improvement (Liu et al. 2020a). Our results showed that the

412 application of organic amendment and planting with ramie resulted in an increase in
413 soil pH, soil CaCl₂-EOC, TC, TN and nutrient concentrations. The organic amendment
414 is a source of organic matter as well as macronutrients and micronutrients, which are
415 critical for supporting plants growth and adaptation in contaminated soils (Meeinkuirt
416 et al. 2016). The introduction of plant and organic amendment may also promote the
417 formation of stable aggregates, providing space for root growth and for the survival and
418 breeding of soil invertebrates and microorganisms (Chiang et al. 2006).

419

420 The soil pH was among the most obvious factors controlling the concentrations of
421 extractable REE and Al in the mine tailing soils (Table 1). Under strong acid soil
422 conditions in the bare tailings (pH 4.4), REEs and Al that adsorbed on clays, organic
423 matter and Fe-/Mn- oxides may be released into the soil solution. With the increase of
424 soil pH in the reclaimed soils, the REEs and Al in the soil solution would be precipitated
425 by REE/Al hydroxides and Fe-/Mn- oxides (Dinali et al. 2004). Significant correlations
426 between soil REE/Al and TC concentrations were also observed, indicating that REEs
427 and Al could be bound by the functional groups (*e.g.* hydroxyl and carboxyl) of organic
428 matter (Migaszewski and Gałuszka 2015). Moreover, with the increase of P
429 concentrations, the REE and Al ions may also be precipitated by phosphates. The
430 reasons why REE and Al showed a similar behavior could be that both REEs (except
431 Ce and Eu in some conditions) and Al are trivalent elements, which show many
432 similarities of chemical properties during the geochemical processes (Pletnev and

433 Zernov 2002). Therefore, the phytostabilization practices with ramie planting and
434 organic amendment can protect the plants from REEs and Al toxicity, and may reduce
435 the risk of groundwater contamination and other biological exposure. The significant
436 differences of soil pH, EC, TN, and soil total P, Ca, K, REE concentrations between the
437 zones A and B may be ascribed to the different planting strategies and amendment
438 additions. The higher percentages of extractable REE and Al in the soils of zone B than
439 zone A may be due to the lower soil pH, and soil TC and P concentrations of zone B.

440

441 *4.2 Root development and effects of root activities on dynamics of REEs, Al and* 442 *nutrients in soil*

443 Soil properties may constrain the plant and root development and the morphological
444 characteristics of the root system. Matrices of correlation (Table 2) indicate that the
445 beneficial soil physico-chemical properties (pH, TC and nutrients) promote the fine root
446 growth of ramie, however, the potential toxic REE and Al have adverse effects on the
447 fine root length. Previous studies have reported that the most obvious toxicity
448 phenomenon of Al and REE to plant is the inhibition of root elongation and activities
449 (Tyler 2004; Abdulaha-Al et al. 2018). A recent study found that the rice root
450 morphological features (*e.g.* the number of lateral root of adventitious roots) were
451 sensitive to high concentration of REE (Shi et al. 2021). The difference of age of ramie
452 could also contribute to the differences in root morphology observed between the zones
453 A and B. Physical properties could also be a limiting factor for root development in the

454 mine tailings and should be taken into consideration in future studies.

455

456 In turn, the root activity and changes of the root morphological parameters may affect
457 the soil properties in the rhizosphere. Significant enrichment of C and nutrients can be
458 seen in the rhizosphere samples compared to bulk soil samples (Fig. 2), indicating that
459 in addition to soil amendment, ramie planting could further improve the soil properties.

460 This enrichment of C and nutrients in rhizosphere soils has been previously reported
461 for other mine soils phytoremediation practices by the planting of *Digitaria sanguinalis*,
462 *Picris hieracioides*, *Conyza albida*, *Setaria viridis* (Campillo-Cora et al. 2019). On the
463 one hand, plant roots can directly release exudates or protons into the rhizosphere zone,
464 thus influencing nutrient mobility and bioavailability, and other physico-chemical
465 properties (Hinsinger et al. 2005; Qasim et al. 2016). In fact, ramie has been found to
466 enhance soil fertility by fine root turnover and root exudation (Bene et al. 2011). On the
467 other hand, the plant would recruit certain beneficial microbes (*e.g.* P solubilization
468 microbes) in the rhizosphere under nutrient deficiency, thus indirectly increasing
469 nutrient availabilities (Alori et al. 2017). Our former study found that the combination
470 of amendment and ramie planting treatment recruited much more beneficial microbes
471 compared to the only amendment treatment (Liu et al. 2020b).

472

473 A number of studies reported that the planting induces strong rhizosphere effects, which
474 finally induces an increase of available REEs in the soils (Wang et al. 2001; Wiche et

475 al. 2016). Compared to no planting treatment, it was found that planting of a REE
476 hyperaccumulator *Phytolacca americana* significantly decreased soil pH and increased
477 extracted REE concentrations of the REE mine tailings (Liu et al. 2020a). However, in
478 the present study, no significant differences of extractable REE and Al concentrations
479 were found between the rhizosphere and bulk soil samples (Fig. 5). One possible reason
480 is that the rhizosphere effect did not induce a significant decrease of soil pH (Fig. 2a).
481 Another possible reason is that ramie absorbed high amount of REEs and Al from the
482 soil solution and retained them within the roots. Moreover, the REEs show high
483 affinities to oxalate (a root exudate for many plants), forming stable REE-complexes or
484 even precipitates that are insoluble (He et al. 2021).

485

486 *4.3 REE accumulation and fractionation of soil-ramie system*

487 In this study, ramie presented large biomass in underground parts, especially the thick
488 roots (Fig. 4). Consequently, the quantity of REEs and Al accumulated by the plant was
489 mostly retained within the thick roots for both zones. The thick roots are a “storehouse”,
490 which can store a series of nutrients (*e.g.* N, P, K, etc.) (Table S5) (Bai et al. 2016).
491 Ramie might use these nutrients for next growth season, especially under nutrient
492 deficiency (Wu et al. 2021). Most of the REEs and Al in the plant roots are usually
493 tightly complexed by the cell walls (*e.g.* REE hyperaccumulator *Dicranopteris linearis*
494 and normal plant cucumber) (Zhang et al. 2012; Liu et al. 2021c). Thus, the stored REEs
495 and Al in the thick roots of ramie are unlikely to be redistributed in the plant any more.

