



## OPEN Synergistic effects of biochar-lime enhance acidic soil remediation and sustain peanut productivity under continuous cropping systems

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Soil acidification severely limits peanut productivity. Although lime and biochar can individually improve soil conditions, the effects are often short-lived. The combined effect of biochar and lime (BL) across multiple growing seasons remains unclear. This three-year field study investigated the synergy of biochar-lime co-application (BL) in remediating acidic soils and sustaining peanut yields under continuous cropping. BL was more effective than single amendments (BC/LM), operating through a dual mechanism: (1) Lime rapidly neutralized toxic aluminum (Ex-Al<sup>3+</sup>), while biochar helped retain Ca<sup>2+</sup>, prolonging the pH buffering effect and further reducing aluminum toxicity; (2) Biochar enriched soil microbial communities, which increased the activity of key enzymes involved in nutrient cycling (urease: +49.84%; phosphatase: +46.14%). This improved soil environment reduced oxidative stress in peanuts (MDA: −20.01%) and enhanced their antioxidant defense system (SOD: +27.46%; POD: +34.60%), leading to higher and more stable yields (+ 11.07–27.26% vs. CK) with less year-to-year variation (− 4.66% yield decline). Economically, the lasting effects of BL allowed for a 53% reduction in amendment inputs by the third year, resulting in a 22.91% higher net income than using lime alone. These results demonstrate that BL co-application is a promising strategy for managing acidic soils by simultaneously addressing chemical and biological constraints in continuous cropping systems.

**Keywords** Biochar-lime synergy, Soil acidification reversal, Microbial-nutrient coupling, Yield resilience, Degraded monoculture systems

Soil degradation, particularly acidification which affects 30–50% of the world's arable land, poses a major threat to agricultural sustainability, especially in tropical and subtropical regions<sup>1,2</sup>. In the red soil areas of South China, where peanut (*Arachis hypogaea* L.) is an important oil crop, long-term monoculture aggravates soil acidification (pH < 5.0), increases exchangeable aluminum (Ex-Al<sup>3+</sup>) to phytotoxic levels (> 2 cmol/kg) and causes nutrient imbalances that can reduce yields by 30–50%<sup>3,4</sup>. Empirical studies show a 15% decline in peanut yield as soil pH decreases from 5.4 to 4.7<sup>5</sup>, highlighting soil acidity as a key constraint to productivity. Conventional amendments such as lime (CaCO<sub>3</sub>) or biochar provide partial remediation but have inherent drawbacks. Lime rapidly neutralizes acidity, but over-application can induce secondary nutrient deficiencies (Mg, K), phosphorus fixation, and microbial suppression<sup>6–8</sup>. Biochar, characterized by its alkalinity, high surface area, and stable carbon structure, can improve soil physical properties, nutrient retention, and long-term carbon storage. However, its effectiveness in acidic soils varies with feedstock, pyrolysis conditions, and application rate, and it often fails to sufficiently raise soil pH or alleviate aluminum toxicity in strongly acidic conditions with a practical timeframe, making it economically challenging for rapid remediation<sup>9,10</sup>. These limitations underscore the need for integrated strategies that combine rapid pH adjustment with long-term fertility improvement.

Emerging evidence suggests that biochar–lime co-application (BL) could address these challenges through synergistic mechanisms<sup>11–13</sup>: (i) *geochemical synergy*, where biochar's high surface area and functional groups (e.g., carboxyl, phenolic-OH) adsorb Ca<sup>2+</sup> from lime, slowing its dissolution and prolonging pH stabilization, while also immobilizing Al<sup>3+</sup> via ligand exchange; and (ii) *biochemical synergy*, whereby lime-induced pH optimization enhances biochar's ability to stimulate microbial biomass, in turn promoting enzyme-driven nutrient cycling<sup>14</sup>. Nonetheless, mechanistic links between soil physicochemical changes, microbial responses, and crop physiology under long-term monocropping remain poorly understood<sup>15,16</sup>.

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To address this gaps, a three-year field study was conducted to evaluate the interactive effects of biochar and lime on acidic soil remediation and peanut yield sustainability. The study aimed to (i) decouple the roles of biochar and lime in  $\text{Al}^{3+}$  immobilization, pH buffering, and nutrient availability; (ii) quantify microbial mediation by biomass C and key enzyme activities (urease, phosphatase) in soil-crop feedbacks; and (iii) establish causal pathways linking soil improvement to peanut antioxidant activity and yield stability. The findings are expected to support the design of integrated soil management strategies for enhancing productivity and soil health in acid-affected regions.

## Materials and methods

### Experimental site characterization

The experimental site is located in Baima Village, Sanfu Town, Xingan County, Jiangxi Province (115°24'52"E, 27°51'47"N). It belongs to the mid-subtropical climate, with an average annual temperature of 17.7 °C, an accumulated temperature of  $\geq 10$  °C of 5648 °C, an annual rainfall of 1627 mm, and an annual evaporation of 1268 mm. The frost-free period was 274 d, and the annual sunshine duration was 1809 h. Peanut fields that had been continuously planted for 3 years and had never applied biochar and lime were selected. The test soil was red soil developed from Quaternary red clay. Before the test, the soil pH was 4.78, the soil organic matter was 18.3 g kg<sup>-1</sup>, and the contents of alkali-hydrolyzable nitrogen, available phosphorus and available potassium were 81.36, 26.69 and 89 mg kg<sup>-1</sup>, respectively. The cation exchange capacity (CEC) and exchangeable aluminum (Ex- $\text{Al}^{3+}$ ) content were 10.57 and 2.32 cmol kg<sup>-1</sup>, respectively. Interannual variability in weather conditions was observed during the three-year study period. Notably, the growing season in Year 1 (Y2022) was characterized by a distinct dry during the pod-filling stage (July), with precipitation approximately 20% lower than the 10-year average. In contrast, Year 2 (Y2023) and Year 3 (Y2024) experienced weather conditions closer to the historical average.

