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The impact of compound soil conditioner on the physicochemical properties of acidic farmland soil in Sichuan Province, China

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ABSTRACT

Soil acidification is a critical factor leading to low soil fertility and continuous nutrient loss, severely affecting agricultural production. In this study, a typical acidic soil area in Sichuan, China, was selected as the research region. Based on a systematic analysis of the physicochemical properties of the acidic soils, a compound soil amendment consisting of $Ca(OH)_2$-modified biochar (CBC) and fermented chicken manure was prepared to improve soil fertility and reduce nutrient leaching. Four application rates of CBC (0.5%, 1%, 2%, and 4.5%, based on dry soil weight) were investigated through a soil column leaching experiment. The results showed that the majority of soils were rather poor in fertility under acidic conditions, with several nutrients, including available phosphorus, being insufficient. In addition, the combined application of CBC and fermented chicken manure effectively improved soil fertility and reduced nutrient losses. Compared with the control, all amended treatments increased soil pH and enhanced the contents of ammonium nitrogen, nitrate nitrogen, available phosphorus, available potassium, and organic matter. Among them, the CBC(2%) treatment exhibited the highest available phosphorus content, while the CBC(4.5%) treatment showed superior performance in improving available potassium and organic matter contents. The lowest total nitrogen loss (139.42 mg/L) was observed in the CBC(2%) treatment, whereas the lowest total phosphorus loss (0.90 mg/L) and organic matter loss (224.62 mg/L) were recorded in the CBC(4.5%) treatment. These findings indicate that the combination of $Ca(OH)_2$-modified biochar and fermented chicken manure can effectively enhance nutrient retention and improve the fertility of acidic farmland soils. The proposed amendment provides a simple, low-cost, and sustainable approach for acidic soil remediation and nutrient management in agricultural ecosystems.

Keywords: acidic soil, $Ca(OH)_2$-modified biochar, fermented chicken manure, soil amendment, nutrient leaching, soil fertility.

INTRODUCTION

Soil acidification and nutrient depletion have become major challenges restricting sustainable agricultural development worldwide, especially in subtropical regions with intensive cultivation and abundant rainfall. In China, acidic soils are widely distributed in southern provinces, among which Sichuan Province represents a typical agricultural area characterized by low soil fertility and severe nutrient losses. Excessive soil acidification can accelerate the leaching of base cations such as Ca^{2+}, K^+, and Mg^{2+}, destroy soil aggregate structures, and reduce the availability of essential nutrients, thereby adversely affecting crop growth and productivity (Liu et al., 2013). Furthermore, large-scale land consolidation and intensive agricultural practices often alter soil structure and accelerate nutrient depletion, resulting in a decline in soil quality and limiting the efficiency of agricultural production. Therefore, developing efficient and sustainable approaches to improve acidic soils and enhance nutrient retention has attracted increasing attention (Guo et al., 2010; Zhao et al., 2009; Fenn et al., 1998; Yuan et al., 2011).

Currently, the use of biochar (BC) to improve soil quality is receiving increasing attention and research from scholars. Jeffery has found that biochar can effectively enhance the soil's pH buffering capacity and improve soil fertility (Jeffery et al., 2011). Lehmann and colleagues discovered that biochar contains a large amount of organic anions, inorganic salts, and carbonates, making it predominantly alkaline. The porous structure of biochar, coupled with its surface oxygen-containing functional groups, increases its adsorption capacity for cations, thereby enhancing the cation exchange capacity (CEC) of the soil. The key factor determining soil pH buffering is precisely the CEC (Lehmann et al., 2015). Blanco-Canqui has found that biochar contains numerous micropores, mesopores, and macropores. This porous nature endows biochar with strong adsorption capabilities, enabling it to effectively adsorb nutrients and moisture from the soil. Additionally, it can improve soil structure, facilitating better air and moisture circulation within the soil (Blanco-Canqui, 2017).

Alkali-modified biochar has also become a mainstream trend, often used to study whether it can effectively adsorb heavy metals in soil (Ahmad et al., 2013). $Ca(OH)_2$ has the characteristics of low cost, simple preparation, convenient transportation, and strong alkalinity. $Ca(OH)_2$ solution can be quickly prepared by soaking CaO in water, making it more convenient and efficient for application in agricultural land. Moreover, CaO is easy to obtain and cost-effective. The addition of $Ca(OH)_2$ can more efficiently reduce soil acidity, replenish Ca^+ in the soil, and improve soil structure (Manuel et al., 2021).