496 Contrary to the “storehouse” role of the thick roots, the fine roots function as a “capturer”
497 of nutrients and contaminants from the soil (Bai et al. 2016). This can be explained by
498 the positive correlations between the fine root characteristics and the root
499 REE/Al/nutrient concentrations (Table 2).

500

501 With the increase of atomic number of REE ions, their ability to adsorb on clay minerals
502 decreases gradually, while their ability to be complexed and leached out increases
503 (Tyler 2004). Therefore, soil-to-soil solution step showed a HREE enriched pattern (Fig.
504 6), which was similar to that of soil-*D. linearis* system (Wei et al. 2001). The negative
505 Ce anomaly during soil-to-soil solution process may be due to the fact that Ce mostly
506 exists as Ce oxides in the soil (Tyler 2004). The reason why soil solution-to-fine root
507 process showed an LREE enriched pattern may be ascribed to the preferential uptake
508 of LREE by plant root through Ca^{2+} channel, while the uptake of HREE may be
509 inhibited by the high concentration of Al (Yuan et al. 2017). The HREE enrichment in
510 the leaves compared to the stems measured in ramie was also observed in the REE
511 hyperaccumulator *P. americana*. A previous study carried out on this plant has revealed
512 that organic ligands such as citric acid play an important role in long-distance transport
513 of REEs in the xylem, leading to a preferential enrichment of HREE in the leaves (Yuan
514 et al. 2017). The positive Ce anomalies during the uptake processes (solution-to-fine
515 roots, fine root-to-thick roots, and stems-to-leaves) were also found in our former
516 hydroponic experiment (Liu et al. 2021a). It may be ascribed to the preferential

517 enrichment of CeO₂ precipitation on the root surface. These particles may further
518 activate REE endocytosis at the root cells membrane (Wang et al. 2014). Brioschi et al.
519 (2013) speculated that the REE-oxyhydroxide particles in plant xylem sap could lead
520 to the positive Ce anomaly during the transport process.

521

522 Though the HREE concentrations in the mine tailings are much lower than the LREEs,
523 the HREEs are easier to migrate from soil into the soil solution, and transport from
524 underground part to the shoots. Further studies should not ignore the potential
525 environmental risks of HREEs. Based on the current field trial, high mechanical
526 strength fibers with low REE concentrations have been extracted from the ramie plants
527 grown on the tailings (Segovia et al. 2021). However, further work is needed to ensure
528 sustainable management of this crop and long-term REE/Al phytostabilization of the
529 mine tailings.

530

531 **5. Conclusion**

532 The wide exploitation of ion-adsorption REE deposits in South China have led to a
533 large area of mine tailings with limited remediation. In the present study, a 2-year field
534 trial of phytostabilization combining addition of organic amendment and cultivation of
535 ramie was conducted on a typical ion-adsorption REE mine tailing. Our results showed
536 that this phytostabilization strategy not only improves soil properties, but also decreases
537 the extractable concentrations of potentially toxic elements (REEs and Al). By

538 comparing the soil physico-chemical properties between the rhizosphere soils and the
539 corresponding bulk soils, our study also showed that ramie planting and the root
540 activities further improve soil properties through C input and nutrient mobilization.
541 Moreover, this fiber plant succeeded to grow on the amended mine tailings and the
542 major quantity of REEs taken up by the plant were restricted within the thick roots. In
543 sum, we conclude that phytostabilization practice with organic amendment and ramie
544 cultivation is a promising strategy for the remediation of ion-adsorption REE mine
545 tailings in South China.

546

547

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561

562 **References**

563 Abe, J.J., 2001. Roots: The dynamic interface between plants and the earth. Springer,
564 Dordrecht.

565 Alori, E.T., Glick, B.R., Babalola, O.O., 2017. Microbial phosphorus solubilization and
566 its potential for use in sustainable agriculture. *Front Microbiol.* 8, 971.

567 Bai, Y.C., Yang, R.F., Li, X.L., Liu, N.N., Huang, M.S., Liu, C.X., Cui, G.X., 2016.
568 Research progress of ramie root systems. *J Agr.* 6, 19–23. (*in Chinese*)

569 Baquy, M.A., Li J.Y., Jiang J., Mehmood, K., Shi, R.Y., Xu, R.K., 2018. Critical pH
570 and exchangeable Al of four acidic soils derived from different parent materials
571 for maize crops. *J soil sediment.* 18, 1490–1499.

572 Bene, C.D., Tavarini, S., Mazzoncini, M., Angelini, L.G., 2011. Changes in soil
573 chemical parameters and organic matter balance after 13 years of ramie
574 [*Boehmeria nivea* (L.) Gaud.] cultivation in the Mediterranean region. *Eur J*
575 *Agron.* 35, 154–163.

576 Boehm, W., 1979. *Methods of Studying Root Systems.* Springer, Berlin, Heidelberg.

577 Bolan, N.S., Park, J.H., Robinson, B., Naidu R., Huh K.Y., 2011. Phytostabilization: a
578 green approach to contaminant containment. *Adv Agron.* 112, 145–204.

579 Borst, A.M., Smith, M.P., Finch, A.A., Estrade, G., Villanova-de-Benavent, C., Nason,

580 P., Marquis, E., Horsburgh, N. J., Goodenough, K. M., Xu, C., Kynicky, J.,
581 Geraki, K., 2020. Adsorption of rare earth elements in regolith-hosted clay
582 deposits. *Nat Commun.* 11, 4386.

583 Brioschi, L., Steinmann, M., Lucot, E., Pierret, M.C., Stille, P., Prunier, J., Badot, P.M.,
584 2013. Transfer of rare earth elements (REE) from natural soil to plant systems:
585 Implications for the environmental availability of anthropogenic REE. *Plant*
586 *Soil.* 366, 143.

587 Campillo-Cora, C., Fernández-Calviño, D., Pérez-Rodríguez, P., Fernández-Sanjurjo,
588 M.J., Núñez-Delgado, A., Álvarez-Rodríguez, E., Arias-Estévez, M., Nóvoa-
589 Muñoz, J.C., 2019. Copper and zinc in rhizosphere soil of wild plants growing
590 in long-term acid vineyard soils. Insights on availability and metal remediation.
591 *Sci Total Environ.* 672, 389–399.

