



1 **Conquering Soil Acidification: The Synergistic Effects of**
2 **Basalt Powder, Lime, and P**
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25 **Abstract**

26 Soil acidification poses a substantial threat to agricultural productivity by releasing
27 salt ions, diminishing soil fertility, and increasing susceptibility to aluminum toxicity.
28 The aim of the study was to investigate the potential improvement of acid yellow soil
29 through the combined application of basalt powder, lime, and polyacrylamide (PAM).
30 Herein, 0.1 g mixed basalt powder and CaO with various proportion were added to 10
31 g acidic yellow soil with an initial pH of 4.16 to explore the efficient of mixed soil
32 amendments. X-ray fluorescence (XRF) analysis of basalt powder revealed its
33 effectiveness in supplementing soil mineral nutrients. The optimal results of reduced
34 acidification and ion leaching of soil were obtained when the addition proportion of
35 basalt powder to lime was 8/2 and addition ratio of PAM was 0.0002%. The addition
36 of mixed amendments markedly increased the pH (by up to >2.0 units) and acid-damage
37 capacity (20.3mmol/kg) of soil, meanwhile decreased the leaching of K⁺(58.1%),
38 Na⁺(42.9%), Mg²⁺(26.3%), and Al³⁺ (below the detectable limit) as shown by the
39 optimal tests. The basalt powder undergoes decomposition in the soil solution, resulting
40 in the formation of some weak acids (i.e., H₂SiO₄), the release of OH⁻, and an increase
41 in soil pH. The study reveals the underlying mechanisms of soil remediation with mixed
42 amendment, which has potential guidance for the application of mixed soil amendment
43 and the environment risks prediction of contaminated soil.
44 Keywords: soil acidification; mixed amendment; pH; acid-damage capacity; salt ions



45 **1. Introduction**

46 Soil degradation poses a significant menace to soil health and adverse effects on
47 human productivity, thereby garnering global attention. The various forms of soil
48 degradation encompass soil acidification, soil erosion, soil pollution, fertility depletion,
49 and so on (Kopittke et al., 2012; Liu et al., 2022; Nguyen, 2023; Xu, 2015) . Soil
50 acidification, caused by the increase of H^+ or Al^{3+} concentration, poses a threat to the
51 survival of plants and microorganisms in soil. Meanwhile, the acidification of soil
52 results in an elevation of H^+ and Al^{3+} , which compete with Ca^{2+} , Mg^{2+} , K^+ , Na^+ , and
53 other salt nutrient ions for exchange sites. Consequently, a significant quantity of salt
54 ions are leached, further intensifying the acidification and diminishing soil fertility
55 (Alekseeva et al., 2011; Holland et al., 2018; Huang et al., 2017; Swoboda et al., 2022).
56 Furthermore, in acidic environments, the enhanced solubility of aluminum increased
57 aluminum uptake subsequently in plants and hindered the absorption of iron,
58 magnesium, and calcium, resulting in a deficiency of these essential nutrients and
59 ultimately leading to plant toxicity (Alekseeva et al., 2011; Goulding, 2016; Joris et al.,
60 2013; Nguyen, 2023; Palansooriya et al., 2020; Rahman et al., 2018). Simultaneously,
61 the heavy metal ions present in soil become activated under acidic conditions, thereby
62 potentially leading to heavy metal pollution. Meanwhile, acidified soils exhibit
63 diminished organic matter content and compromised physical structure, thereby
64 predisposing them to soil slumping (Xu, 2015).

65 The addition of soil amendments is a crucial method for enhancing the physical
66 and chemical characteristics as well as the fertility of acidic soil. Currently, acid soil
67 amendments are categorized into three types: single amendments, composite
68 amendments, and mixed amendments (Liu et al., 2022). Single modifiers mainly
69 include lime modifiers (e.g., quicklime, limestone, and slaked lime), minerals (e.g.,



70 basalt powder and hydroxyapatite), industrial by-products (e.g., phosphogypsum, fly
71 ash, and alkali residue), and organic modifiers (e.g., biochar and polyacrylamide
72 (PAM)) (Aquino et al., 2020; Liu et al., 2022; Sun et al., 2020).

73 The utilization of lime to ameliorate soil acidity in agricultural areas is a long-
74 standing agricultural practice and has been subject to thorough investigation (Haque et
75 al., 2020; Mosharrof et al., 2021; Swoboda et al., 2022). Lime possesses the ability to
76 counteract both active and latent soil acids, precipitate hydroxides, mitigate aluminum
77 toxicity, promptly and efficiently diminish the acidity of acidic soils. Furthermore,
78 addition of lime enhances the exchangeable calcium content of the soil and augments
79 the efficacy of soil nutrients (Goulding, 2016; Holland et al., 2018; Joris et al., 2013;
80 Nguyen, 2023). Simultaneously, the transformation of heavy metals into biologically
81 unattainable forms occurs with the addition of lime, thus mitigating the potential for
82 environmental toxicity (Alekseeva et al., 2011). Nevertheless, the extensive and
83 prolonged utilization of lime can potentially give rise to issues such as soil caking,
84 nutrient imbalance, and subsequent pH rebound effects (Ding et al., 2023; Fageria and
85 Baligar, 2008).