The integrated farming and planting circular agricultural model is an agricultural development approach that achieves efficient resource utilization and effective carbon emission control through the mutual consumption of livestock manure and crop straw, forming a complementary relationship. This model operates based on the principles of material circulation and energy flow in ecosystems, viewing farming and planting as an organic whole (Han et al., 2023). Livestock manure such as chicken manure, which is relatively easy to obtain in Sichuan's farming industry, can serve as high-quality fertilizer for planting. When fermented, it can be used as organic fertilizer, reducing the amount of chemical fertilizer applied and consequently lowering carbon emissions during fertilizer production and use, while also increasing soil organic matter (Moshe et al., 2015; Kumar et al., 2013; An et al., 2023). On the other hand, corn straw generated from planting can serve as raw material for biochar, and also as a feed source for the farming industry or used to make bedding for livestock farming, achieving resource recycling. Integrated farming and planting requires the coordination of multiple technologies, including planting, farming, and waste disposal. However, there is currently a lack of mature integrated farming and planting technologies, making it difficult for farmers to master. Additionally, the initial investment is large, and the benefits are slow to materialize, which can increase the burden on migrant workers and affect farmers' enthusiasm (Shanmugam et al. 2024; Qian et al., 2023).

The paper utilizes corn straw, a common material in agricultural land, as the raw material to prepare biochar. Furthermore, it employs $Ca(OH)_2$ for chemical modification and combines it with chicken manure fermented organic fertilizer to create a composite soil amendment. Through material characterization and indoor soil column experiments, the study explores the effects of the composite soil amendment on soil physicochemical properties and compares and analyzes the mechanism of modified biochar on soil improvement under different application rates. The research aims to provide a low-cost and high-efficiency soil improvement method under the integrated farming and breeding model.

MATERIALS AND METHODS

Study area

The study area (in Figure 1) was located in Xiniu Village, Houba Town, Jiangyou City, Sichuan Province, China (105.03°E, 31.95°N). The region belongs to the subtropical humid monsoon climate zone, characterized by mild temperatures, abundant precipitation, and distinct seasons. The annual precipitation ranges from approximately 750 to 1350 mm, with most rainfall occurring from June to September. The mean annual temperature is about 16.5 °C, with a maximum temperature of 37.5 °C and a minimum temperature of -2.9 °C. The frost-free period lasts approximately 280 days annually.

The study area is situated in a hilly valley region with an average elevation of approximately 647 m above sea level. The dominant soil type is loam, and dry farmland is the primary land-use type. Major crops cultivated in the area include maize and wheat, while rapeseed is the main oil crop. Due to long-term cultivation and intensive agricultural activities, some farmland soils in the region have experienced acidification and nutrient depletion, resulting in reduced soil fertility and decreased agricultural productivity. Therefore, this area was selected as a representative region for investigating the effects of compound soil amendments on acidic farmland soils.

Preparation of $Ca(OH)_2$-modified biochar

Maize straw collected from local farmland was used as the feedstock for biochar production. The biochar was prepared through pyrolysis under oxygen-limited conditions using a tube furnace. Prior to pyrolysis, helium gas was continuously introduced into the furnace for 30 min at a flow rate of 60 mL min^{-1} to remove residual oxygen. Subsequently, the air-dried maize straw (100 g) was heated from room temperature to 500 °C at a heating rate of 5 °C min^{-1} and maintained at this temperature for 4 h. After naturally cooling to room temperature, the obtained product was collected and designated as pristine biochar.

To prepare $Ca(OH)_2$-modified biochar, 25 g of BC wrapped in nylon gauze was immersed in 1 L of saturated $Ca(OH)_2$ solution for 24 h. The treated biochar was then removed and dried in an oven at 30 °C until a constant weight was reached. The resulting material was denoted as $Ca(OH)_2$-modified biochar (CBC) (Cheng et al., 2023).