### Experimental design and amendments

#### Amendment materials

**Lime** CaO-dominant (75% purity, pH 12.2; Jiangxi Dingsheng Lime Co., China). Lime (CaO-dominant) was selected based on prevalent local amendment practices for its rapid neutralization capacity, which is critical for immediate alleviation of aluminium toxicity in strongly acidic soils at the onset of the cropping season. Its faster dissolution kinetics, compared to  $\text{CaCO}_3$ , were considered integral to establishing the initial conditions for synergy with the slower-release biochar.

**Biochar** Rice straw and husk feedstock pyrolyzed at 500 °C under oxygen-limited conditions<sup>17</sup>, with pH 9.30, total carbon 605.7 g kg<sup>-1</sup>, and total N/P/K contents of 7.6, 4.23, and 0.88 g kg<sup>-1</sup>, respectively. Specific Surface Area is 6.25 m<sup>2</sup> g<sup>-1</sup>, an average pore volume of 0.15 cm<sup>3</sup> g<sup>-1</sup>, cation exchange capacity (CEC) is 33.22 cmol kg<sup>-1</sup> and ash content with 32.16%. The cadmium (Cd) content is 0.10 mg kg<sup>-1</sup>.

#### Field trial setup (2022–2024)

A randomized complete block design with four treatments:

CK: Control (no amendments).

BC: Biochar alone (6,000 kg ha<sup>-1</sup> yr<sup>-1</sup>).

LM: Lime alone (900 kg ha<sup>-1</sup> yr<sup>-1</sup>).

BL: Biochar + lime co-application (In the BL treatment, amendment rates were reduced in Years 2 and 3 based on the observed strong residual effect from the initial application, to assess the potential for sustained benefits with lower long-term inputs).

Each treatment was replicated four times (plot size: 30 m<sup>2</sup>; planting density: 20 cm × 40 cm spacing, two seeds per hole). The peanut cultivar Ganhua 5 which was purchased from local agricultural supply companies was sown mid-April and harvested late August annually. Fertilization followed local practices (Table 1): 40% of urea-N and KCl-K applied as basal fertilizer, 60% top-dressed at early flowering, with calcium-magnesium phosphate fertilizer (P), lime, and biochar fully incorporated into the 0–20 cm soil layer during tillage. The biochar application rate was selected based on previous research demonstrating its efficacy for ameliorating degraded acidic red soils in South China<sup>18,19</sup>.

Treatment	Fertilization amount (kg hm <sup>-2</sup> )			Soil conditioner (kg hm <sup>-2</sup> )					
				Y2022		Y2023		Y2024	
	N (kg hm <sup>-2</sup> )	P <sub>2</sub> O <sub>5</sub> (kg hm <sup>-2</sup> )	K <sub>2</sub> O (kg hm <sup>-2</sup> )	BC	LM	BC	LM	BC	LM
CK	120	75	120	/	/	/	/	/	/
BC	120	75	120	6000	/	6000	/	6000	/
LM	120	75	120	/	900	/	900	/	900
BL	120	75	120	9000	1200	4500	750	3000	300

**Table 1.** Application rates of fertilizers and amendments for each treatment. In the BL treatment, amendment rates were reduced in Y2023 and Y2024 based on the observed strong residual effect from the initial application, to assess the potential for sustained benefits with lower long-term inputs.

## Sampling and analytical methods

### Soil sampling

Post-harvest composite soil samples (0–20 cm depth) were collected annually from five random points per plot. Air-dried soils were sieved (<2 mm) for physicochemical analyses (pH, SOM, available nutrients, Ex-Al<sup>3+</sup>, CEC).

Soil pH was measured with a PB-10 pH meter (soil-water mass ratio was 1: 2.5) and soil organic matter (SOM) was determined by the potassium dichromate oxidation capacity method<sup>20</sup>. Available N, available P, available K, Ex-Al<sup>3+</sup> and cation exchange capacity (CEC) are measured by the method<sup>21</sup>.

Fresh subsamples (stored at 4 °C) were analyzed for microbial biomass carbon (chloroform fumigation-extraction<sup>22</sup>, urease (indophenol colorimetry) and phosphatase (Sodium phenylphosphate colorimetric method) activities<sup>23</sup>.

### Plant sampling

Physiological assays: Fully expanded leaves from podding-stage plants were analyzed for superoxide dismutase (SOD, NBT photoreduction), peroxidase (POD, guaiacol oxidation), and malondialdehyde (MDA, thiobarbituric acid reaction)<sup>24</sup>.

Yield components: At maturity, five plants per plot were assessed for pods per plant, 100-pod weight, and kernel ratio. Plot yields (kg ha<sup>-1</sup>) were calculated as:

$$\text{Pod yield} = \frac{\text{Plot yield (kg)}}{\text{Plot area (m}^2\text{)}} \times 10000 \quad (1)$$

$$\text{Yield Reduction Rate} = \left(1 - \frac{\text{Yield}_{\text{year}_n}}{\text{Yield}_{\text{year}_1}}\right) \times 100\% \quad (2)$$

where *year 1* is the first year of amendment application (Y2022).

## Statistical analysis

Data were processed using Microsoft Excel 2019 and SPSS 26.0. Treatment effects were evaluated via one-way ANOVA with LSD post-hoc tests ( $p < 0.05$ ). Results represent means  $\pm$  standard deviation (SD) ( $n = 4$ , based on independent field plot replicates).

