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Conquering Soil Acidification: The Synergistic Effects of Basalt Powder, Lime, and PAM

Qianmei. Zhang[a], Xiuhong. Peng[a,b*], Hongxia. Zhu[c*]

[a]College of Earth and Planetary Sciences, Chengdu University of Technology, Chengdu 610059, China

[b]Applied Nuclear Technology in Geosciences Key Laboratory of Sichuan Province (Chengdu University of Technology), Chengdu 610059, China

[c]State Key Laboratory of Geohazard Prevention and Geo-environment Protection (Chengdu University of Technology), Chengdu 610059, China.

*Corresponding author:
Dr. Xiuhong, Peng
College of Earth and Planetary Sciences,
Chengdu University of Technology, Chengdu 610059, China.
E-mail: pengxh@cdut.edu.cn

*Corresponding author:
Dr. Hongxia, Zhu
State Key Laboratory of Geohazard Prevention and Geo-environment Protection (Chengdu University of Technology), Chengdu 610059, China.
E-mail: 670553294@qq.com

First author:
Dr. Qianmei, Zhang
College of Earth and Planetary Sciences,
Chengdu University of Technology, Chengdu 610059, China.
E-mail: 3294236310@qq.com

Abstract

Soil acidification poses a substantial threat to agricultural productivity by releasing salt ions, diminishing soil fertility, and increasing susceptibility to aluminum toxicity. The aim of the study was to investigate the potential improvement of acid yellow soil through the combined application of basalt powder, lime, and polyacrylamide (PAM). Herein, 0.1 g mixed basalt powder and CaO with various proportion were added to 10 g acidic yellow soil with an initial pH of 4.16 to explore the efficient of mixed soil amendments. X-ray fluorescence (XRF) analysis of basalt powder revealed its effectiveness in supplementing soil mineral nutrients. The optimal results of reduced acidification and ion leaching of soil were obtained when the addition proportion of basalt powder to lime was 8/2 and addition ratio of PAM was 0.0002%. The addition of mixed amendments markedly increased the pH (by up to >2.0 units) and acid-damage capacity (20.3mmol/kg) of soil, meanwhile decreased the leaching of K^+(58.1%), Na^+(42.9%), Mg^{2+}(26.3%), and Al^{3+} (below the detectable limit) as shown by the optimal tests. The basalt powder undergoes decomposition in the soil solution, resulting in the formation of some weak acids (i.e., H_2SiO_4), the release of OH^-, and an increase in soil pH. The study reveals the underlying mechanisms of soil remediation with mixed amendment, which has potential guidance for the application of mixed soil amendment and the environment risks prediction of contaminated soil.

Keywords: soil acidification; mixed amendment; pH; acid-damage capacity; salt ions

1. Introduction

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

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

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

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

In addition to the lime, the amendment of ground silicate rock powders (SRPs) could improve soil properties effectively. However, there is little research on the utilization of SRPs in the form of silicate, despite their multifaceted role in replenishing soil nutrients, enhancing soil pH, alleviating aluminum toxicity, and ultimately improving crop yields. The limited application was caused by the slow and inconsistent weathering rate of SRPs (Anda et al., 2015; Gillman et al., 2002; Haynes, 2014; Kleiv and Thornhill, 2007; Nunes et al., 2014; Panhwar et al., 2014). Numerous scholars have conducted research on the dissolution kinetics of silicate rock powders, demonstrating that while they cannot fully replace lime-based amendments in terms of soil acid neutralization, they do present notable benefits in terms of environmental sustainability and nutrient enrichment (Celimar Dalmora et al., 2020; Heřmanská et al., 2023; Swoboda et al., 2022). Hence, further investigation of the mixed modifier and weathering mechanism is warranted. Moreover, driven by the principles of environmental sustainability and resource efficiency, the organic polymer (such as PAM) is increasingly being utilized for soil enhancement. Previous studies indicated that PAM primarily regulated soil through the augmentation of soil aggregates, the enhancement of overall soil porosity, and the prevention of soil compaction (Sang et al., 2023; Zhang et al., 2023). Additionally, its adsorption capabilities contributed to the improved retention of nutrients and water in the soil, mitigation of soil erosion and wind erosion control (Xuan et al., 2023). Moreover, the utilization of PAM has been found to enhance agricultural productivity by augmenting crop yield and enhancing crop quality (Mulualem et al., 2021).