Fermented chicken manure used in this study was supplied by a local livestock farm. Fresh chicken manure was subjected to high-temperature composting and windrow fermentation to eliminate pathogens and stabilize organic matter. The fermented product was subsequently used as the organic fertilizer component in the compound soil amendment (Petric et al., 2012).

Experimental design

A soil column leaching experiment was conducted to evaluate the effects of different application rates of $Ca(OH)_2$-modified biochar combined with fermented chicken manure on nutrient retention and soil fertility. Transparent polyvinyl chloride (PVC) columns with a height of 30 cm and an inner diameter of 10 cm were used. Prior to filling, a thin layer of petroleum jelly was applied to the inner wall of each column to minimize preferential flow along the column wall. A 20-cm soil layer (approximately 1.5 kg air-dried soil) was packed in the middle section of each

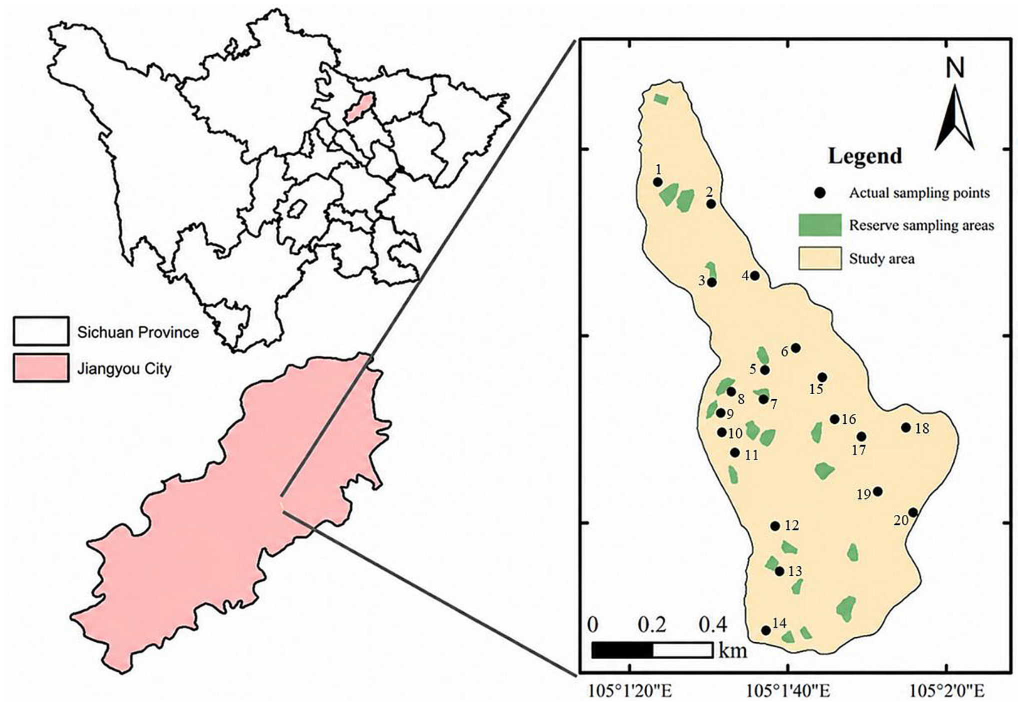

Figure 1. Geographical location of the research area

column, and a 1-cm quartz sand layer was placed both above and below the soil layer. Nylon mesh was installed at the bottom outlet and at the interfaces between soil and quartz sand to prevent particle loss during leaching.

Five treatments were established in this study. The control treatment (CK) consisted of 1.5 kg of air-dried soil without any amendment. In the amended treatments, a constant amount of 20 g fermented chicken manure was added together with different amounts of CBC, corresponding to 0.5%, 1%, 2%, and 4.5% of the dry soil weight. Specifically, treatment $S_{0.5}$ contained 7.5 g CBC, treatment S1 contained 15 g CBC, treatment S_2 contained 30 g CBC, and treatment $S_{4.5}$ contained 67.5 g CBC (He et al., 2022; Ute et al., 2014; Jebarathanam et al., 2019; Major et al., 2012).