## Result and analysis

### Process-driven soil remediation

BL sustainably reversed soil acidification by integrating two complementary processes: Geochemical buffering: Lime can rapidly enhance H<sup>+</sup> neutralization, while biochar may act as a Ca<sup>2+</sup> reservoir, potentially slowing lime dissolution and contributing to pH stability. This three-year study indicates that biochar lime (BL) can synergistically remediate acidified soils, BL elevated soil pH by 19.25–25.31% relative to initial conditions, outperforming CK (control), BC (biochar alone), and LM (lime alone) (Fig. 1a). BL also increased soil organic matter (SOM) by 31.17–46.67% annually compared to CK, establishing a positive feedback loop with pH stabilization (Fig. 1b). Concurrently, cation exchange capacity (CEC) under BL rose by 36.29% yearly (Fig. 1c), strongly correlating with SOM accumulation ( $R^2 = 0.81$ ,  $p < 0.001$ ). Soil Ex-Al<sup>3+</sup> content of BL was the lowest, which was lower than CK, BC and LM by 60.08%, 48.70% and 31.78%, respectively (Fig. 1d).

Nutrient activation: Biochar's alkaline functional groups (e.g., carbonates, silicates) solubilized fixed phosphorus, while lime prevented P re-fixation by Fe/Al oxides, elevating available P by 34.73%. Concurrently, biochar's porous structure retained K<sup>+</sup>, reducing leaching losses (Table 2). These findings align with the research<sup>25</sup>, confirming BLs dual role in nutrient activation and aluminum toxicity alleviation.

### Microbial mediation of nutrient cycling

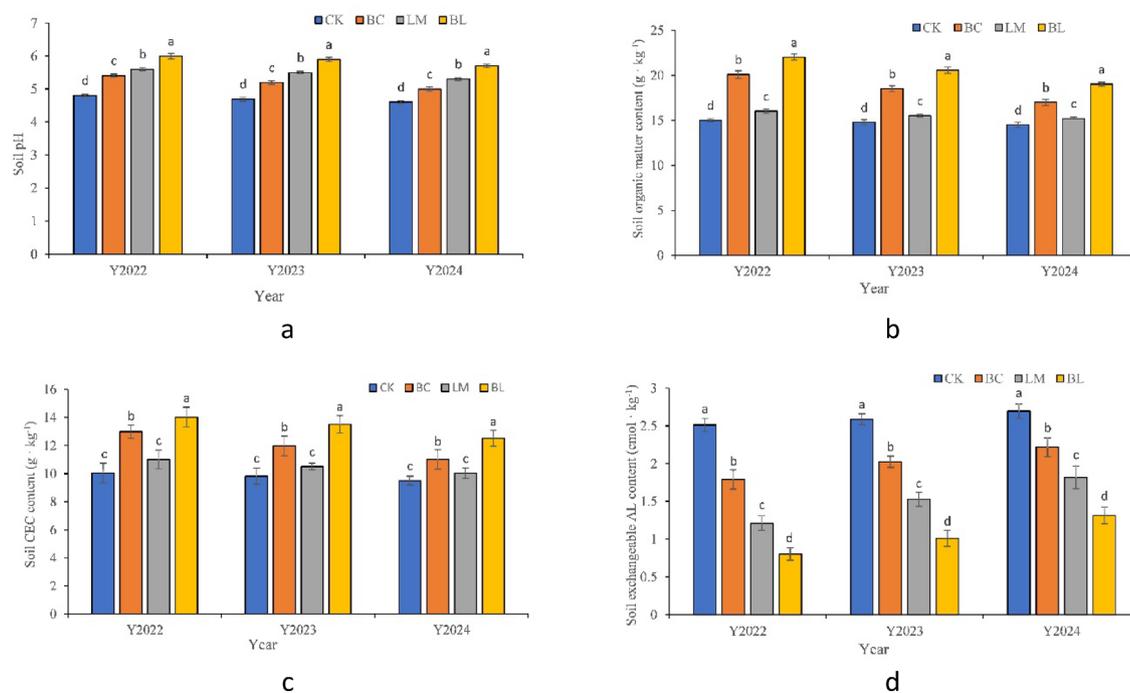
BL enhanced microbial biomass C (SMBC) by 53.24% over CK by alleviating Al<sup>3+</sup> toxicity and supplying labile C (Fig. 2a; Table 3). SMBC dynamics strongly correlated with SOM ( $R^2 = 0.77$ ,  $p < 0.001$ ) (Fig. 2b), underscoring carbon availability as a microbial activity regulator. This stimulated extracellular enzyme production:

Urease activity increased 49.84% under BL, potentially due to lime-facilitated improved conditions for ureolytic microorganisms (Fig. 3a). Phosphatase activity rose 46.14%, likely driven by enhanced microbial P demand and activity stimulated by biochar (Fig. 3b). The synergy fostered a self-sustaining pH-microbe-enzyme system, critical for long-term soil fertility.

### Crop physiological and yield responses

Superoxide dismutase (SOD) and peroxidase (POD) are used to evaluate the activity of antioxidant enzymes in organisms, in order to understand their resistance to oxidative stress and health status<sup>27–29</sup>. BL enhanced peanut oxidative stress resilience, elevating superoxide dismutase (SOD) and peroxidase (POD) activities by 29.24% and 37.53%, respectively, over CK (Fig. 4a,b). Malondialdehyde (MDA), a lipid peroxidation marker, decreased by 20.01% in BL versus CK, indicating reduced oxidative damage (Fig. 4c; Table 4).

Yield data revealed BLs systemic benefits across all three years, despite the interannual climatic variations (Tables 5 and 6). BL treatment consistently achieved the highest pod yield, with a significant yield of 16.80%, 26.59%, and 38.39% over CK in Y2022, Y2023, and Y2024, respectively. It is noteworthy that the high yield achieved by BL compared to CK occurred in relatively dry years in Y2022. This suggests that the synergy in BL treatment, particularly biochar's documented ability to enhance soil water retention<sup>30</sup>, may have provided greater resilience against water stress, thereby amplifying its yield advantage under adverse conditions. The lowest yield



**Fig. 1.** Differences in physical and chemical properties of soils in different treatments: (a) Effects of different treatments on soil pH; (b) Effects of different treatments on the soil organic matter; (c) Effects of different treatments on the soil CEC; (d) Effects of different treatments on the content of soil Ex-Al<sup>3+</sup>. Different lowercase letters in the same column mean significant difference among treatments at 0.05. Error bars represent  $\pm$  standard deviation (SD) ( $n = 4$ ).