592 Chao, Y.Q., Liu, W.S., Chen, Y.M., Chen, W.H., Zhao, L.H., Ding, Q.B., Wang, S.Z.,
593 Tang, Y.T., Tong, Z., Qiu, R.L., 2016. Structure, variation, and co-occurrence of
594 soil microbial communities in abandoned sites of a rare earth elements mine,
595 *Environ Sci Technol.* 50, 11481–11490.

596 Chen, Y.T., Wang, Y., Yeh, K.C., 2017. Role of root exudates in metal acquisition and
597 tolerance. *Curr Opin Plant Biol.* 39, 66–72.

598 Chen, Y.Y., Liu, W.S., Ding K.B., Tang, Y.T., Qiu, R.L., 2018. Effects of organic
599 amendments and biochar on ecological remediation of ionic rare earth mine
600 tailings. *Acta Sci Circumst.* 38, 4769–4778. (*in Chinese*)

601 Chiang, K.Y., Wang, Y.N., Wang, M.K., Chiang, P.N., 2006. Low-molecular-weight
602 organic acids and metal speciation in rhizosphere and bulk soils of a temperate
603 rain forest in Chitou, Taiwan. *Taiwan J For Sci.* 21, 327–337.

604 Christopher, F.S., Jonathan, P.L., 2020. Root secondary growth: an unexplored
605 component of soil resource acquisition. *Ann Bot.* 126, 205–218.

606 Cui, H.B., 2011. Study on the remediation of heavy metal Cu and Cd contaminated soil
607 by different ameliorators. Anhui Agricultural University, Anhui. (*in Chinese*)

608 Dakora, F.D., Phillips, D.A., 2002. Root exudates as mediators of mineral acquisition
609 in low-nutrient environments. *Plant Soil.* 245, 35–47.

610 Dinali, G.S., Root, R.A., Amistadi, M.K., Chorover, J., Lopes, G., Guilherme, L.R.G.,
611 2019. Rare earth elements (REY) sorption on soils of contrasting mineralogy
612 and texture. *Environ Int.* 128, 279–291.

613 Ding, K.B., Wu, Q., Wei, H., Yang, W.J., Séré, G., Wang, S.Z., Echevarria, G., Tang
614 Y.T., Tao, J., Morel, J.L., Qiu, R.L., 2018. Ecosystem services provided by
615 heavy metal-contaminated soils in China. *J Soil Sediment.* 18: 380–390

616 Groenenberg, J.E., Roemkens, P.F.A.M., Comans, R.N.J., Luster, J., Pampura, T.,
617 Shotbolt, L., Tipping, E., De Vries. W., 2010. Transfer functions for solid-
618 solution partitioning of cadmium, copper, nickel, lead and zinc in soils:
619 derivation of relationships for free metal ion activities and validation with
620 independent data. *Eur J Soil Sci.* 61, 58–73.

621 He, L., Xu, Q., Li, W., Dong, Q., Sun, W., 2021. One-step separation and recovery of

622 rare earth and iron from NdFeB slurry via phosphoric acid leaching. J Rare
623 Earth. <https://doi.org/10.1016/j.jre.2021.01.003>.

624 Hill, J.O., Simpson, R.J., Moore, A.D., 2006. Morphology and response of roots of
625 pasture species to phosphorus and nitrogen nutrition. Plant Soil. 286, 7–19.

626 Hinsinger, P., Gobran, G.R., Gregory, P.J., Wenzel, W.W., 2005. Rhizosphere geometry
627 and heterogeneity arising from root-mediated physical and chemical processes.
628 New Phytol. 168, 293–303.

629 Houben, D., Pircar, J., Sonnet, P., 2012. Heavy metal immobilization by cost-effective
630 amendments in a contaminated soil: Effects on metal leaching and
631 phytoavailability. J Geochem Explor. 123, 87–94.

632 Lambers, H., Hayes, P.E., Laliberté, E., Oliveira, R.S., Turner, B.L., 2015. Leaf
633 manganese accumulation and phosphorus-acquisition efficiency. Trends Plant
634 Sci. 20, 83–90.

635 Lambers, H., Colmer, T.D., 2005. Root Physiology: from Gene to Function. Springer,
636 Netherlands.

637 Li, X.F., Chen, Z.B., Chen, Z.Q., Zhang, Y.H., 2013. A human health risk assessment
638 of rare earth elements in soil and vegetables from a mining area in Fujian
639 Province, Southeast China. Chemosphere. 93, 1240–1246.

640 Liu, C., Liu, W.S., Huot, H., Yang, Y.M., Guo, M.N., Morel, J.L., Tang, Y.T., Qiu, R.L.,
641 2021a. Responses of ramie (*Boehmeria nivea* L.) to increasing rare earth
642 element (REE) concentrations in a hydroponic system. J Rare Earths.

643 <https://doi.org/10.1016/j.jre.2021.04.002>.

644 Liu, C., Yuan, M., Liu, W.S., Guo, M.N., Zheng, H.X., Huot, H., Jally, B., Tang, Y.T.,
645 Laubie, B., Simonnot, M.O., Morel, J.L., Qiu, R.L., 2021b. Element case studies:
646 rare earth elements, in Van der Ent, A., Echevarria, G., J.M. Baker, A., Morel,
647 J.L. (Eds.), *Agromining: farming for metals*. Springer, Switzerland, pp. 471–
648 483.

649 Liu, W.S., Laird, J.S., Ryan, C.G., Tang, Y.T., van der Ent, A., 2021c. Rare earth
650 elements, aluminium and silicon distribution in the fern *Dicranopteris linearis*
651 revealed by μ PIXE Maia analysis, *Ann Bot.* 128: 17–30.

652 Liu, W.S., Chen, Y.Y., Huot, H., Liu, C., Guo, M.N., Qiu, R.L., Morel, J.L., Tang, Y.T.,
653 2020a. Phytoextraction of rare earth elements from ion-adsorption mine tailings
654 by *Phytolacca americana*: Effects of organic material and biochar amendment.
655 *J Clean Prod.* 275, 122959.

656 Liu, Y., Zhong, X., Huot, H., Liu, W.S., Liu, C., Guo, M.N., Li, Y.Y., Fei, Y.H., Chao,
657 Y.Q., Wang, S.Z., Tang, Y.T., Qiu, R.L., 2020b. Reclamation with organic
658 amendments and plants remodels the diversity and structure of bacterial
659 community in ion-adsorption rare earth element mine tailings. *J Soil Sediment.*
660 20, 3669–3680.