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

2. Materials and methods

2.1. Soil

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

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

2.2. Amendments

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

2.3. Experimental design and suspension preparation

1% amendment of PAM did not effectively change the soil pH according to the preliminary experiments with varied proportion addition of PAM, as the pH value of PAM was almost neutral and had negligible impact on pH regulation. Consequently, the addition of PAM in tests was set to a constant (0.0002%) based on pre-experiment. The aim of this study is to adjust the soil pH to a nearly neutral level and examine the impact of modifiers on the base and aluminum ions leaching, and thus CaO was added into each experimental group due to its excellent acid improvement effect in soil. The basalt powder was added in each experimental group as a base component in mixed amendments. The total mass of basalt powder and CaO added in each experiment was 0.1 g, but with varied additive proportion. A pre-experiment showed that the soil pH < 6 when the proportion of basalt powder ≥90 %, and soil pH value > 9 when the proportion of basalt powder ≤ 60%. Accordingly, the proportion of basalt powder was set at 90%, 80%, 70%, and the experiment design was shown in Table 3.

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

2.4. Acid damage capacity

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

The pH measurement of soil suspension was conducted in 50 ml centrifuge tube. 10 g soil samples were added in 50 ml centrifuge tube and shook evenly with 25 mL distilled water. After shaking for 1 hour using a bifunctional water bath constant temperature oscillator, the original pH value of soil was measured. Soil sample pH was adjusted by 1mol/L sulfuric acid using a micro-injector. After the addition of 1mol/L sulfuric acid and shaking for 10 min, the soil pH was measured and documented. The procedures of sulfuric acid addition were repeated until the soil suspension pH dropped 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 8×10^{-5} $g\cdot ml^{-1}$ and contained K^+, Na^+, Ca^{2+}, Mg^{2+} and Al^{3+} at concentrations of 100 $\mu g\cdot ml^{-1}$, 100 $\mu g\cdot ml^{-1}$, 100 $\mu g\cdot ml^{-1}$, 100 $\mu g\cdot ml^{-1}$,20 $\mu g\cdot ml^{-1}$, 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 ($(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$),

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feldspar($(Na,K,Ca)Al_2Si_3O_8$), serpentine ($(Mg,Fe)_3(Si_2O_5)(OH)_4$), and quartz (SiO_2). The presence of serpentinite suggested that the basalt had undergone hydrothermal alteration, while quartz served as the filling material within the basalt's pores.

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

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

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

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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 ($\mu mol \cdot g^{-1}$) 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.).

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

4. Discussion

4.1 Advantages of mineral structure for basalt powder

The weathering of basalt led to the liberation of nutrient elements inherent in the rock, thereby enriching the soil's nutritional content. Furthermore, this process produces silicic acid, releases OH- ions, and raises the soil pH (Anda et al., 2015). The pace of weathering is predominantly determined by the mineral composition, pH level, and particle size of the rock powder. Statistical analyses of the dissolution rate of silicate rocks as influenced by pH levels have revealed that Al-containing silicate rocks exhibit the slowest dissolution rates in neutral environments (Rinder and Hagke, 2021). Additionally, scholarly studies have proposed that silicate rocks rich in Mg content weathering faster than rocks rich in Ca content (Deer et al., 2013; Swoboda et al., 2022). This phenomenon can be explained by the bonding energy and characteristics of the bonds present. The metallic bonds of Mg-O and Ca-O exhibit similarities in the arrangement of electrons outside the nucleus, with Mg^{2+} and Ca^{2+} sharing comparable electron configurations. However, calcium possesses a higher relative atomic mass, stronger attraction, and greater bonding energy than magnesium. When selecting rock powder for agricultural purposes, it is important to take into account not only the variety of nutrient elements present, but also the mineral composition. Rocks with high basal ultramafic magnesium content, such as basalt powder containing pyroxene and feldspar, are rich in essential nutrients and are more easily weathered, making them a favorable option in the application of soil conditioner.