Treatment	Available P(mg/kg)			Available k(mg/kg)		
	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024
CK	24.96(23.46,26.45)d	23.98(22.34,25.61)b	23.03(21.74,24.33)d	80.05(76.34,83.76)d	78.01(74.36,81.66)d	74.98(71.54,78.41)d
BC	31.97(30.47,33.46)b	30.07(28.43,31.70)a	28.05(26.75,29.35)b	105.08(101.37,108.79)b	100.00(96.35,103.65)b	95.05(91.62,98.49)b
LM	28.06(26.56,29.56)c	26.07(24.44,27.70)b	25.09(23.79,26.38)c	90.01(86.30,93.72)c	85.02(81.37,88.66)c	80.04(76.60,83.47)c
BL	35.01(33.52,36.51)a	32.05(30.41,33.68)a	30.00(28.70,31.30)a	115.06(111.35,118.77)a	108.00(104.35,111.64)a	100.09(96.65,103.52)a
F value	47.20	27.31	27.14	157.14	127.29	114.72
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
$\eta^2p$	0.85	0.82	0.87	0.92	0.91	0.90

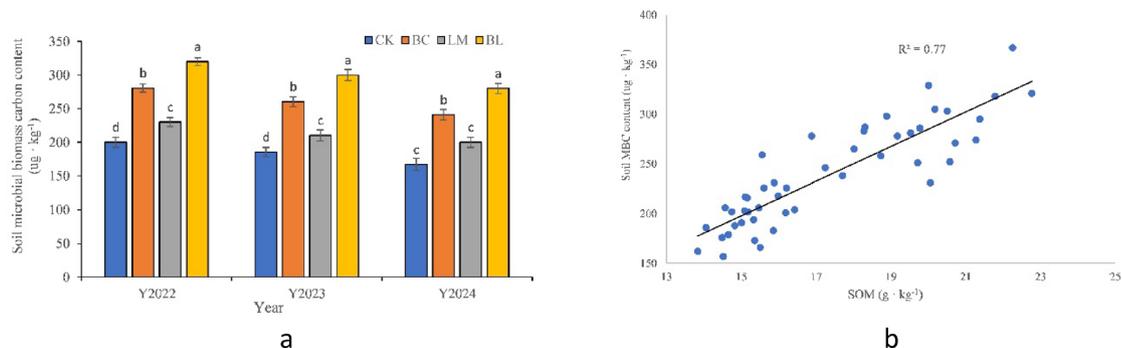
**Table 2.** Soil available nutrient content under different treatments. Values are presented as mean. Within each treatment, means followed by different lowercase letters are significantly different according to LSD post-hoc test ( $p \leq 0.05$ ). The F-value and p-value are from a one-way ANOVA for each nutrient and year.  $\eta^2p$  = partial eta squared (small effect  $\geq 0.01$ , medium effect  $\geq 0.06$ , large effect  $\geq 0.14$ ).

reduction rate was also observed under BL ( $-4.66\%$  and CK's  $-19.53\%$  from Y2022 to Y2024), underscoring its role in enhancing yield stability.

BL reduces Al<sup>3+</sup> toxicity (a major abiotic stressor) and improves nutrient availability.

### Economic feasibility of amendment strategies

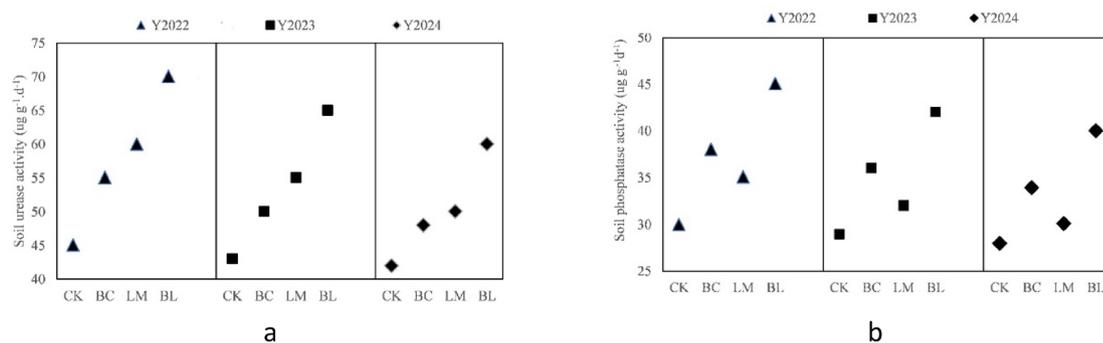
BL demonstrated superior long-term profitability despite higher initial costs (Table 6). Economic calculations were based on local market prices (2022–2024) in Jiangxi Province. Biochar cost: 800 CNY (Chinese Yuan)  $t^{-1}$  (including transportation). Lime cost: 500 CNY  $t^{-1}$  (including transportation). Transportation cost: 50 CNY  $t^{-1}$ . Application cost: 30 CNY  $t^{-1}$ . Peanut price: 8.6 CNY  $kg^{-1}$ . Over three years, BL reduced lime inputs annually (from 1,200 to 300  $kg ha^{-1}$ ) while supplementing biochar (from 9,000 to 3,000  $kg ha^{-1}$ ). Although BL's net income was initially 3,192 CNY  $ha^{-1}$  lower than LM, residual effects ( $\geq 3$  years) saved 4,698 CNY in cumulative lime costs. Coupled with yield premiums (15,480 CNY  $ha^{-1}$ ), BL's three-year net income surpassed LM by 22.91%. While LM maximized short-term returns, BL offered sustainable advantages: enhanced yield stability, reduced environmental risks, and alignment with site-time-material-specific agricultural practices.