Before the leaching experiment, approximately 450 mL of deionized water was added to each soil column to achieve an initial soil moisture content corresponding to about 80% saturation. The columns were then equilibrated at room temperature for 24 h to establish a relatively stable soil environment (Xiao et al., 2016). During the experimental period, 150 mL of deionized water was applied to each column every two days, and a total of seven leaching events were performed over 14 days. Soil moisture was maintained at approximately 70% of the field water-holding capacity throughout the experiment.

Leachate samples were collected every two days through a plastic tube connected to the outlet at the bottom of each column. After filtration, the concentrations of total nitrogen (TN), total phosphorus (TP), total potassium (TK), and total organic carbon (TOC) in the leachates were determined to assess nutrient losses (Jebarathanam et al., 2019).

At the end of the experiment, the soil columns were destructively sampled at 10-cm intervals. Two soil samples were obtained from each column, resulting in a total of ten samples. The collected soil samples were air-dried, homogenized, and analyzed for ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3-N), available phosphorus (AP), available potassium (AK), and soil organic matter (SOM) contents to evaluate the effects of different treatments on soil fertility.

Characterization and analytical methods

The morphological characteristics of BC and CBC were observed using a field emission scanning electron microscope (SEM; Sigma 300, ZEISS, Germany). The surface morphology and pore structures of the biochar samples were analyzed at different magnifications to evaluate the effects of alkali modification on the physical structure of biochar.

The pore characteristics of BC and CBC were determined by nitrogen adsorption–desorption measurements using a Brunauer–Emmett–Teller (BET) surface area analyzer (BELSORP MINI X, MicrotracBEL, Japan). Prior to analysis, the samples were degassed under vacuum to remove moisture and impurities. The specific surface area, pore volume, and average pore diameter were calculated from the adsorption–desorption isotherms. In addition, the Barrett–Joyner–Halenda (BJH) method was employed to analyze the pore size distribution of the biochar samples.

The surface functional groups of BC and CBC were characterized by Fourier transform infrared spectroscopy (FTIR; Tensor II, Bruker, Germany). The spectra were recorded over the wavelength range of 4000–400 cm−1 to identify the changes in chemical functional groups after $Ca(OH)_2$ modification.

To evaluate the effects of the compound soil amendment on nutrient retention, leachate samples collected during the experiment were filtered and analyzed for TN, TP, TK, and TOC. After completion of the leaching experiment, soil samples from different depths were collected, air-dried, homogenized, and subjected to physicochemical analyses. Soil pH was determined using the potentiometric method (HJ 962-2018), and soil moisture content was measured by the gravimetric method (HJ 613-2011). The concentrations of ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), available phosphorus (AP), and available potassium (AK) were determined using a soil nutrient analyzer (HM-TYD, China). SOM content was also measured to evaluate changes in soil fertility after amendment application (Agegnehu et al., 2017).

RESULTS

Initial soil properties and spatial distribution

Twenty surface soil samples were collected from the study area to investigate the initial physicochemical characteristics of the farmland soils. Considerable variations in soil properties were observed among different sampling sites. Soil pH values ranged from 4.60 to 8.02, indicating that most soils in the study area were acidic. Soil moisture content varied between 10.86% and 23.10%, while the oxidation-reduction potential (Eh) ranged from 86.8 to 291.4 mV. In addition, the concentrations of ammonium nitrogen, nitrate nitrogen, available phosphorus, available potassium, and soil organic matter exhibited substantial spatial heterogeneity.

Through research and analysis of the data in the Table 1, we can understand that the soil in this area is mostly acidic. Furthermore, the soil is infertile, with some nutrients (such as available phosphorus) in the soil far below the average standard. Some studies (Guo et al., 2010) have shown that soil acidification can cause plant roots to secrete toxic substances, leading to plant autotoxicity. Additionally, soil acidification can destroy the normal granular structure in the soil, exacerbating soil compaction issues.

To further characterize the spatial distribution patterns of soil properties, inverse distance weighting (IDW) interpolation was performed using ArcMap 10.7 based on the measured data from the twenty sampling sites. The spatial distributions of soil pH, ammonium nitrogen, nitrate nitrogen, available phosphorus, available potassium, and soil organic matter are presented in Figure 2.