661 Liu, S., Liu, W., Yang, M., Zhou, L., Liang, H., 2016. The genetic diversity of soil
662 bacteria affected by phytoremediation in a typical barren rare earth mined site
663 of South China. *Springerplus.* 5: 1131

664 Liu, W.S., Liu C., Wang Z.W., Teng W.K., Tang Y.T., Qiu R.L., 2015. Limiting factors
665 for restoration of dumping sites of ionic rare earth mine tailings. *Acta Pedol Sin.*
666 52, 879–87. (*in Chinses*)

667 Migaszewski, Z.M., Galuszka, A., 2015. The characteristics, occurrence, and
668 geochemical behavior of rare earth elements in the environment: a review. *Crit*
669 *Rev Environ Sci Technol.* 45, 429–471.

670 Meeinkuirt, W., Kruatrachue, M., Pichtel, J., Phusantisampan, T., Saengwilai, P., 2016.
671 Influence of organic amendments on phytostabilization of Cd-contaminated soil
672 by *Eucalyptus camaldulensis*. *Scienceasia.* 42, 83–91.

673 Otero, X.L., Álvarez, E., Fernández-Sanjurjo, M.J., Macías, F., 2012. Micronutrients
674 and toxic trace metals in the bulk and rhizosphere soil of the spontaneous
675 vegetation at an abandoned copper mine in Galicia (NW Spain). *J Geochem*
676 *Explor.* 112: 84–92.

677 Pierzynski, G.M., Lambert, M., Hetrick, B.A.D., Sweeney, D.W., Erickson, L.E., 2002.
678 Phytostabilization of metal mine tailings using tall fescue. *Period Hazard Toxic*
679 *Radioact Waste Manage.* 6, 212–217.

680 Pletnev, I.V., Zernov, V.V., 2002. Classification of metal ions according to their
681 complexing properties: a data-driven approach. *Anal Chim Acta.* 455, 131–142.

682 Qasim, B., Motelica-Heino, M., Bourgerie, S., Gauthier, A., Morabito, D., 2016.
683 Rhizosphere effects of *Populus euramericana* Dorskamp on the mobility of Zn,
684 Pb and Cd in contaminated technosols. *J Soil Sediment.* 16, 811–820.

685 Sasse, J., Kant, J., Cole, B.J., Klein, A.P., Arsova, B., Schlaepfer, P., Gao, J., Lewald,
686 K., Zhalnina, K., Kosina, S., Bowen, B.P., Treen, D., Vogel, J., Visel, A., Watt,
687 M., Dangl, J.L., Northen, T.R., 2019. Multilab EcoFAB study shows highly
688 reproducible physiology and depletion of soil metabolites by a model grass.
689 *New Phytol.* 222, 1149–1160.

690 Segovia, C., Hedri, M., Huot, H., Zigler-Devin, I., Liu, C., Tang, Y.T., Qiu, R.L., Morel,
691 J.L., Brosse, N., 2021. Industrial ramie growing on reclaimed ion-adsorption
692 rare earth elements mine tailings in southern China: defibration and fibers
693 quality. *Waste Biomass Valori.* <https://doi.org/10.1007/s12649-021-01442-w>.

694 Shi, K., Liu, C., Liu, D., Lyu, K., Chen, J., Wang, X., 2021. The accumulation and effect
695 of rare earth element neodymium on the root of rice seedlings. *Environ Sci*
696 *Pollut Res.* 28, 48656–48665.

697 Shi, Y.L., Zhang, M., Yao, N., Zeng, P., Feng, B., Chen, M., Li, F.D., Zhang, Y.Z., 2020.
698 Water pollution status and nitrogen pollution distribution patterns around ion
699 absorbed rare earth tailings in Dingnan county, Jiangxi province. *Res Environ*
700 *Sci.* 23, 94–103. (*in Chinese*)

701 Tyler, G., 2004. Rare earth elements in soil and plant systems - A review. *Plant Soil.*
702 267, 191–206.

703 Wang, Z.W., Shan, X.Q., Zhang, S.Z., 2001. Comparison of speciation and
704 bioavailability of rare earth elements between wet rhizosphere soil and air-dried
705 bulk soil. *Anal Chim Acta.* 441, 147–156.

- 706 Wang, L., Ji, B., Hu, Y., Liu, R., Sun, W., 2017. A review on in situ phytoremediation
707 of mine tailings, *Chemosphere*, 184, 594–600.
- 708 Wang, L., Li, J., Zhou, Q., Yang, G., Ding, X. L., Li, X., Cai, C.X., Zhang, Z., Wei, H.
709 Y., Lu, T. H., Deng, X. W., Huang, X. H., 2014. Rare earth elements activate
710 endocytosis in plant cells. *Proc Natl Acad Sci U.S.A.* 111, 12936–12941.
- 711 Wen, X.J., Duan, C.Q., Zhang, D.C., 2013. Effect of simulated acid rain on soil
712 acidification and rare earth elements leaching loss in soils of rare earth mining
713 area in southern Jiangxi Province of China. *Environ. Earth Sci.* 69, 843–853.
- 714 Wei, F.S., Liu, T.L., Teng, E.J., Rui, K.S., 1991. 15 Rare Earth Elements in Chinese
715 Soil. *Environ Sci.* 12, 78–82. (*in Chinses*)
- 716 Wei, Z.G., Yin, M., Zhang, X., Hong, F.S., Li, B., Tao, Y., Zhao, G.W., Yan, C.H., 2001.
717 Rare earth elements in naturally grown fern *Dicranopteris linearis* in relation to
718 their variation in soils in South-Jiangxi region (Southern China). *Environ Pollut.*
719 114, 345–355.
- 720 Wei, Z.W., Hao, Z.K., Li, X.H., Guan, Z.B., Cai, Y.J., Liao, X.R., 2019. The effects of
721 phytoremediation on soil bacterial communities in an abandoned mine site of
722 rare earth elements. *Sci Total Environ.* 670, 950–960.
- 723 Wiche, O., Kummer, N.A., Heilmeier, H., 2016. Interspecific root interactions between
724 white lupin and barley enhance the uptake of rare earth elements (REEs) and
725 nutrients in shoots of barley. *Plant Soil.* 402, 235–45.
- 726 Wu, S., Xue, S., Iqbal, Y., Xing, H., Jie, Y., 2021. Seasonal nutrient cycling and

727 enrichment of nutrient-related soil microbes aid in the adaptation of ramie
728 (*Boehmeria nivea* L.) to nutrient-deficient conditions. *Front Plant Sci.* 12:
729 644904.