**Fig. 2.** The relationship between Soil MBC and SOM (a) Effects of different treatments on soil MBC; (b) The relationship between SOM and Soil MBC (Linear regression,  $R^2 = 0.77$ ,  $p < 0.001$ ). Different lowercase letters in the same column mean significant difference among treatments at 0.05. Error bars represent  $\pm$  standard deviation (SD) ( $n = 4$ ).

Treatment	Compared to CK increase(%)			Compared to BC increase (%)			Compared to LM increase(%)		
	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024
BC	40.25	33.12	27.04						
LM	15.00	7.54	6.07						
BL	60.00	50.72	48.99	14.08	13.22	17.27	39.13	40.15	40.46

**Table 3.** The increase in soil MBC content under different treatments.



**Fig. 3.** Soil urease and phosphatase activity (a) Effects of different treatments on soil urease activity; (b) Effects of different treatments on soil phosphatase activity.

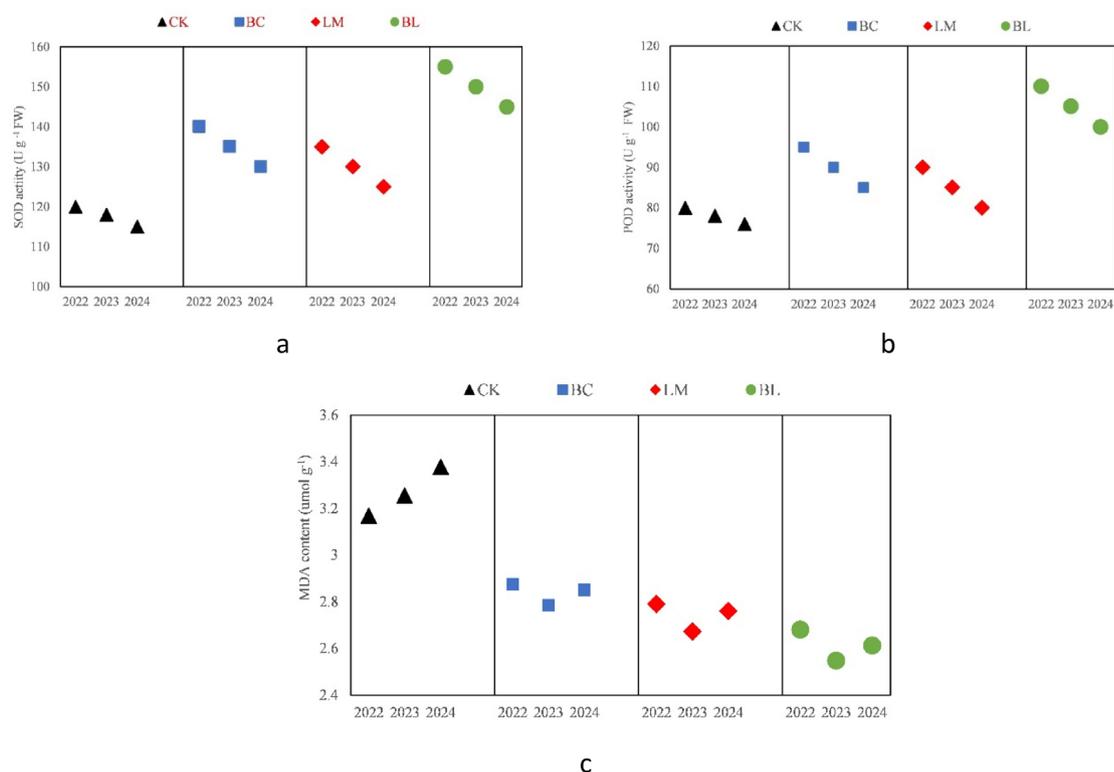
## Discussion

This three-year field study shows that using biochar and lime together (BL) creates a synergistic effect in repairing acidic soil and supporting sustainable peanut production. The BL treatment helped build a self-reinforcing “soil-microbe-crop” system, leading to better results than using either amendment alone. The main mechanism involves a connected series of changes starting from soil chemistry and ending with plant physiological responses.

### How soil chemistry influences crop productivity

The combined use of biochar and lime (BL) showed synergistic effects starting from complementary soil chemical processes. Lime quickly neutralized soil acidity and reduced toxic aluminum ( $Al^{3+}$ ) levels. Biochar acted like a slow-release reservoir, absorbing calcium ( $Ca^{2+}$ ) from the lime, which reduced nutrient loss and helped maintain a stable soil pH for a longer time. This “carbon-calcium complementarity” led to a more balanced soil environment<sup>31–34</sup>.

The improved soil conditions, along with the extra carbon from biochar, increased soil microbial biomass carbon (SMBC). More SMBC was linked to higher soil organic matter, showing that carbon is important for microbial growth<sup>35</sup>. Notably, BL’s efficacy intensified over time despite reduced inputs. By Year 3, SMBC in BL exceeded BC by 17.27%, contradicting traditional models of amendment attenuation<sup>36,37</sup>. These active microbes then increased the activity of enzymes (urease and phosphatase) that break down nutrients. This improved



**Fig. 4.** (a) changes in SOD under different treatment, (b) changes in POD under different treatments, (c) changes in MDA under different treatments).

Treatment	Decrease compared to CK(%)			Decrease compared to BC(%)			Decrease compared to LM(%)		
	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024
BC	9.31	14.57	15.68	/	/	/	/	/	/
LM	11.99	18.02	18.34	/	/	/	/	/	/
BL	15.46	21.86	22.71	6.94	8.69	8.33	3.94	4.68	5.34

**Table 4.** The decrease in MDA content in peanut leaves under different treatments.

“microbial-nutrient cycling” released more phosphorus and nitrogen from organic matter, increasing soil nutrient supply and reducing the need for fertilizer.