As shown in Figure 2, soil pH generally exhibited an increasing trend from north to south and a decreasing trend from west to east. Relatively high concentrations of soil organic matter, available phosphorus, and nitrate nitrogen were mainly distributed in the central part of the study area, whereas lower values were observed in the northern and southern regions. In contrast, ammonium nitrogen and available potassium tended to increase from north to south. Overall, the high-value zones of most soil properties were concentrated in the central region, while relatively low nutrient levels were found in the northern area.

These spatial variations may be related to differences in topography, land use patterns, fertilization practices, and vegetation coverage. According to the comprehensive evaluation of soil physicochemical characteristics, to address the issues of soil acidification and low nutrient content in this area, combined with the above-mentioned

Table 1. Initial physicochemical properties of the farmland soils in the study area

Sample location	pH	Water content /%	Redox potential /mV	Conductivity /(μs/cm)	Ammonium ammonia /(mg/kg)	Nitrate nitrogen /(mg/kg)	Available phosphorus /(mg/kg)	Available potassium/ (mg/kg)	Organic matter /(g/kg)
1	4.597	16.05	291.4	159.6	144.5	117.69	21.28	102.1	19.81
2	6.822	16.64	145.1	73.0	24.16	118.80	27.06	208.1	20.54
3	5.347	19.06	265.0	63.7	72.20	119.32	16.70	170.3	17.35
4	5.460	19.63	249.7	68.6	128.2	225.18	35.74	106.6	21.26
5	7.779	12.32	102.0	164.7	47.95	224.16	17.36	183.3	18.84
6	7.918	12.70	96.5	131.2	35.69	121.75	28.70	156.2	19.64
7	7.838	10.86	86.8	158.6	261.5	216.98	22.13	203.3	22.35
8	7.890	15.84	95.5	156.2	16.55	117.32	56.21	193.2	25.42
9	6.081	16.34	219.0	55.8	32.69	114.25	23.70	174.1	21.84
10	5.957	18.53	218.6	47.9	48.23	119.28	33.20	203.9	26.25
11	8.015	17.91	115.9	179.2	160.1	214.86	36.80	180.2	19.74
12	7.791	14.88	114.8	150.8	64.54	127.30	25.70	254.9	18.93
13	7.439	15.42	133.9	124.7	207.2	126.54	16.15	125.2	19.38
14	5.877	16.24	226.8	55.5	131.2	118.13	25.02	215.7	17.69
15	6.289	23.10	147.5	79.2	60.07	119.24	39.22	165.73	20.64
16	5.325	21.72	265.7	77.3	95.3	123.18	22.59	195.12	20.89
17	5.918	21.85	204.5	53.2	41.38	163.1	22.60	128.9	27.85
18	5.904	19.81	162.8	105.7	47.99	126.33	31.12	171.8	23.83
19	7.017	19.27	141.4	150.6	16.55	219.50	21.48	189.6	19.54
20	7.817	15.97	107.8	199.0	80.27	125.07	15.96	124.9	19.14

physicochemical property analysis results, soil sample No. 17 was selected for the subsequent soil column experiment because of its relatively low pH and nutrient contents, making it representative of degraded acidic farmland soils in the study area.

Characterization of $Ca(OH)_2$-modified biochar

The surface morphology of CBC was examined using SEM. As shown in Figure 3a, the modified biochar exhibited a rough and irregular surface with abundant pores of different sizes and shapes. Numerous folds and cavities were observed, indicating the development of a porous structure after alkali modification. The pore structures and surface irregularities of CBC provide favorable sites for nutrient adsorption and microbial colonization. In addition, the interconnected pore network may facilitate water movement and improve the aeration characteristics of the soil.

The nitrogen adsorption–desorption isotherms of BC and CBC are presented in Figure 3d. Both BC and CBC exhibited typical type IV adsorption isotherms with H3 hysteresis loops, indicating the presence of mesoporous structures. The pore size distribution curves obtained using the Barrett–Joyner–Halenda (BJH) method are shown in Figure 3b. The results demonstrated that CBC possessed a wider pore size distribution and a larger average pore diameter compared with BC.