86 In addition to the lime, the amendment of ground silicate rock powders (SRPs)
87 could improve soil properties effectively. However, there is little research on the
88 utilization of SRPs in the form of silicate, despite their multifaceted role in replenishing
89 soil nutrients, enhancing soil pH, alleviating aluminum toxicity, and ultimately
90 improving crop yields. The limited application was caused by the slow and inconsistent
91 weathering rate of SRPs (Anda et al., 2015; Gillman et al., 2002; Haynes, 2014; Kleiv
92 and Thornhill, 2007; Nunes et al., 2014; Panhwar et al., 2014). Numerous scholars have
93 conducted research on the dissolution kinetics of silicate rock powders, demonstrating
94 that while they cannot fully replace lime-based amendments in terms of soil acid



95 neutralization, they do present notable benefits in terms of environmental sustainability
96 and nutrient enrichment (Celimar Dalmora et al., 2020; Heřmanská et al., 2023;
97 Swoboda et al., 2022). Hence, further investigation of the mixed modifier and
98 weathering mechanism is warranted. Moreover, driven by the principles of
99 environmental sustainability and resource efficiency, the organic polymer (such as
100 PAM) is increasingly being utilized for soil enhancement. Previous studies indicated
101 that PAM primarily regulated soil through the augmentation of soil aggregates, the
102 enhancement of overall soil porosity, and the prevention of soil compaction (Sang et
103 al., 2023; Zhang et al., 2023). Additionally, its adsorption capabilities contributed to
104 the improved retention of nutrients and water in the soil, mitigation of soil erosion and
105 wind erosion control (Xuan et al., 2023). Moreover, the utilization of PAM has been
106 found to enhance agricultural productivity by augmenting crop yield and enhancing
107 crop quality (Mulualem et al., 2021).

108 The research on mixed modifiers is still in its early stages and often involves
109 intricate preparation procedures. This thesis employed basalt as the primary material,
110 supplemented with a specific proportion of CaO, for the remediation of acidic soil.
111 Additionally, a certain quantity of PAM was introduced to examine the impact and
112 underlying remediation mechanisms of combined application of these three
113 amendments on acidification control and salt ions leaching in acidic soils. It is worth
114 noting that the three materials under investigation are readily available, cost-effective,
115 and have no adverse environmental impact. The combination of these materials may
116 offer novel approaches to enhancing acidic soil.

117 **2. Materials and methods**

118 **2.1. Soil**

119 The experimental soil sample was obtained from Jiangxi Province, China and



120 classified as yellow loam. The soil exhibited a pH value of 4.16, an organic matter
121 content of 12.91 mg/kg (Zhang et al., 2022). The mechanical and chemical
122 compositions are presented in Table 1 and Table 2.

123 2.2. Amendments

124 Lime powder (> 98.0%) and PAM (molecular weight ≥ 3 million) were purchased
125 from Chengdu Cologne Chemical Co., Ltd. The tested basalt powder was chosen from
126 preliminary experiment based on the pH value. Five original basalt samples, collected
127 in Sichuan, China, were pulverized to a particle size and passed through a 400-mesh
128 sieve. The pH values of five powders were 9.57, 9.66, 9.46, 9.71, and 9.18, respectively,
129 wherein the powder with the highest pH value (pH=9.71) was selected based on the
130 potential for acid soil improvement for further structural analysis and soil amendment
131 test. The concentrations of light and heavy elements present in basalt powder were
132 determined using X-ray fluorescence spectroscopy conducted by a CIT-3000SY X-ray
133 fluorescence spectrometer. The sample analyzed was a dense basalt with minimal
134 weathering, sporadic air holes, and a quartz filler.

135 2.3. Experimental design and suspension preparation

136 1% amendment of PAM did not effectively change the soil pH according to the
137 preliminary experiments with varied proportion addition of PAM, as the pH value of
138 PAM was almost neutral and had negligible impact on pH regulation. Consequently,
139 the addition of PAM in tests was set to a constant (0.0002%) based on pre-experiment.
140 The aim of this study is to adjust the soil pH to a nearly neutral level and examine the
141 impact of modifiers on the base and aluminum ions leaching, and thus CaO was added
142 into each experimental group due to its excellent acid improvement effect in soil. The
143 basalt powder was added in each experimental group as a base component in mixed



144 amendments. The total mass of basalt powder and CaO added in each experiment was
145 0.1 g, but with varied additive proportion. A pre-experiment showed that the soil pH <
146 6 when the proportion of basalt powder $\geq 90\%$, and soil pH value > 9 when the
147 proportion of basalt powder $\leq 60\%$. Accordingly, the proportion of basalt powder was
148 set at 90%, 80%, 70%, and the experiment design was shown in Table 3.

149 The suspension was prepared by initially measuring 10 g soil samples in a beaker,
150 followed by the addition of the appropriate quantities of powder and CaO as indicated
151 in Table 3. 25ml distilled water was added and then shaken evenly. In addition, 25ml
152 of $8.0 \times 10^{-6} \text{ g} \cdot \text{ml}^{-1}$ PAM solution was added in the experimental groups. The mixture
153 was sealed with a plastic film to prevent contamination, and left undisturbed for 2 days.
154 All test groups were marked as shown in Table 3.

155 2.4. Acid damage capacity

156 Soil acid damage capacity was defined as the quantity of acid necessary for a given
157 unit of soil to reach the threshold pH value at which plant damage occurs, thereby
158 indicating the soil's resilience to acidity. Herein, the soil acid damage capacity was
159 determined by the amount of acid required per unit of soil when the pH value reached
160 3.5 (Wang, 1994; Ma et al., 2020).