These positive changes in the soil further enhanced peanut plant health. With less aluminum stress and better nutrient availability, the plants experienced less oxidative damage (lower MDA) and showed stronger antioxidant activity (higher SOD and POD). These physiological improvements led to better yield outcomes—more pods per plant, heavier pods, and an overall yield increase of 11.07–27.26%. The greater yield benefit under drier conditions in the first year suggests that BL may help crops cope with climate-related stresses such as drought.

### Comparison with related research

The study on synergistic effect between carbon and calcium builds upon earlier reports of synergistic yield effects from biochar–lime amendments in other cropping systems, such as maize grown in tropical acidic soils<sup>38</sup>. The combined application of lime and biochar improves acid soil and promotes increased yield of cowpea<sup>39</sup>. Here, we identify a multi-year pathway under field conditions by which sustained improvements in soil chemistry influence microbial function and, in turn, crop physiology. The strength of these effects is expected to vary with soil type, climate, and biochar properties<sup>40</sup>. Therefore, while the results are relevant to peanut production in red soil regions, their applicability to other cropping systems and environments requires local validation.

### Prospects and challenges for field application

The high application rates (e.g., biochar at 6000–9000 kg ha<sup>-1</sup>) present an economic barrier to adoption. However, the significant residual effect observed, which allowed for a 53% reduction in amendment rates in subsequent years without yield loss, improved the three-year net income for BL compared to lime alone by 22.91%. This suggests that the combined application of biochar and lime can be viewed as a long-term investment in soil



Treatment	Pod yield(kg hm <sup>-2</sup> )			Increase compared with CK(%)			Increase compared with BC(%)			Increase compared with LM(%)		
	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024	Y2022	Y2023	Y2024
CK	3429.11(3392.24,3465.98)c	3085.88(3031.43,3140.34)d	2759.30(2697.21,2821.39)c	/	/	/	/	/	/	/	/	/
BC	3619.60(3582.72,3656.47)b	3432.62(3378.16,3487.07)c	3300.40(3238.30,3362.49)b	5.56	11.87	19.61	/	/	/	/	/	/
LM	3631.10(3594.22,3667.96)b	3494.34(3439.88,3548.79)b	3295.99(3233.89,3358.08)b	5.89	13.88	19.45	/	/	/	/	/	/
BL	4005.24(3968.37,4042.11)a	3884.4(3829.95,3938.87)a	3818.62(3756.52,3880.71)a	16.80	26.59	38.39	10.65	13.16	15.70	6.18	11.16	15.86
F value	203.08	171.40	230.30									
p-value	<0.001	<0.001	<0.001									
η <sup>2</sup> p	0.93	0.94	0.92									

**Table 6.** Effects of BL on peanut pod yield under varying interannual climatic conditions. Note: Values are presented as mean. Within each column, means followed by different lowercase letters are significantly different according to LSD test ( $p \leq 0.05$ ). The growing season of Year 2 (2023) was notably drier than Years 1 and 3, with a 20% rainfall reduction during the pod-filling stage. The F-value and p-value are from a one-way ANOVA. η<sup>2</sup>p = partial eta squared (small effect  $\geq 0.01$ , medium effect  $\geq 0.06$ , large effect  $\geq 0.14$ ).

Treatment	Biochar (CNY ha <sup>-1</sup> )	Lime (CNY ha <sup>-1</sup> )	Transportation cost (CNY ha <sup>-1</sup> )	Labor cost (CNY ha <sup>-1</sup> )	Total cost (CNY ha <sup>-1</sup> )	Peanut yield value (CNY ha <sup>-1</sup> )	Net income (CNY ha <sup>-1</sup> )	BCR(%)
BC	14,400	/	900	540	15,840	89,032	71,392	4.51
LM	/	1,350	135	81	1,566	89,624	88,058	56.23
BL	13,200	1,125	938	563	11,127	116,171	105,044	9.44

**Table 7.** Economic analysis of different soil amendment treatments. BCR (%) = (Net income/Total cost)<sup>2</sup>100; All monetary values in Chinese yuan (CNY) per hectare (yuan/ha); “/” indicates no application. Economic calculations were based on local market prices (2022–2024) in Jiangxi Province. Biochar cost: 800 CNY t<sup>-1</sup> (including transportation). Lime cost: 500 CNY t<sup>-1</sup> (including transportation). Transportation cost: 50 CNY t<sup>-1</sup>. Labor cost: 30 CNY t<sup>-1</sup>. Peanut price: 8.6 CNY kg<sup>-1</sup>. The net income (CNY ha<sup>-1</sup>) was calculated as: (Peanut Yield × Price) - Total Cost.

health. Therefore, subsidies to offset initial expenses or the development of low-cost technologies are crucial to enable smallholder adoption.

Potential limitations require consideration. Although the biochar used in this study had low heavy metal content, feedstock source dictates inherent safety. This practice may result in reduced fertilizer efficiency due to nutrient leaching, at high application rates warrants further investigation<sup>41–43</sup>. Once initial soil remediation is achieved, a reduced maintenance dosage could enhance the long-term sustainability of the practice.

### Limitations and future research

This study had several limitations. Microbial analysis was confined to biomass and enzyme activity; employing molecular techniques would provide deeper insight into community structure. Soil moisture dynamics were not quantitatively monitored, so the role of biochar in drought mitigation remains inferred. Future research should prioritize (i) determining optimal BL application rates for soils with varying initial acidification levels, (ii) quantifying the long-term (> 5 years) soil carbon sequestration potential, and (iii) evaluating the adaptability of this approach across diverse agro-ecological zones.