730 Xiao, Y.F., Huang, X.W., Feng, Z.Y., Dong, J.S., Huang, L., Long, Z.Q., 2015. Progress
731 in the green extraction technology for rare earth from ion-adsorption type rare
732 earths ore. *Chin Rare Earths.* 36, 109–115. (*in Chinese*)

733 Yang, B., Zhou, M., Shu, W.S., Lan, C.Y., Ye, Z.H., Qiu, R.L., Jie, Y.C., Cui, G.X.,
734 Wong, M.H., 2010. Constitutional tolerance to heavy metals of a fiber crop,
735 ramie (*Boehmeria nivea*), and its potential usage. *Environ Pollut.* 158, 551–558.

736 Yang, X.J., Lin, A.J., Li, X.L., Wu, Y.D., Zhou, W.B., Chen, Z.H., 2013. China's ion-
737 adsorption rare earth resources, mining consequences and preservation. *Environ*
738 *Dev.* 8, 131–136.

739 Yuan, M., Guo, M.N., Liu, W.S., Liu, C., van der Ent, A., Morel, J.L., Huot, H., Zhao,
740 W.Y., Wei, X.G., Qiu, R.L., Tang, Y.T., 2017. The accumulation and
741 fractionation of rare earth elements in hydroponically grown *Phytolacca*
742 *americana* L. *Plant Soil.* 1–16.

743 Zhang, P., Ma, Y.H., Zhang, Z.Y., He, X., Guo, Z., Tai, R.Z., Ding, Y.Y., Zhao, Y.L.,
744 Chai, Z.F., 2012. Comparative toxicity of nanoparticulate/bulk Yb₂O₃ and
745 YbCl₃ to cucumber (*Cucumis sativus*). *Environ Sci Technol.* 46, 1834–1841.

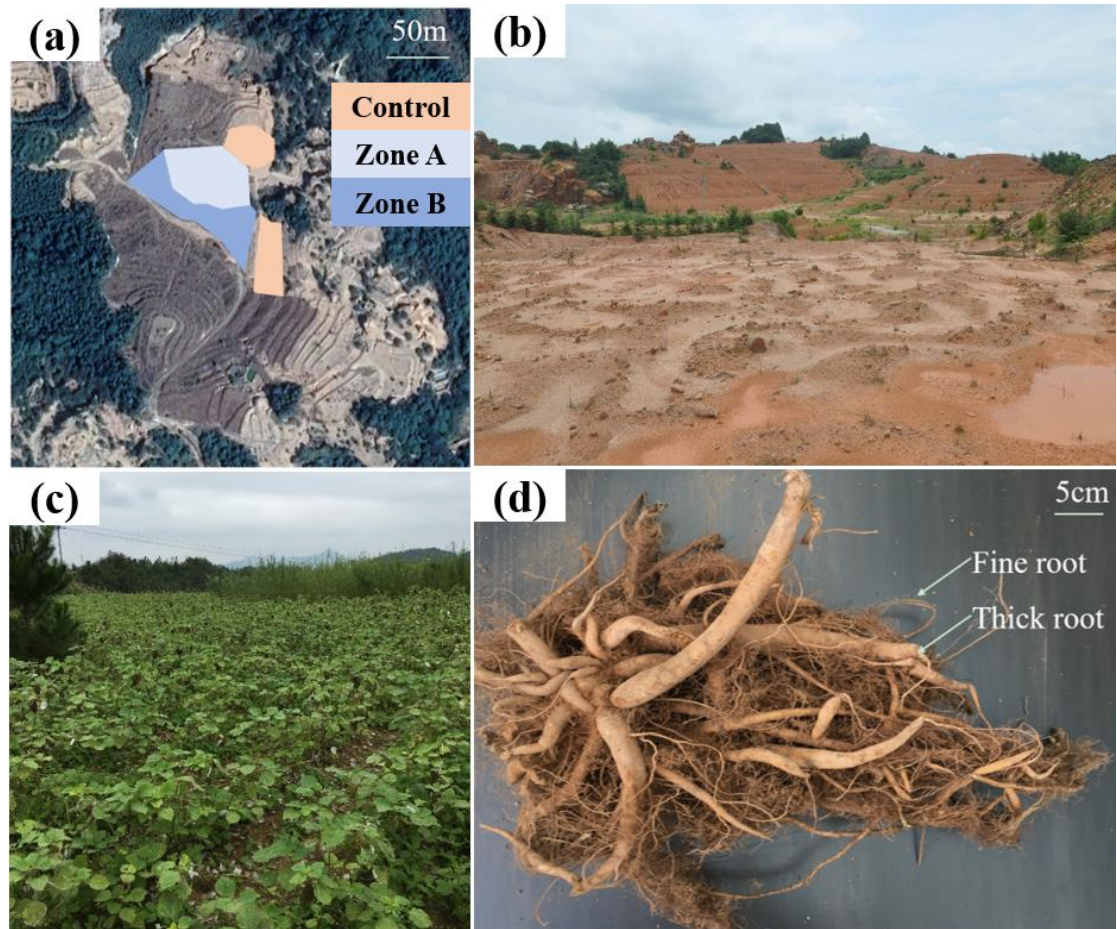
746 Zhao, C.M., Shi, X., Xie, S.Q., Liu, W.S., He, E.K., Tang, Y.T., Qiu, R.L., 2019.
747 Ecological risk assessment of neodymium and yttrium on rare earth element

748 mine sites in Ganzhou, China. *B Environ Contam Tox.* 103, 565–570.