161 The pH measurement of soil suspension was conducted in 50 ml centrifuge tube.
162 10 g soil samples were added in 50 ml centrifuge tube and shook evenly with 25 mL
163 distilled water. After shaking for 1 hour using a bifunctional water bath constant
164 temperature oscillator, the original pH value of soil was measured. Soil sample pH was
165 adjusted by 1mol/L sulfuric acid using a micro-injector. After the addition of 1mol/L
166 sulfuric acid and shaking for 10 min, the soil pH was measured and documented. The
167 procedures of sulfuric acid addition were repeated until the soil suspension pH dropped
168 to 3.5, and the quantity of added acid was adjusted based on the last measured pH value.



2.5. Leaching and adsorption of ions

In the context of soil ion leaching, a 10 g sample of soil was carefully measured. Amendments were subsequently incorporated based on the specific experimental group conditions, and then 25ml of distilled water was added to the soil sample and thoroughly mixed before being allowed to settle for a duration of 2 days. The resulting soil suspension was then transferred to a 50 ml centrifuge tube and subjected to agitation on a water bath constant temperature oscillator for a period of 1.5 hours. Subsequently, a predetermined quantity of acid was introduced, and the mixture was vigorously shaken for an additional 2 hours. In the ion adsorption experiment of PAM, a mixture was prepared using the PAM solution and ion standard solution. The resulting mixture had a PAM concentration of $8 \times 10^{-5} \text{ g} \cdot \text{ml}^{-1}$ and contained K^+ , Na^+ , Ca^{2+} , Mg^{2+} and Al^{3+} at concentrations of $100 \text{ } \mu\text{g} \cdot \text{ml}^{-1}$, $100 \text{ } \mu\text{g} \cdot \text{ml}^{-1}$, $100 \text{ } \mu\text{g} \cdot \text{ml}^{-1}$, $100 \text{ } \mu\text{g} \cdot \text{ml}^{-1}$, $20 \text{ } \mu\text{g} \cdot \text{ml}^{-1}$, respectively. To ensure the adsorption equilibrium was achieved, the mixture was allowed to stand undisturbed for a period of 2 days. The aqueous solutions were separated by centrifuging at 1500 r/min for 10 min using a TDL-80-2B low-speed centrifuge. The concentrations of K^+ , Na^+ , Ca^{2+} , and Mg^{2+} were determined using an AA-7001 atomic absorption spectrophotometer at 766.5nm (K^+), 589.0 nm (Na^+), 422.7 nm (Ca^{2+}) and 285.2 nm (Mg^{2+}), while the concentration of Al^{3+} was determined using a UV-5500 ultraviolet-visible spectrophotometer at 660 nm.

3. Results

3.1. Mineral and chemical composition of basalt powder

Mineral nutrients play a crucial role in the plant growth and quality improvement of agricultural products, and primarily obtained through mineral weathering and decomposition processes. The main mineral composition of basalt powder, as shown in Fig.2, included pyroxene $((\text{Ca}, \text{Na})(\text{Mg}, \text{Fe}, \text{Al}, \text{Ti})(\text{Si}, \text{Al})_2\text{O}_6)$,



194 feldspar((Na,K,Ca)Al₂Si₃O₈), serpentine ((Mg,Fe)₃(Si₂O₅)(OH)₄), and quartz (SiO₂).
195 The presence of serpentinite suggested that the basalt had undergone hydrothermal
196 alteration, while quartz served as the filling material within the basalt's pores.

197 The analysis of the chemical composition of basalt powder (Table 4) indicated the
198 presence of numerous nutrients essential for plant growth. The basalt powder utilized
199 in this study exhibited a notably high concentration of silicon oxide, reaching levels of
200 up to 45.72% by weight. The significance of Si accumulation lies in its ability to
201 alleviate the toxicity of specific heavy metals, enhance the uptake of K, P& Ca, mitigate
202 the impacts of drought, either bolster crop resilience against pathogens and pests (Flore
203 et al., 2012; Rinder and Hagke, 2021). The P, K, Mg, and Ca were the primary elements
204 constituting essential nutrient elements for plants. The Fe was trace elements essential
205 for plant growth. The Na and Ti were beneficial elements for plant growth. In addition
206 to the constituents outlined in the mineral chemical formula of basalt powder depicted
207 in Fig.2, there were additional elements that were essential for the formation of
208 accessory minerals or present within the mineral lattice through isomorphism. These
209 elements could also be released through the process of basalt weathering, with the
210 release of base ions being particularly noticeable. Several base ions were integral
211 components of the primary minerals found in basalt powder.

212 3.2. Variation of soil pH and acid damage capacity after amendments addition

213 All kinds of mixed amendments could significantly increase the soil pH at least 2
214 units as shown by Fig.3a. Notably, the highest soil pH value of mixed amendment with
215 and without PAM corresponded to the addition of BCP730 (7.86) and BCP731 (7.96),
216 respectively, which was higher than the optimum pH range (6.5-7.5) for plants growth.
217 The addition of BCP911 and BCP910 adjusted the soil pH to 6.22 and 6.26, respectively,
218 which was lower than the optimum pH range (6.5-7.5) for plants growth. Only BCP821



consistently adhered to the principle of adjusting soil pH within the optimal range of 6.5-7.5, accordingly facilitating plant growth. The process of soil acidification was simulated through acid soaking.