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

Herein, the basalt powder possessed a particle size of approximately 38μm, and the predominant rock-forming minerals were pyroxene and serpentine, which were rich in magnesium. These minerals contributed to enhancing the weathering rate to a certain extent and it could maintain dissolving behavior more than 10 years based on the calculation of Rinder and Hagke (2021). Therefore, the utilization of basalt powder can serve as a valuable means to enhance the presence of essential nutrients and advantageous elements within soil, thereby promoting the growth of crops.

4.2 Effect of amendments in soil pH and acid damage capacity

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

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

4.3 Effect of amendments in salt-based ion leaching

To provide a more comprehensive explanation of the ion leaching results, supplementary adsorption experiments of PAM on ions (Fig.6) and the ion release of basalt powder (Fig.7) were conducted. Similar trend was observed in the acid soaking experiment of basalt powder (Fig. 7). The acid (1mol/L H_2SO_4) presented in the basalt powder within the range of 0-500umol (adjusted for concentration conversion) underwent a rapid decomposition phase followed by a slower rate of change as shown by Fig. 7b, which can be attributed to the unstable structure and properties of the basalt powder, leading to the decomposition of minerals under acidic conditions. The observation is further supported by the mineral composition analysis of the basalt powder, which indicated that minerals such as pyroxene and serpentine, with higher iron and magnesium content, were more susceptible to weathering. Additionally, it is worth noting that pyroxene exhibited higher calcium content than other components. Hence, the process of basaltic acid soaking resulted in a greater release of Ca^{2+} and Mg^{2+}.

The large increase in Ca^{2+} leaching did not imply that the mixing amendments had a deleterious effect on soil calcium ions, because CaO reacted with the soil solution to rapidly produce large amounts of Ca^{2+} (Fig. 5a), and basalt powder decomposition also produced a certain amount of Ca^{2+} (Fig. 7). These processes effectively replenished soil Ca^{2+}. The reduction of K^+, Na^+, Mg^{2+} and Al^{3+} leaching by the mixed amendment can be attributed to several factors. Firstly, the inclusion of basalt powder with fine particles resulted in a significant increase in specific surface area. The enhanced surface area was characterized by the presence of hydroxyl groups (-OH) and negatively-charged functional groups (Si-O), which exhibited superior ion adsorption capabilities.

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

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

The experimental group consistently exhibited a significantly lower leaching amount of Mg^{2+} and Al^{3+} compared to the control group, which potentially attributable to the stronger adsorption effect for Mg^{2+} and Al^{3+} with large charge in contrast to K^+ and Na^+. In comparison to BCP820, the leaching rate of Mg^{2+} decreased in BCP821 while the leaching rate of Al^{3+} increased, which might be attributed to the adsorption of PAM. Notably, the adsorption rate of Mg^{2+} by PAM was significantly higher than that of Al^{3+} (Fig. 6). The adsorption capacity of PAM on Mg^{2+} is greater than the reduction in adsorption capacity resulting from the mutual adsorption of PAM and basalt powder, thereby occupying the adsorption site. However, this effect was insufficient for Al^{3+}.

5. Conclusion

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

Author contribution

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

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

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

Competing interests

The contact author has declared that noneof the authors has any competing 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_2O_3	SiO_2	Al_2O_3	K_2O	MnO	Na_2O	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_2O_3	0.24
Fe_2O_3	12.44	TiO_2	3.84	MnO	0.17
Al_2O_3	12.49	K_2O	1.84	Na_2O	1.41
CaO	7.64	Na_2O	1.41		