749 Zhou, L.Y., Li, Z.L. Liu, W., Liu, S.H., Zhang, L.M., Zhong, L.Y., Luo, X.M., Liang.

750 H., 2015. Restoration of rare earth mine areas: organic amendments and

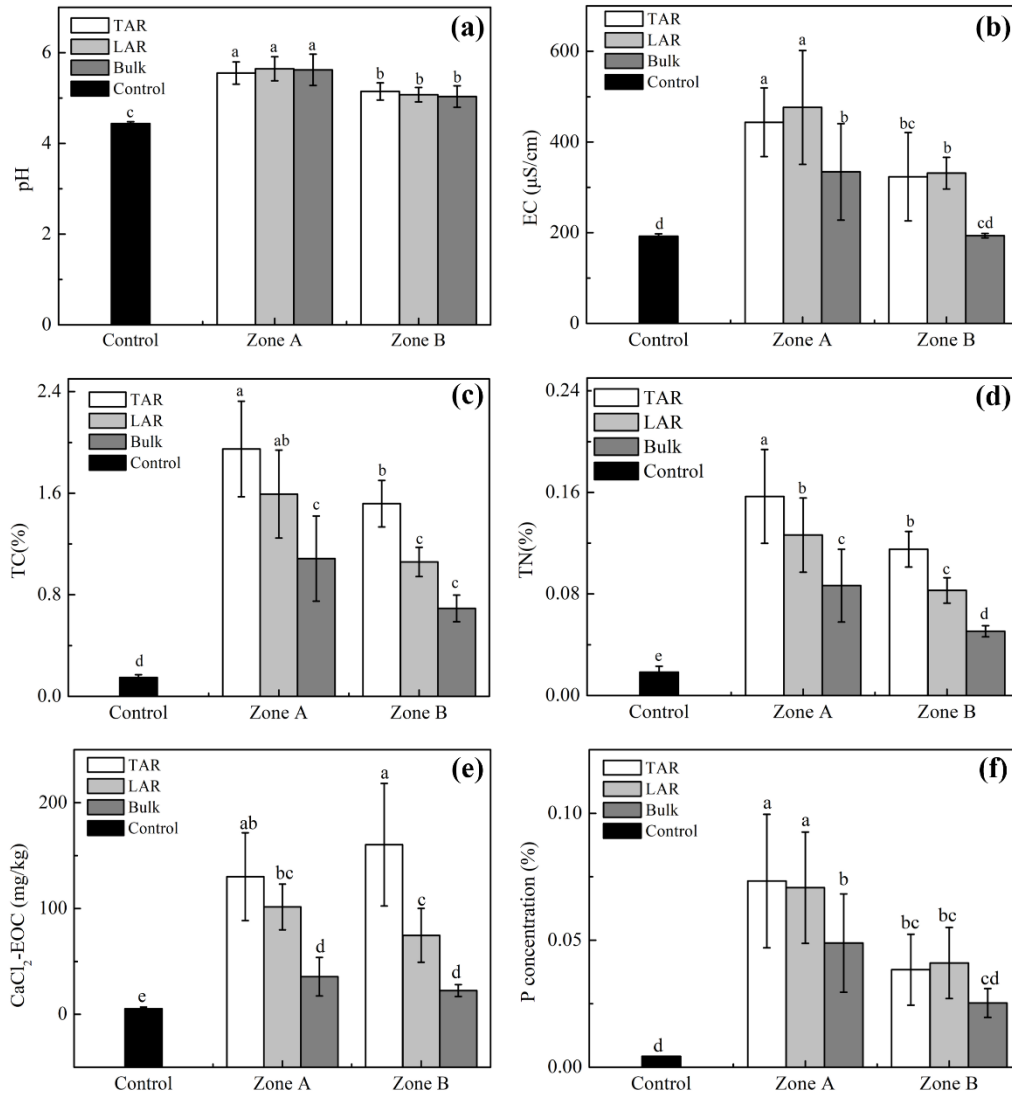
751 phytoremediation. *Environ Sci Pollut Res.* 22, 17151–17160.



752

753 Fig. 1. Location of the experiment plots in an ion-adsorption rare earth element mine
 754 tailing in South China (a); bare tailings without remediation (b); tailings after
 755 remediation by the addition of organic amendment and the planting of ramie (c); root
 756 structure of ramie plant grown in the tailings (d).

757 Zone A: the tailings were amended and planted with an annual fiber plant in 2015; plants were then
 758 removed, and the tailings were amended again and planted with ramie in 2016; Zone B: the tailings were
 759 amended and planted with ramie in 2015; the aboveground parts of ramie plants were harvested and
 760 fertilizers (N/P/K) was added in 2016.



761

762 Fig. 2. Selected chemical properties in bulk and rhizosphere (LAR and TAR) soil

763 fractions in amended and planted tailings (zones A and B) and in bare tailings (control):

764 pH (a); electrical conductivity in soil CaCl₂ extracts (b); total concentrations of C (c);

765 total concentrations of N (d); CaCl₂-extractable concentrations of organic C (e); total P

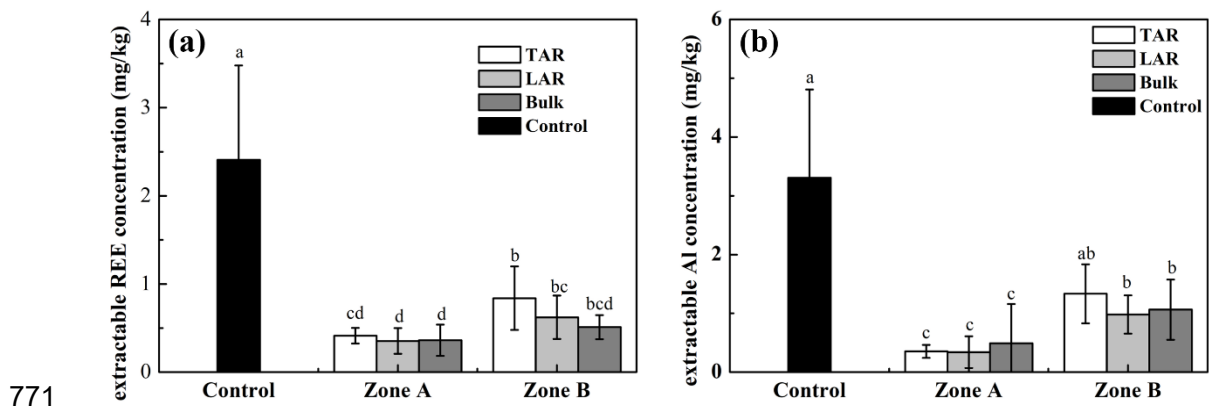
766 concentrations (f).