The acid damage capacity of the soil was determined by the ratio of acid consumption to soil mass ($\mu\text{mol}\cdot\text{g}^{-1}$) until the soil pH value decreased to 3.5 and as illustrated in Fig. 3b. The acid damage capacity of BCP821 was found to be 5 and 6.5 higher than that of BCP911 and BCP910, respectively. Furthermore, the addition of basalt powder and quicklime resulted in a more gradual acid buffering curve compared to the control group (Fig.4), which indicated that the mixed amendments were resistant to soil acidification and could significantly improve the soil's buffering capacity against acid.

3.3 Variation of soil salt ions and Al^{3+} leaching after amendments addition

Fig.5a demonstrated a notable decrease in the leaching of K^+ , Na^+ , and Mg^{2+} in BCP820 and BCP821 compared to the control group. Specifically, the leaching of K^+ , Na^+ , and Mg^{2+} in BCP821 decreased by 58.1%, 42.9%, and 26.3%, respectively. Similarly, the leaching of K^+ , Na^+ , and Mg^{2+} in BCP820 decreased by 50.3%, 35.4%, and 33.5%, respectively. Whereas, the leaching of Ca^{2+} experienced a substantial increase with the addition of BCP820 and BCP821.

The leaching of Al^{3+} in BCP820 was 37.2% lower than the control group, while the leaching of Al^{3+} in BCP821 was below the detectable limit. Generally, the leaching quantities of K^+ , Na^+ , Ca^{2+} , Mg^{2+} , and Al^{3+} exhibited an upward trend with the addition of acid in both the control and experimental groups, suggesting that the soil minerals, including the added basalt powder, underwent gradual decomposition in the acidic environment, resulting in the release of basic ions. Meanwhile, the decrease in soil pH also led to the gradual release of Al^{3+} (Fig. 5a-f.).



244 Based on the ion leaching data presented in Fig.5, several observations could be
245 made. Firstly, the leaching amount of Ca^{2+} , both during the initial stage and the acid
246 addition process, was considerably higher compared to the control group. Conversely,
247 the addition of PAM did not significantly affect the leaching results. Secondly, the
248 initial leaching of K^+ , Na^+ , Ca^{2+} , Mg^{2+} , and Al^{3+} was notably lower than that of the
249 control group. However, with the addition of PAM, there was a slight increase in the
250 leaching of K^+ and Na^+ , while the leaching of Ca^{2+} , Mg^{2+} , and Al^{3+} decreased. Thirdly,
251 the introduction of PAM resulted in a slight increase in the leaching of K^+ and Na^+ ,
252 while the leaching of Ca^{2+} , Mg^{2+} , and Al^{3+} decreased. Furthermore, the leaching amount
253 of Mg^{2+} and Al^{3+} ions in the experimental group was lower than the control group.
254 Additionally, the addition of PAM led to a decrease in the leaching rate of Mg^{2+} and an
255 increase in the leaching rate of Al^{3+} .

256 4. Discussion

257 4.1 Advantages of mineral structure for basalt powder

258 The weathering of basalt led to the liberation of nutrient elements inherent in the
259 rock, thereby enriching the soil's nutritional content. Furthermore, this process produces
260 silicic acid, releases OH^- ions, and raises the soil pH (Anda et al., 2015). The pace of
261 weathering is predominantly determined by the mineral composition, pH level, and
262 particle size of the rock powder. Statistical analyses of the dissolution rate of silicate
263 rocks as influenced by pH levels have revealed that Al-containing silicate rocks exhibit
264 the slowest dissolution rates in neutral environments (Rinder and Hagke, 2021).
265 Additionally, scholarly studies have proposed that silicate rocks rich in Mg content
266 weathering faster than rocks rich in Ca content (Deer et al., 2013; Swoboda et al., 2022).
267 This phenomenon can be explained by the bonding energy and characteristics of the
268 bonds present. The metallic bonds of Mg-O and Ca-O exhibit similarities in the



269 arrangement of electrons outside the nucleus, with Mg^{2+} and Ca^{2+} sharing comparable
270 electron configurations. However, calcium possesses a higher relative atomic mass,
271 stronger attraction, and greater bonding energy than magnesium. When selecting rock
272 powder for agricultural purposes, it is important to take into account not only the variety
273 of nutrient elements present, but also the mineral composition. Rocks with high basal
274 ultramafic magnesium content, such as basalt powder containing pyroxene and feldspar,
275 are rich in essential nutrients and are more easily weathered, making them a favorable
276 option in the application of soil conditioner.

277 In a recent study, Swoboda et al., (2022) conducted a comprehensive analysis was
278 conducted on the utilization of silicate rock powder for soil enhancement. The findings
279 indicated that smaller particles of the same rock powder exhibited a higher weathering
280 rate, thereby providing greater benefits to the improvement of soil nutrients and the
281 increase of crop yield. Furthermore, the investigation of Vanderkloot and Ryan (2023)
282 indicated that the weathering rate of particles $<45\mu m$ exhibits a twofold increase
283 compared to particles with a size of $150-500\mu m$. Furthermore, despite the fact that fine
284 particles could enhance the weathering rate of basalt powder, the long-term efficacy of
285 basalt powder in soil remained intact. Rinder and Hagke (2021) calculated the amount
286 of powder dissolved within a time frame of 10 years is approximately 16% ($<100\mu m$),
287 55% ($<10\mu m$) and 99.9% ($<1\mu m$).