The corresponding pore structural parameters are summarized in Table 2. The pore volume and average pore diameter increased from 0.053266 cm^3/g and 3.8164 nm in BC to 0.063863 cm^3/g

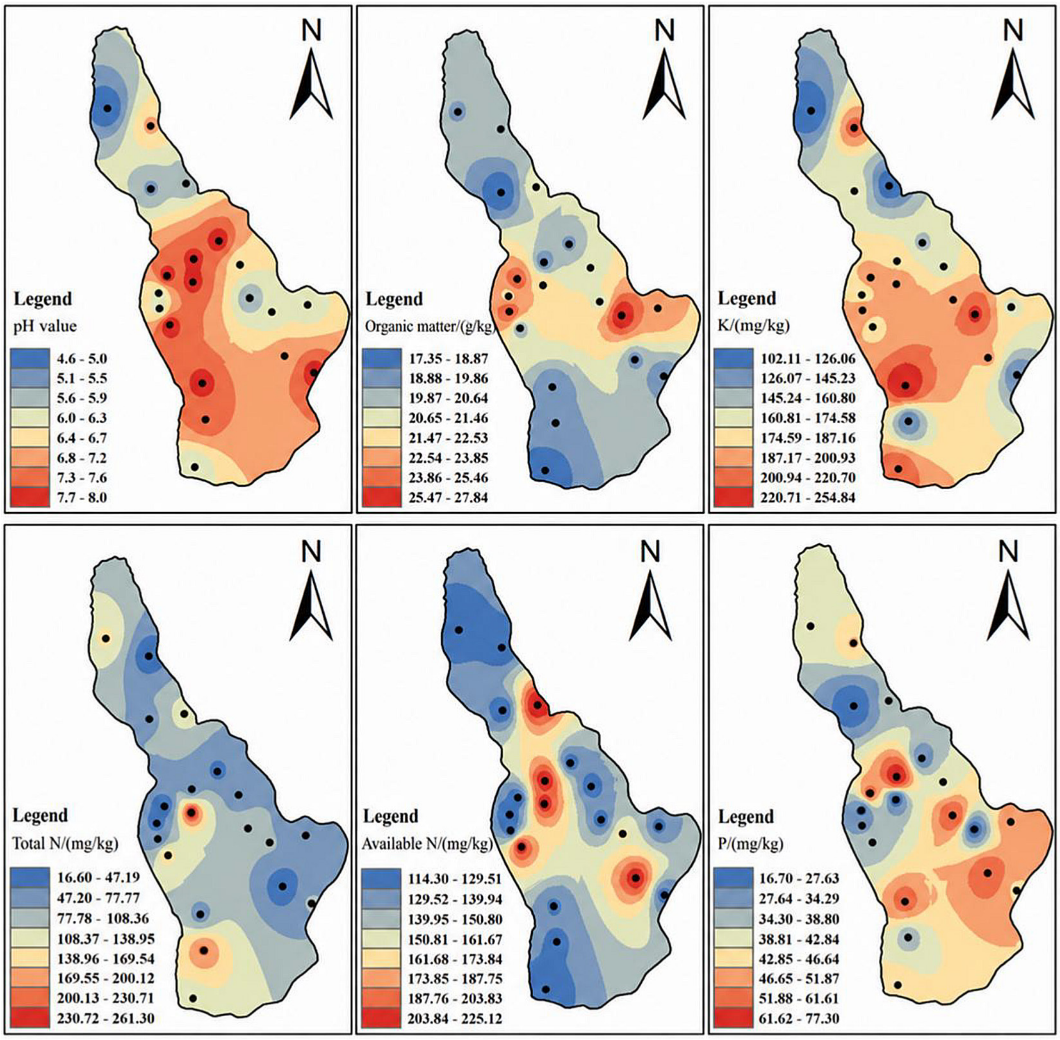

Figure 2. Spatial distribution of selected soil physicochemical properties in the study area obtained by inverse distance weighting interpolation