767 The bars represent the mean values and the error bars the standard deviation calculated on five samples

768 per zone. LAR, loosely adhering soil to roots; TAR, tightly adhering soil to roots. The significance tests

769 were conducted between all the soil groups (TAR, LAR and bulk soils from zones A and B and the

770 controls).



771

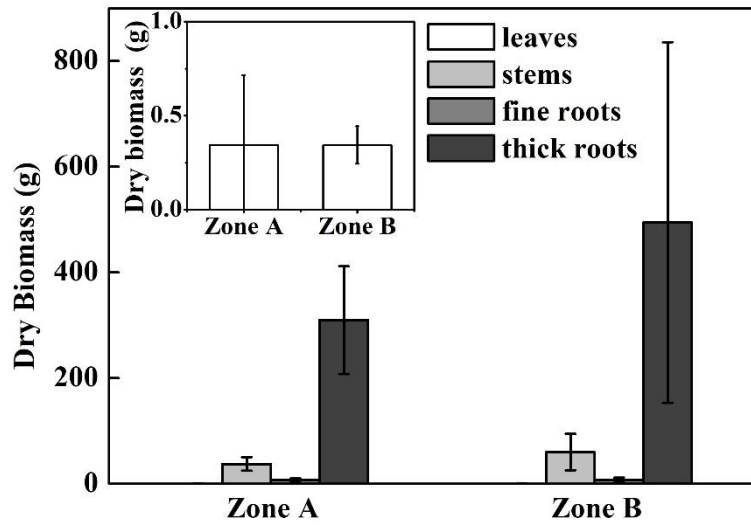
772 Fig. 3. CaCl₂-extractable concentrations of rare earth elements (a) and of Al (b) in bulk
 773 and rhizosphere (LAR and TAR) soil fractions in amended and planted tailings (zones
 774 A and B) and in bare tailings (control).

775 The bars represent the mean values and the error bars the standard deviation calculated on five samples

776 per zone. LAR, loosely adhering soil to roots; TAR, tightly adhering soil to roots. The significance tests

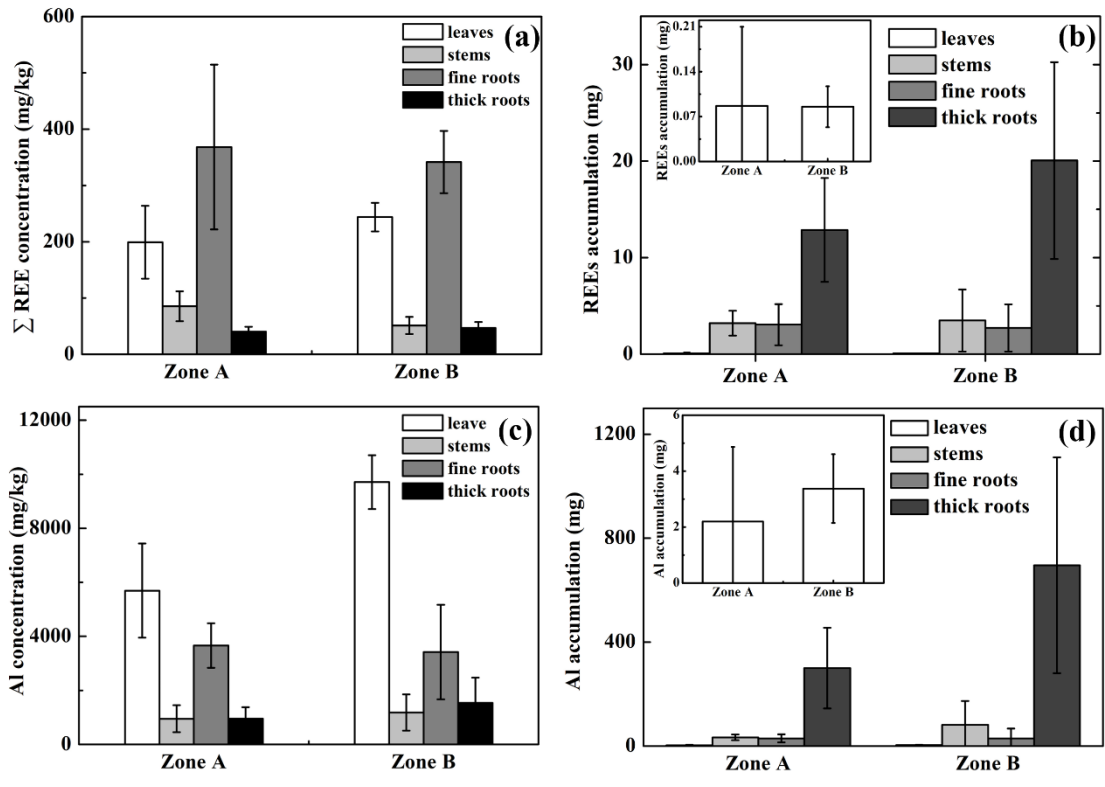
777 were conducted between all the soil groups (TAR, LAR and bulk soils from zones A and B and the

778 controls).



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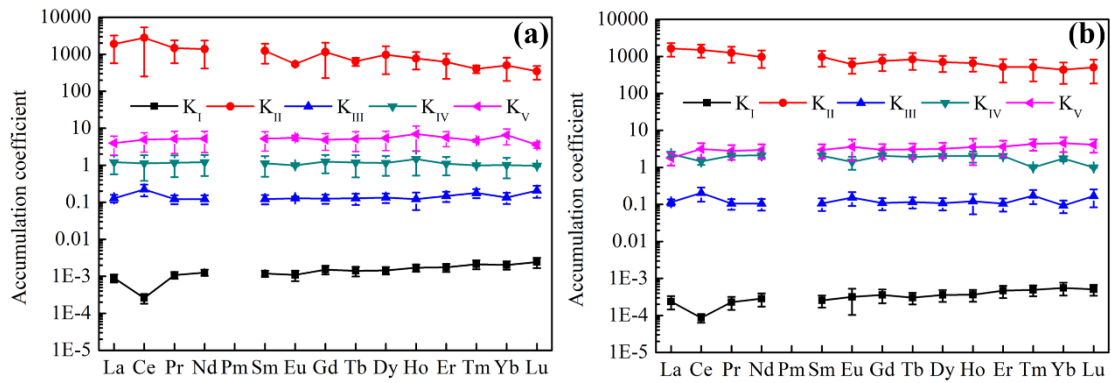
780 Fig. 4. Dry biomass of different organs of the ramie plant (mean \pm s.d. n=5)



781

782 Fig. 5. Rare earth elements concentrations (mg/kg) (a) and accumulated quantities
 783 mg/plant) (b), Al concentrations (mg/kg) (c) and accumulated quantities (mg/plant) (d)
 784 in the different plant organs of ramie grown on two zones (A and B) of reclaimed ion-
 785 adsorption REE mine tailings. The elemental accumulation was calculated as the
 786 product of elemental concentration and the organ biomass of ramie.