288 Herein, the basalt powder possessed a particle size of approximately $38\mu m$, and
289 the predominant rock-forming minerals were pyroxene and serpentine, which were rich
290 in magnesium. These minerals contributed to enhancing the weathering rate to a certain
291 extent and it could maintain dissolving behavior more than 10 years based on the
292 calculation of Rinder and Hagke (2021). Therefore, the utilization of basalt powder can
293 serve as a valuable means to enhance the presence of essential nutrients and



294 advantageous elements within soil, thereby promoting the growth of crops.

295 4.2 Effect of amendments in soil pH and acid damage capacity

296 The study conducted by Panhard et al., (2014) demonstrated that the application
297 of Ground magnesium limestone and bio-fertilizer at a rate of 4 tons/hectare resulted in
298 a maximum increase in soil pH from 3.8 to 5.4, representing a change of 1.6 units.
299 Similarly, Huang et al., (2017) found that the application of 40 tons biochar per hectare
300 increased soil pH from 5.76 to 5.89, indicating a change of 0.13 units. This study has
301 demonstrated significant enhancements in soil pH through the application of a basalt
302 powder and CaO mixture at a ratio of 8:2, resulting in an increase in soil pH from 4.16
303 to 6.86. Additionally, the substantial buffering capacity of the additive has led to a
304 considerable increase in the soil's acid damage capacity, with improvements of at least
305 300%.

306 CaO was the primary determinant of soil pH increase as shown by the positive
307 correlation between the addition amounts of CaO and soil pH (Fig. 3a). The soil acidity
308 or alkalinity enhanced by soil amendment involved the rapid reaction of CaO with the
309 soil solution, accordingly resulting in the generation of a significant quantity of OH⁻.
310 and facilitates the adjustment of soil pH levels. Additionally, the reaction can be
311 contributed to the addition of basalt powder, too. However, it is important to note that
312 the decomposition of basalt powder is heavily influenced by the pH value of the soil
313 solution. Specifically, a lower pH value promotes a more favorable weathering process
314 (Swoboda et al., 2022). The swift elevation of soil pH subsequent to the application of
315 lime hinders the weathering process of basalt powder, thereby indicating its enduring
316 impact and expediting said process during soil erosion caused by acidity. The release
317 of OH⁻ serves to increase the soil pH value, thus establishing a mutually beneficial
318 association between the two. PAM exhibited near neutrality and exerts minimal



319 influence on soil pH value due to its minute dosage and weak efficacy.

320 4.3 Effect of amendments in salt-based ion leaching

321 To provide a more comprehensive explanation of the ion leaching results,
322 supplementary adsorption experiments of PAM on ions (Fig.6) and the ion release of
323 basalt powder (Fig.7) were conducted. Similar trend was observed in the acid soaking
324 experiment of basalt powder (Fig. 7). The acid (1mol/L H₂SO₄) presented in the basalt
325 powder within the range of 0-500umol (adjusted for concentration conversion)
326 underwent a rapid decomposition phase followed by a slower rate of change as shown
327 by Fig. 7b, which can be attributed to the unstable structure and properties of the basalt
328 powder, leading to the decomposition of minerals under acidic conditions. The
329 observation is further supported by the mineral composition analysis of the basalt
330 powder, which indicated that minerals such as pyroxene and serpentine, with higher
331 iron and magnesium content, were more susceptible to weathering. Additionally, it is
332 worth noting that pyroxene exhibited higher calcium content than other components.
333 Hence, the process of basaltic acid soaking resulted in a greater release of Ca²⁺ and
334 Mg²⁺.

335 The large increase in Ca²⁺ leaching did not imply that the mixing amendments had
336 a deleterious effect on soil calcium ions, because CaO reacted with the soil solution to
337 rapidly produce large amounts of Ca²⁺ (Fig. 5a), and basalt powder decomposition also
338 produced a certain amount of Ca²⁺ (Fig. 7). These processes effectively replenished soil
339 Ca²⁺. The reduction of K⁺, Na⁺, Mg²⁺ and Al³⁺ leaching by the mixed amendment can
340 be attributed to several factors. Firstly, the inclusion of basalt powder with fine particles
341 resulted in a significant increase in specific surface area. The enhanced surface area was
342 characterized by the presence of hydroxyl groups (-OH) and negatively-charged
343 functional groups (Si-O), which exhibited superior ion adsorption capabilities.



344 Moreover, previous studies had explored the utilization of fine silicate rock powder as
345 effective adsorbents and filter membranes (Ouyang et al., 2019; Zhang et al., 2021).
346 Additionally, PAM exhibited a high adsorption capacity and demonstrated superior
347 adsorption properties for the three types of ions (Fig. 6). Furthermore, the elevation of
348 pH levels results in the conversion of Al^{3+} to $\text{Al}(\text{OH})_3$, thereby intensifying the negative
349 charge on the soil colloid surface and consequently facilitating the adsorption of basic
350 cations.