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

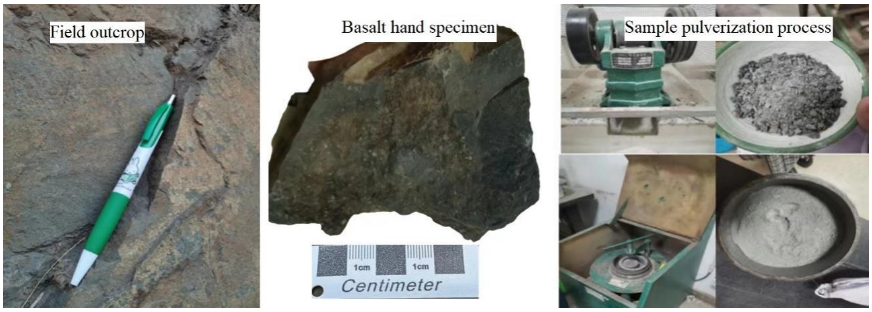

Figure 1 Collection and production of basalt powder

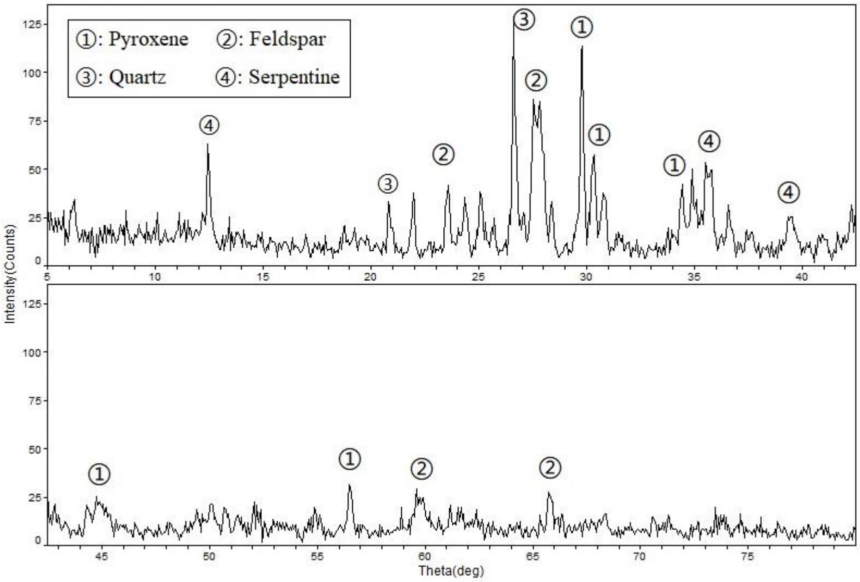

Figure 2 X-ray diffraction spectroscopy of basalt powder

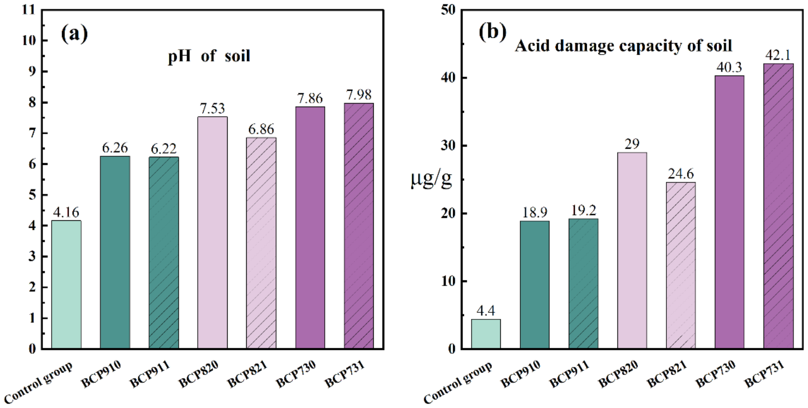

Figure 3 The pH value of the soil after the amendments addition (a); Acid damage capacity of soil after the amendments addition (b).