### Conclusion

This three-year study shows that using biochar and lime together improves acidic soil, supports microbial nutrient cycles, and enhances crop function, leading to higher and more stable peanut yields. The interaction between carbon and calcium supports long-term soil improvement. Although the initial cost is greater, it should be considered a long-term investment, as the persistent benefits over multiple seasons can lead to favorable economic returns. This combined method helps manage soil acidity and common problems in continuous cropping systems in southern China's red soil areas. For farmers to use it more widely, support is needed to reduce initial costs, methods must be made more practical, and its effectiveness should be confirmed through longer-term testing in various farming environments.

### Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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### References

- Xu, D. H. et al. Major drivers of soil acidification over 30 years differ in paddy and upland soils in China. *Sci. Total Environ.* <https://doi.org/10.1016/j.scitotenv.2024.170189> (2024).
- Casanova, J. J., Huggins, D. R. & Phillips, C. L. A classification system for describing N-fertilizer performance in dryland wheat crops of the inland Pacific Northwest. *J. Environ. Qual.* **54** (3), 732–746. <https://doi.org/10.1002/jeq2.70017> (2025).
- Li, H. Y., Li, C. H., Song, X., Li, J. Y. & Li, Z. L. Impacts of continuous and rotational cropping practices on soil chemical properties and microbial communities during peanut cultivation. *Sci. Rep.* **12** (1), 18–28. <https://doi.org/10.1038/s41598-021-04028-7> (2022).
- Sible, C. N., Kent, A. D., Margenot, A. J. & Below, F. E. Long-term continuous maize: Impacts on the soil microbiome and implications for residue management. *Soil. Sci. Soc. Am. J.* **88**(4), 1109–1126. <https://doi.org/10.1002/saj2.20681> (2024).
- Zhang, F. S. Current situation and impact of farmland soil acidification in China. *Demo Sci.* <https://doi.org/10.3969/j.issn.1003-0026.2016.06.009> (2016).
- Xiao, Q. et al. Long-term liming mitigates the positive responses of soil carbon mineralization to warming and labile carbon input. *J. Environ. Manage.* **354**, 120498. <https://doi.org/10.1016/j.jenvman.2024.120498> (2024).
- Yan, Z. H., Hu, Z. H., Wang, S. C., Li, J. & Liao, Y. L. Effects of lime dosage on soil acidity, soil nutrients and crop growth in rice-rapeseed rotation area. *Sci. Agri Sinica.* **52** (23), 4285–4295. <https://doi.org/10.3864/j.issn.0578-1752.2019.23.009> (2019).
- Acosta-Martinez, V. & Tabatabai, M. A. Enzyme activities in a limed agricultural soil. *Bio Fert Soils.* **31** (1), 85–91. <https://doi.org/10.1007/s003740050628> (2000).
- Hale, S. E. et al. The effect of biochar, lime and Ash on maize yield in a long-term field trial in a ultisol in the humid tropics. *Sci. Total Environ.* **81** (1), 109–118. <https://doi.org/10.4067/S0718-58392021000100109> (2021).
- Jin, Z. et al. Soil acidity, available phosphorus content, and optimal Biochar and nitrogen fertilizer application rates: A five-year field trial in upland red soil, China. *Field Crop Res.* **232**, 77–87. <https://doi.org/10.1016/j.fcr.2018.12.013> (2019).
- Zhang, K. L. et al. The effects of combinations of biochar, lime, and organic fertilizer on nitrification and nitrifiers. *Biol. Fert Soils.* **53** (1), 77–87. <https://doi.org/10.1007/s00374-016-1154-0> (2017).