351 The addition of PAM resulted in a slight increase in the leaching of K^+ and Na^+ ,
352 while the leaching of Ca^{2+} , Mg^{2+} , and Al^{3+} decreased. The different trends of ions could
353 be attributed to the mutual adsorption between basalt powder and PAM, which could
354 occupy the cation adsorption sites. The large charge of Ca^{2+} , Mg^{2+} , and Al^{3+} allowed
355 them to preferentially occupy the adsorption sites in the competitive adsorption of ions,
356 thereby reducing leaching amounts. Conversely, the reduced availability of residual
357 sites for K^+ and Na^+ led to an increase in their leaching amounts. During the simulated
358 acidification process, the leaching of K^+ and Na^+ in BCP821 consistently surpassed that
359 of BCP820, indicating the persistent effect of PAM in BCP821. Notably, when the
360 quantity of acid added exceeded $240\ \mu\text{mol}$, the leaching of K^+ in BCP821 exceeded that
361 of the control group. Similarly, when the quantity of acid added surpassed $120\ \mu\text{mol}$,
362 the leaching of Na^+ in BCP821 exceeded the control group. The disparity was likely
363 attributed to the release of elements during the decomposition of basalt powder and the
364 reduction of cation adsorption sites under acidic conditions.

365 The experimental group consistently exhibited a significantly lower leaching
366 amount of Mg^{2+} and Al^{3+} compared to the control group, which potentially attributable
367 to the stronger adsorption effect for Mg^{2+} and Al^{3+} with large charge in contrast to K^+
368 and Na^+ . In comparison to BCP820, the leaching rate of Mg^{2+} decreased in BCP821



369 while the leaching rate of Al^{3+} increased, which might be attributed to the adsorption of
370 PAM. Notably, the adsorption rate of Mg^{2+} by PAM was significantly higher than that
371 of Al^{3+} (Fig. 6). The adsorption capacity of PAM on Mg^{2+} is greater than the reduction
372 in adsorption capacity resulting from the mutual adsorption of PAM and basalt powder,
373 thereby occupying the adsorption site. However, this effect was insufficient for Al^{3+} .

374 5. Conclusion

375 This study examines the impact of a combination of basalt powder, CaO, and PAM
376 mixed modifier on soil enhancement. The findings indicated that the optimal pH (4.16
377 to 6.86) adjustment effect was achieved when the ratio of basalt powder to CaO is 8 to
378 2. Furthermore, the application of the mixed modifier demonstrated the potential for
379 soil nutrition supplementing, increased the acid-damage capacity (20.3 mmol/kg),
380 effective mitigation of K^+ , Na^+ , Mg^{2+} depletion, and aluminum toxicity reduction. The
381 results suggested that the combined utilization of these three modifiers holds promise
382 for improving the characteristics of acidic soil. However, variations in the chemical
383 composition and mineral structure of silicate rocks across different regions result in
384 distinct properties of soil. Consequently, it is imperative to conduct further research
385 tailored to the specific local conditions.

386 Author contribution

387 Qianmei Zhang (First Author): Conceptualization, Methodology, Investigation,
388 Writing - Original Draft, Writing - Review & Editing, Supervision;

389 Xiuhong Peng (Corresponding Author): Conceptualization, Resources, Writing -
390 Review & Editing, Supervision, Project administration;

391 Hongxia Zhu (Corresponding Author): Methodology, Investigation, Writing -
392 Review & Editing, Supervision.



393 **Competing interests**

394 The contact author has declared that none of the authors has any competing
395 interests.

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Caption of the Tables and Figures.

Table 1 Mechanical composition of tested soil.

Table 2 Main chemical composition of tested soil (%).

Table 3 Experimental groups and corresponding codes.

Table 4 Elemental content of basalt powder.

Figure 1 Collection and production of basalt powder.

Figure 2 X-ray diffraction spectroscopy of basalt powder.

Figure 3 The pH value of the soil after the amendments addition (a); Acid damage capacity of soil after the amendments addition (b).

Figure 4 Soil acid buffer curve.

Figure 5 Leaching amount of base salt ions and aluminum ions (a); Leaching amount of ions under simulated acidification conditions (b-f).

Figure 6 Adsorption of K^+ , Na^+ , Mg^{2+} , Ca^{2+} and Al^{3+} by PAM.

Figure 7 Ion leaching of basalt powder under neutral acidic condition.



Table 1 Mechanical composition of tested soil.

Composition	Clay		Powder	
Size (mm)	<0.005	0.01~0.005	0.05~0.01	0.075~0.01
Content (%)	43.1	11.1	28.8	5.6
Composition	Sand			
Size (mm)	0.25~0.075	0.5~0.25	1.0~0.5	
Content (%)	9.4	0.9	1.1	



Table 2 Main chemical composition of tested soil (%).

Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	K ₂ O	MnO	Na ₂ O	CaO	MgO
2.71	50.37	14.23	16.15	0.017	0.19	0.14	0.47



Table 3 Experimental groups and corresponding codes

Amendments (mg/g)	Control	BCP910	BCP820	BCP730	BCP911	BCP821	BCP731
Basalt powder	0	9	8	7	9	8	7
CaO	0	1	2	3	1	2	3
PAM	0	0	0	0	0.002	0.002	0.002



Table 4 Elemental content of basalt powder

Element	(wt%)	Element	(wt%)	Element	(wt%)
SiO ₂	45.72	MgO	6.85	P ₂ O ₃	0.24
Fe ₂ O ₃	12.44	TiO ₂	3.84	MnO	0.17
Al ₂ O ₃	12.49	K ₂ O	1.84	Na ₂ O	1.41
CaO	7.64	Na ₂ O	1.41		

Note: The detection limit is 0.0001% (i.e., 1ppm)