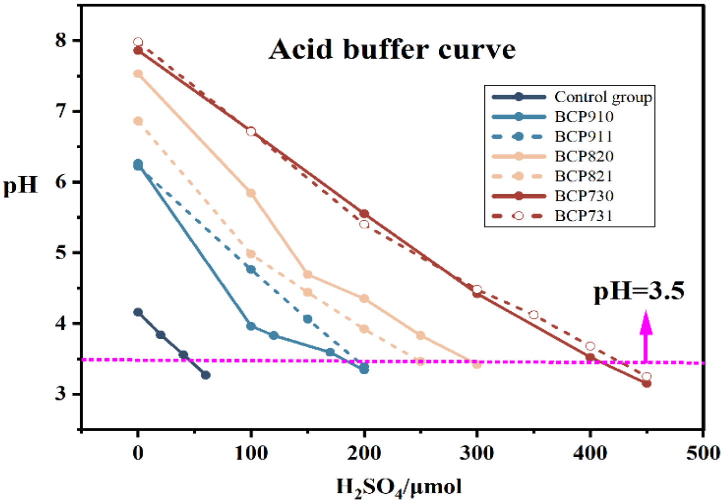

Figure 4 Soil acid buffer curve.

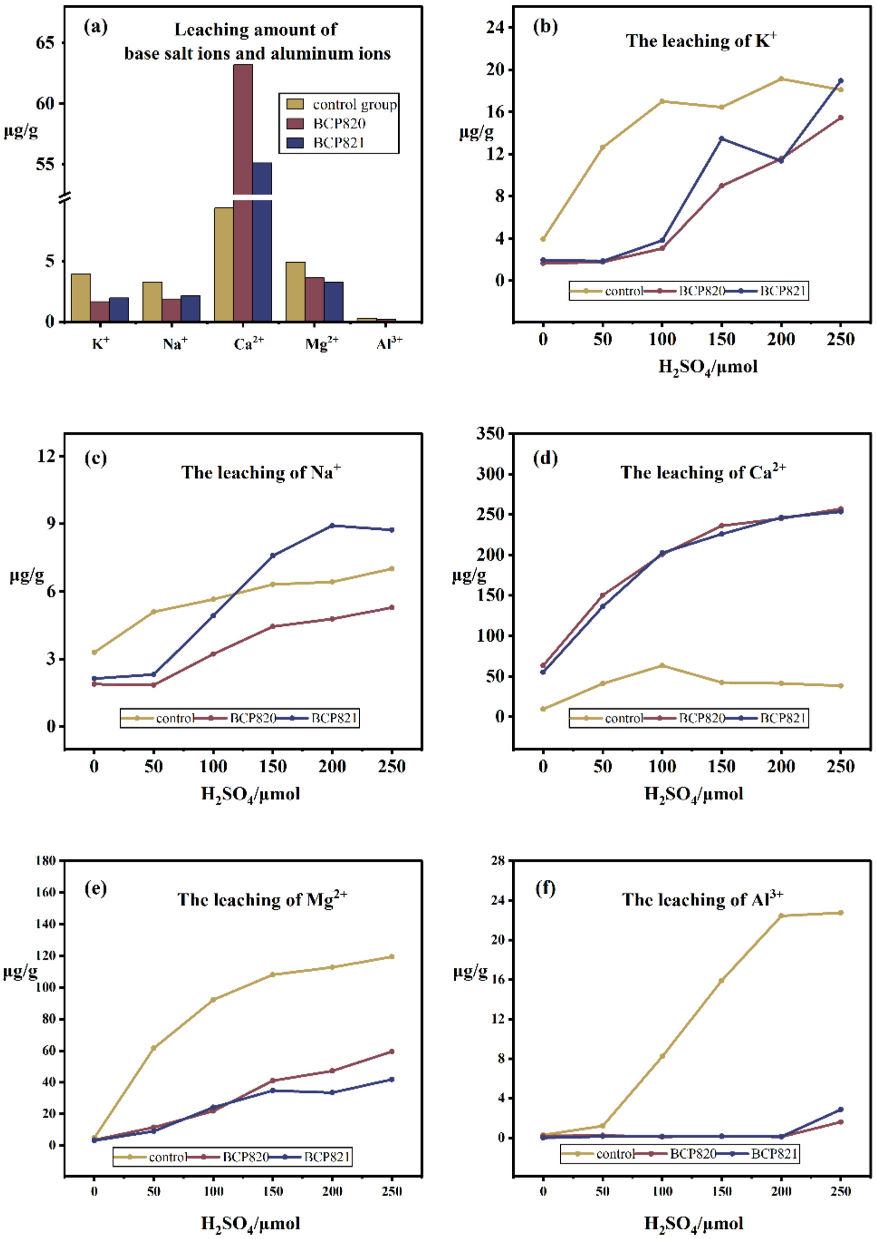

Figure 5 Leaching amount of base salt ions and aluminum ions (a); Leaching amount of ions under simulated acidification conditions (b-f).