12. Mikajlo, I. et al. Composted biochar versus compost with biochar: effects on soil properties and plant growth. *Bcha* **6**(1), 85. <https://doi.org/10.1007/s42773-024-00379-2> (2024).
13. Wang, L. et al. Effect of crop residue Biochar on soil acidity amelioration in strongly acidic tea garden soils. *Soil. Use Manage.* **30**, 119–128. <https://doi.org/10.1111/sum.12096> (2014).
14. Nguyen, T. X. T., Nguyen, B. T. & Thai, B. V. Amelioration of salt-affected soil using combined amendments for synergistic effects: impacts and management implications. *Soil. Use Manage.* **40** (3), e13104. <https://doi.org/10.1111/sum.13104> (2024).
15. Suo, Y. Y., Zhang, X., Si, X. Z., Zhang, T. L. & Li, J. X. Effects of lime and Biochar application on nitrogen uptake and yield of peanut in acidic soil. *Chin. J. Oil Crop Sci.* **45** (1), 148–154 (2023).
16. Zhang, S. W. et al. Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis. *J. Environ. Manage.* **345**, 118531. <https://doi.org/10.1016/j.jenvman.2023.118531> (2023).
17. Chen, F., Zhang, K. K., Gu, S. C., Li, Y. Y. & Li, P. F. Effects of different types of Biochar and application rates on rice growth and soil nutrients. *J. Huazhong Agric. Univ.* **38** (5), 57–63 (2019).
18. Tumanyan, A. F., Shcherbakova, N. A., Tusaint, F., Seliverstova, A. P. & Tyutyuma, N. V. Heavy metal contents in soils and vegetables of Southern Russia. *Chem. Tech. Fuels Oil.* **54** (6), 766–770. <https://doi.org/10.1007/s10553-019-00985y> (2019).
19. Mosharrof, M. et al. Influence of Rice Husk Biochar and Lime in Reducing Phosphorus Application Rate in Acid Soil: A Field Trial with Maize. *Sustainability-basel* <https://doi.org/10.3390/su14127418> (2022).
20. He, L. L. et al. Long-Term Successive Seasonal Application of Rice Straw-Derived Biochar Improves the Acidity and Fertility of Red Soil in Southern China. *Agronomy-basel* <https://doi.org/10.3390/agronomy13020505> (2023).
21. Bao, S. D. Soil Agrochemical Analysis, 3rd ed. *China Agriculture Press: Beijing*. 1–120 (2000).
22. Chen, W. M., Wu, Z. S., Liu, C. H., Zhang, Z. Y. & Liu, X. C. Biochar combined with *Bacillus subtilis* SL-44 as an eco-friendly strategy to improve soil fertility, reduce fusarium wilt, and promote radish growth. *Ecotox Environ. Safe.* **251**, 114509. <https://doi.org/10.1016/j.ecoenv.2023.114509> (2023).
23. Guan, S. Y. Soil enzymes and research methods. *Agricultural Press: Beijing* 274–339 (1986).
24. Wang, X. K. Principles and Techniques of Plant Physiological and Biochemical Experiments, 2nd ed. *Higher Education Press: Beijing* (2006).
25. Mosharrof, M. et al. Combined application of Biochar and lime increases maize yield and accelerates carbon loss from an acidic soil. *Agronomy* **11** (7), 1313. <https://doi.org/10.3390/agronomy11071313> (2021).
26. Yin, Q. J., Jiang, J. W., Yin, H. Q., Li, Z. Y. & Li, T. X. Effects of organic materials input on soil nutrients and microbial metabolism in newly reclaimed farmland. *Chin. J. Appl. Ecol.* **36** (4), 1001–9332. <https://doi.org/10.13287/j.1001-9332.202504.007> (2025).
27. Xu, X. L. et al. 44-Years of fertilization altered soil microbial community structure by changing soil Physical, chemical properties and enzyme activity. *J. Soil. Sci. Plant. Nut.* **24** (2), 3150–3161. <https://doi.org/10.1007/s42729-024-0740-x> (2024).
28. Radziemska, M. et al. Compost-diatomite-based phytostabilization course under extreme environmental conditions in terms of high pollutant contents and low temperatures. *Sci. Total Environ.* **948**, 174917. <https://doi.org/10.1016/j.scitotenv.2024.174917> (2024).
29. Li, Z., Jiang, L. G., Tang, R. H., Liu, H. L. & Zhou, G. S. Effects of continuous cropping on soil enzyme activity, nutrient content and plant yield of peanut. *Acta Pedol. Sin.* **50** (3), 491–497 (2018).
30. Daraei, E., Bayat, H. & Gregory, A. S. Impact of natural biochar on soil water retention capacity and quinoa plant growth in different soil textures. *Soil. Till Res.* <https://doi.org/10.1016/j.still.2024.106281> (2024).
31. Song, W. H. et al. Mulching Practices Improve Soil Moisture and Enzyme Activity in Drylands, Increasing Potato Yield. *Agronomy-Basel* **14**(5), 1077. <https://doi.org/10.3390/agronomy14051077> (2024).
32. Ullah, A., Ren, W. L., Tian, P. & Yu, X. Z. Biochar as a green strategy in alleviating cd mobility in soil and uptake in plants: A step towards cd-free food. *Int. Biodeter Biodegr.* **190**, 105787. <https://doi.org/10.1016/j.ibiod.2024.105787> (2024).
33. Pandit, N. R. et al. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil. *Sci. Total Environ.* **625**, 1380–1389. <https://doi.org/10.1016/j.scitotenv.2018.01.022> (2018).
34. Li, Z. M. et al. Effects of phytolith rice-straw biochar, soil buffering capacity and pH on silicon bioavailability. *Plant. Soil.* **438** (1–2), 187–203. <https://doi.org/10.1007/s11104-019-04013-2> (2019).
35. Lehmann, J. & Kleber, M. The contentious nature of soil organic matter. *Nature* **528** (7580), 60–68. <https://doi.org/10.1038/nature16069> (2015).
36. Yan, Y. et al. Biochar stability and impact on soil organic carbon mineralization depend on Biochar processing, aging and soil clay content. *Soil. Biol. Biochem.* **169**, 108657. <https://doi.org/10.1016/j.soilbio.2022.108657> (2022).
37. Li, S. et al. Short-term lime application impacts microbial community composition and potential function in an acid black soil. *Plant. Soil.* **470** (1–2), 35–50. <https://doi.org/10.1007/s11104-021-04913-0> (2022).
38. Mosharrof, M. et al. Combined application of Biochar and lime increases maize yield and accelerates carbon loss from an acidic soil. *Agronomy-basel* **11** (7), 1084. <https://doi.org/10.3390/agronomy11071313> (2021).
39. Adekiya, A. O., Ayorinde, B. B. & Ogunbode, T. Combined lime and Biochar application enhances Cowpea growth and yield in tropical Alfisol. *Sci. Rep.* **14** (1), 1389. <https://doi.org/10.1038/s41598-024-52102-7> (2024).
40. Jeffery, S. et al. Biochar boosts tropical but not temperate crop yields. *Environ. Res. Lett.* **12** (5), 053001. (2017).
41. Be, S., Vinitnantharat, S. & Pinisakul, A. Effect of Mangrove Biochar residue amended shrimp pond sediment on nitrogen adsorption and leaching. *Sustainability* **13** (13), 7230. <https://doi.org/10.3390/su13137230> (2021).
42. Ukwattage, N. L., Li, Y. C., Gan, Y. D., Li, T. T. & Gamage, R. P. Effect of Biochar and coal fly Ash soil amendments on the leaching loss of phosphorus in subtropical sandy ultisols. *Water Air Soil. Poll.* **231** (2), 56. <https://doi.org/10.1007/s11270-020-4393-5> (2020).
43. Lv, Y. et al. Effect of Biochar on the migration and leaching of phosphorus in black soil. *Paddy Water Environ.* **19** (1), 1–9. <https://doi.org/10.1007/s10333-020-00815-6> (2021).

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## Declarations

### Competing interests

The authors declare no competing interests.

### Declaration of test materials

We hereby promise and declare that the use of plant materials in the experiment strictly complies with all relevant institutional, national, and international guidelines and regulations, and there are no violations whatsoever.

### Additional information

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-24775-1>.

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