Figure 1 Collection and production of basalt powder

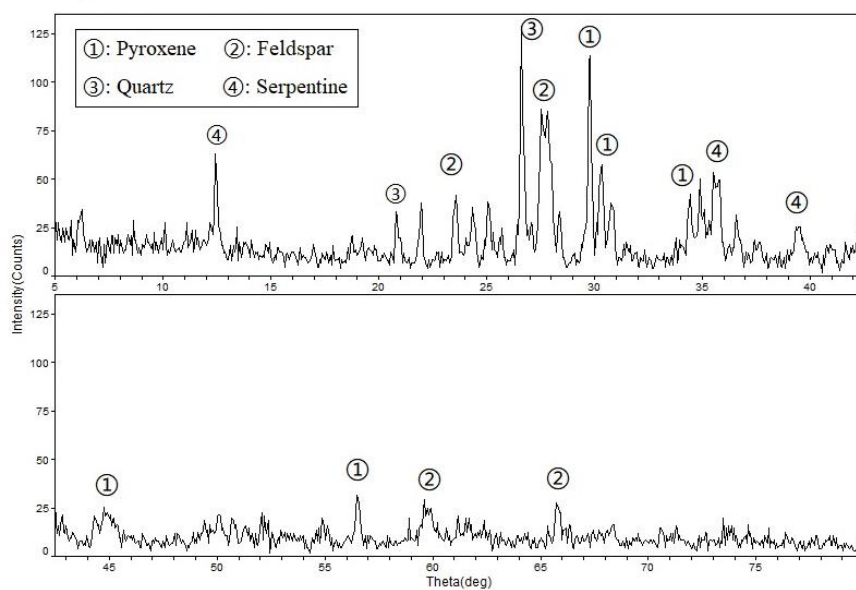


Figure 2 X-ray diffraction spectroscopy of basalt powder

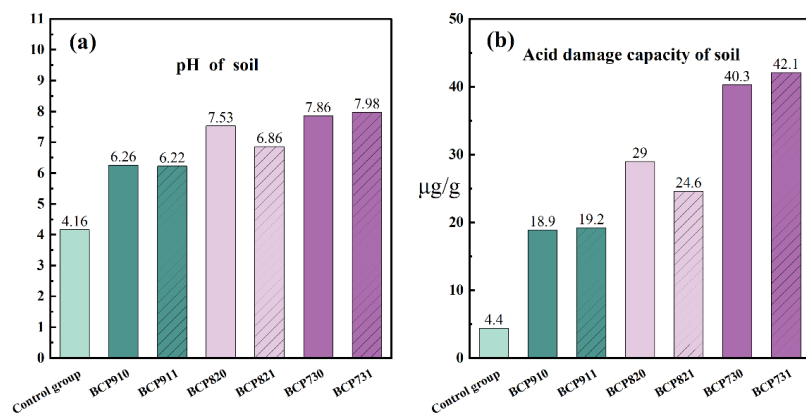


Figure 3 The pH value of the soil after the amendments addition (a); Acid damage capacity of soil after the amendments addition (b).

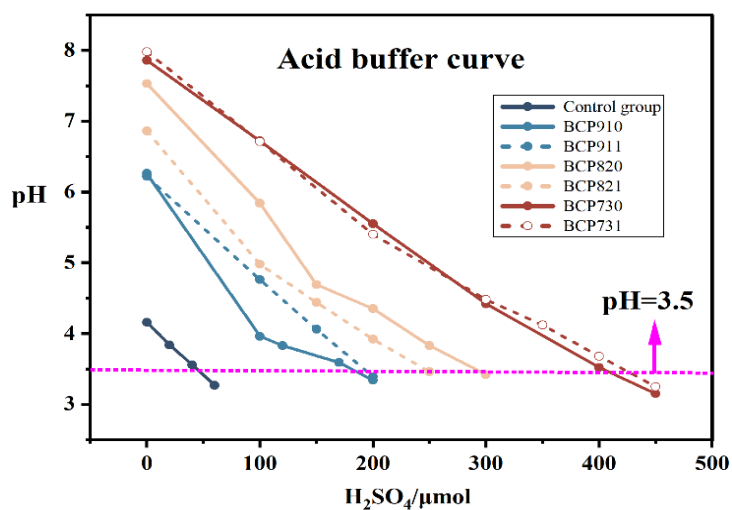


Figure 4 Soil acid buffer curve.