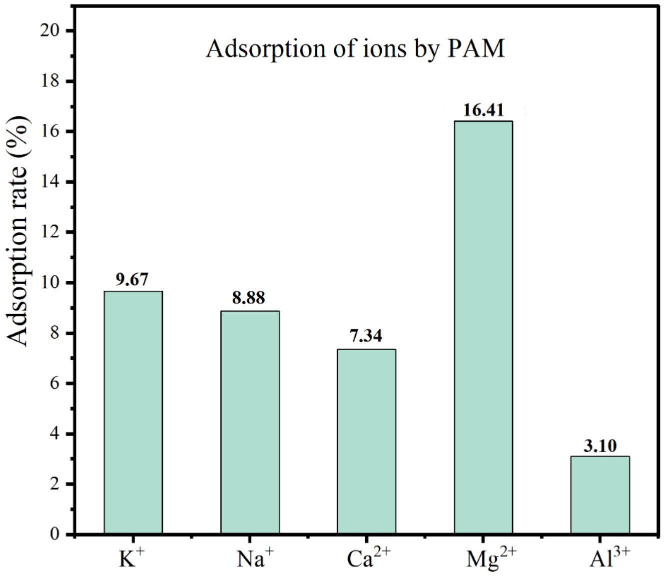

Figure 6 Adsorption of K^+, Na^+, Mg^{2+},Ca^{2+} and Al^{3+} by PAM.

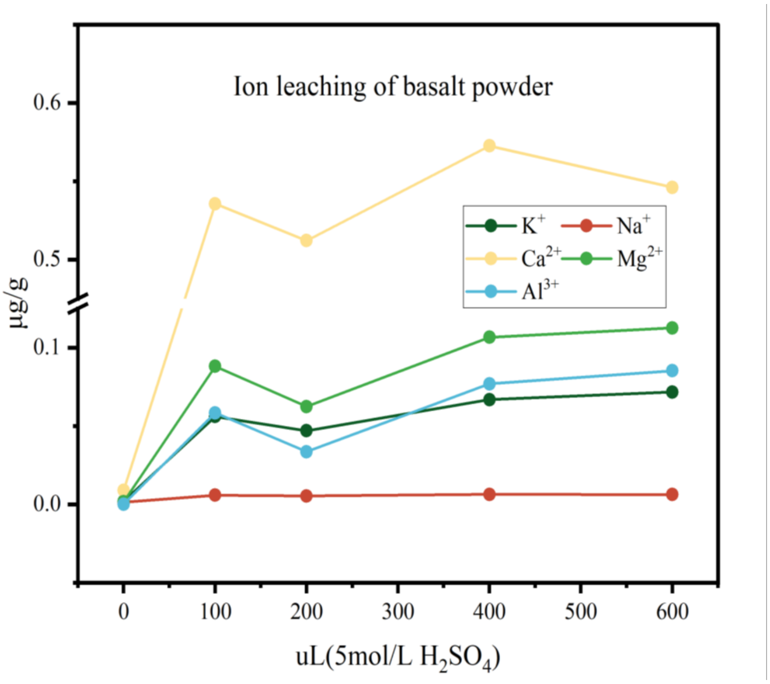

Figure 7 Ion leaching of basalt powder under neutral acidic condition.