787



788

789 Fig. 6. Patterns of rare earth elements (REE) transfer factors in the soil-ramie system in
 790 the zone A (a) and the zone B (b). Steps I, TAR soil total REE concentrations to TAR
 791 soil CaCl₂-extractable REE concentrations; II, TAR soil CaCl₂-extractable REE
 792 concentrations to fine root REE concentrations; III, fine root REE concentrations to
 793 thick root REE concentrations; IV, thick root REE concentrations to stem REE
 794 concentrations; V, stem REE concentrations to leaf REE concentrations.

795 LAR, loosely adhering soil to roots; TAR, tightly adhering soil to roots.

796

797 Table 1 Correlation matrix of selected physico-chemical properties of bare and reclaimed tailings (bulk and rhizosphere soils)

	pH	EC	TC	TN	Fe	Al	Mn	K	Ca	P	Si	REEs	E-Al	E-REEs
pH	1													
EC	0.75*	1												
TC	0.77*	0.85*	1											
TN	0.75*	0.87*	0.99*	1										
Fe	0.17	0.11	0.10	0.10	1									
Al	0.28	0.23	0.22	0.26	0.14	1								
Mn	0.59*	0.67*	0.58*	0.59*	0.27	0.46*	1							
K	0.07	-0.14	0.14	0.09	-0.05	-0.00	-0.30	1						
Ca	0.90*	0.91*	0.89*	0.90*	0.14	0.29	0.66*	-0.06	1					
P	0.83*	0.90*	0.90*	0.90*	0.14	0.27	0.70*	-0.03	0.95*	1				
Si	-0.70*	-0.72*	-0.79*	-0.80*	-0.24	-0.76*	-0.70*	-0.06	-0.78*	-0.77*	1			
REEs	0.76*	0.78*	0.64*	0.67*	0.09	0.50*	0.74*	-0.28	0.83*	0.82*	-0.74*	1		
E-Al	-0.71*	-0.45*	-0.58*	-0.55*	-0.31	-0.31	-0.26	-0.28	-0.59*	-0.59*	0.62*	-0.38*	1	
E-REEs	-0.69*	-0.39*	-0.55*	-0.52*	-0.20	-0.35*	-0.13	-0.50*	-0.54*	-0.52*	0.59*	-0.34*	0.93*	1

798 The values in the matrix are the Pearson correlation coefficient (R) between element concentrations. The higher the R value is, the higher degree of correlation (positive or
799 negative) between the two physico-chemical properties. The * refers to the significance level of the correlation (p-value), * p<0.05.

800 E: CaCl₂-extractable concentration

801 Table 2 Correlation matrices of TAR soil physico-chemical properties, fine root morphology indicators and composition, and plant REE
 802 accumulation

	Fine roots				Whole plant	TAR						
	REE	P	Ca	Al	REE	pH	TC	P	E-Al	E-Mg	E-Si	E-REE
TL	0.71*	0.96*	0.92*	0.83*	0.65*	0.84*	0.68*	0.71*	-0.37	0.82*	0.65*	-0.30
SA	0.71*	0.97*	0.95*	0.86*	0.71*	0.80*	0.64*	0.67*	-0.32	0.80*	0.60	-0.25
RV	0.70*	0.98*	0.97*	0.88*	0.77*	0.74*	0.58	0.62	-0.25	0.76*	0.53	-0.17
AD	-0.31	-0.58	-0.46	-0.40	0.01	-0.79*	-0.65*	-0.66*	0.71*	-0.67*	-0.80*	0.72*
L (0-0.2)	0.69*	0.89*	0.82*	0.80*	0.55	0.81*	0.62	0.67*	-0.44	0.70*	0.56	-0.49
L (0-2)	0.70*	0.96*	0.93*	0.81*	0.67*	0.82*	0.68*	0.71*	-0.34	0.85*	0.67*	-0.22
SRL	0.47	0.49	0.29	0.23	-0.10	0.73*	0.77*	0.73*	-0.60	0.62	0.83*	-0.58
SRA	0.43	0.34	0.14	0.08	-0.16	0.54	0.67*	0.62	-0.44	0.46	0.70*	-0.43
SFRP	-0.26	0.15	0.08	0.05	-0.29	0.26	0.11	0.20	-0.76*	0.11	0.37	-0.84*
RTD	-0.01	-0.34	-0.08	0.19	0.18	-0.05	-0.31	-0.23	-0.05	-0.05	-0.24	-0.03

803 The values in the matrix are the Pearson correlation coefficient (R) between element concentrations and plant characteristics. The higher the R value is, the higher degree of
 804 correlation (positive or negative) between the two physico-chemical properties. The * refers to the significance level of the correlation (p-value), * p<0.05.

805 E: CaCl₂-extractable concentrations; L (0-0.2): root length for roots with a diameter 0.00<d<=0.20 mm; L (0-2): root length for roots with a diameter 0.00<d<=2.00 mm. TL,
 806 fine root length; SA, surface area; AD, average diameter; RV, volume (RV); SRL, specific root length; SRA, specific root surface area; SFRP, small fine root percentage.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

None.

Credit authorship contribution statement

Chang Liu: Conceptualization, Methodology, Investigation, Writing - Original Draft, Visualization. **When-Shen Liu, Hermine Huot:** Methodology, Investigation, Writing - Review & Editing. **Mei-Na Guo, Shi-Chen Zhu, Hong-Xiang Zheng:** Methodology, Investigation. **Jean Louis Morel, Ye-Tao Tang, Rong-Liang Qiu:** Methodology, Investigation, Supervision, Writing - Review & Editing, Funding acquisition.