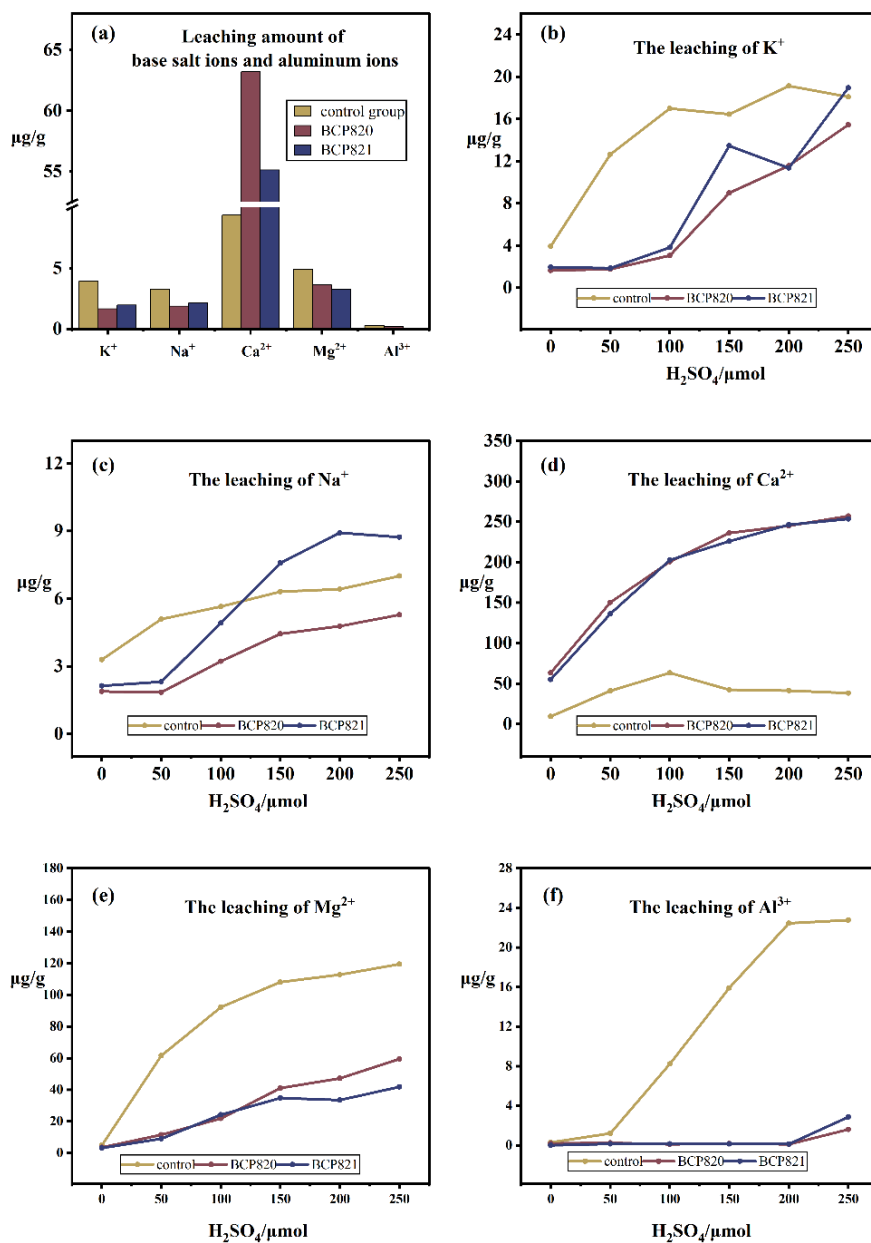


Figure 5 Leaching amount of base salt ions and aluminum ions (a); Leaching amount of ions under simulated acidification conditions (b-f).

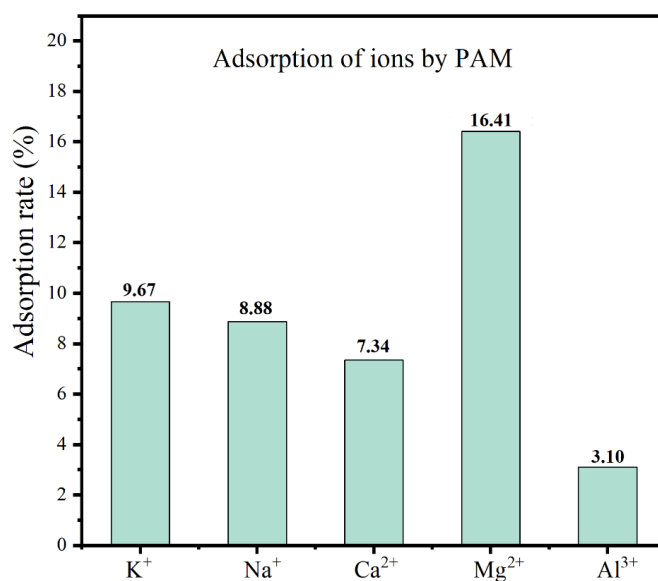


Figure 6 Adsorption of K⁺, Na⁺, Mg²⁺, Ca²⁺ and Al³⁺ by PAM.

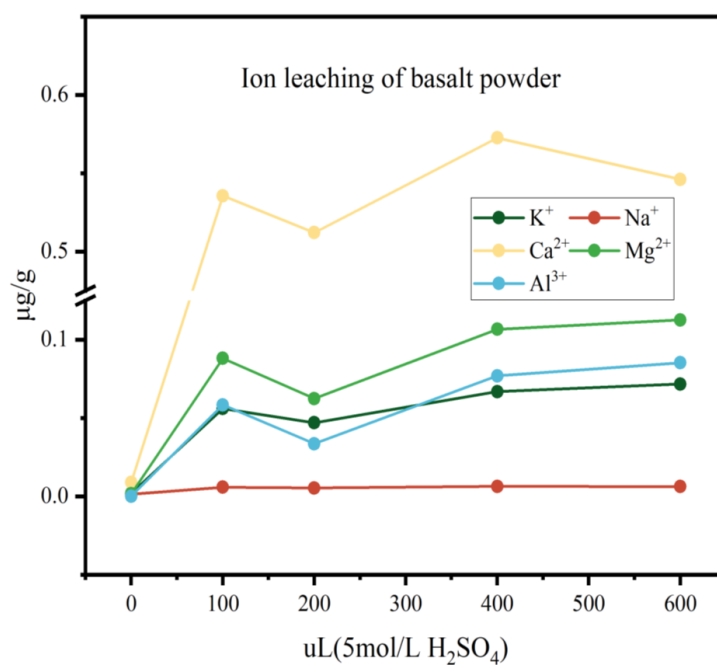


Figure 7 Ion leaching of basalt powder under neutral acidic condition.