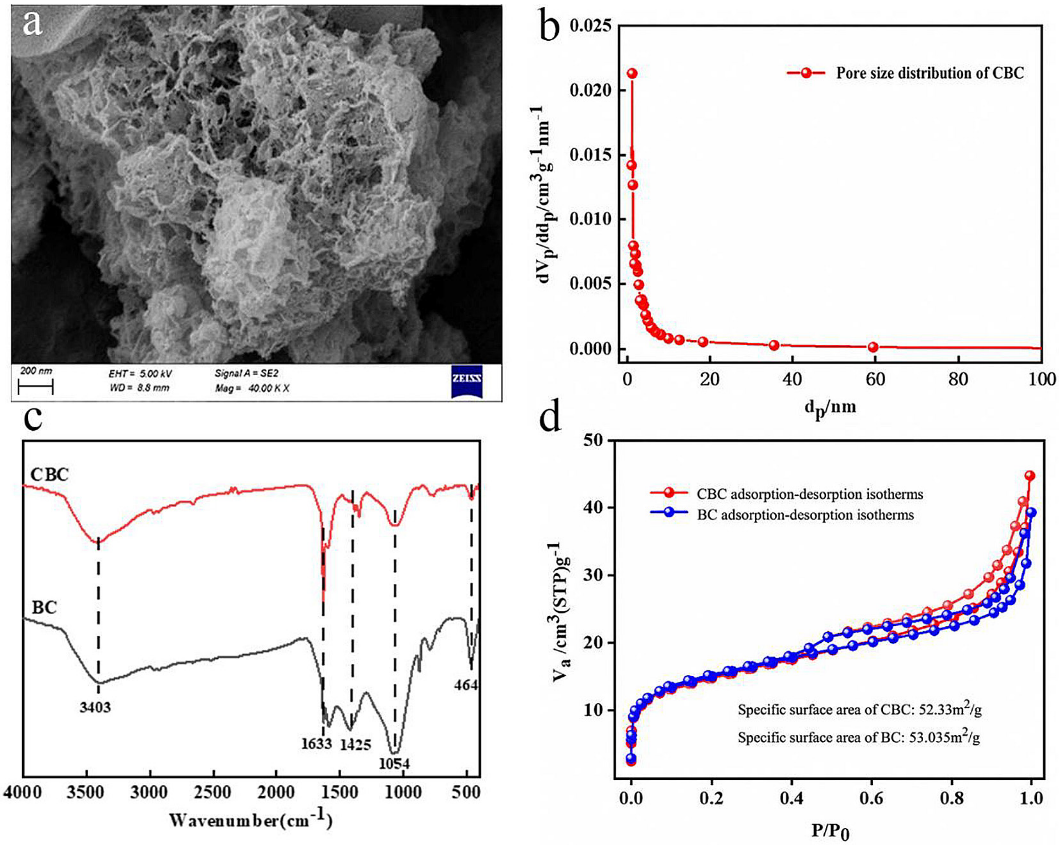

Figure 3. The characterizes of $Ca(OH)_2$-modified biochar (CBC). a: SEM image; b: BJH pore size distribution curves; c: FTIR spectra; d: N_2 adsorption–desorption isotherms

and 4.4235 nm in CBC, respectively. In contrast, the specific surface area changed only slightly after modification. These results indicate that $Ca(OH)_2$ treatment altered the pore characteristics of biochar and increased the pore volume and average pore size.

The Fourier transform infrared (FTIR) spectra of BC and CBC are shown in Figure 3c. A broad absorption peak observed at approximately 3403 cm^{-1} corresponded to the stretching vibrations of hydroxyl (O–H) and amino (N–H) groups. The absorption peak around 1633 cm^{-1} was attributed to the stretching vibrations of C=C and C=N bonds, indicating the presence of aromatic structures and unsaturated functional groups (Beesley et al., 2011). In addition, the absorption peaks near 1054 cm-1 are due to the stretching and bending vibrations of C=O and C-O-C bonds, indicating the presence of ester and phenolic organic linkages (Liang et al., 2006). From the information collated above, it can be seen that CBC possesses a relatively rich array of functional groups, some of which are unsaturated, including amino, carboxyl, and hydroxyl groups. This is a key factor that makes it a promising adsorbent.

The physicochemical properties of CBC and fermented chicken manure are listed in Table 3. CBC exhibited an alkaline nature with a pH value of 10.45 and contained relatively high contents of nitrogen, phosphorus, potassium, and organic carbon.

Effects of CBC on nutrient leaching

The concentrations of TN, TP, TK, and organic matter in the leachates collected during the experiment were determined every two days. A total of seven sampling events were conducted over a 14-day period to investigate the influence of different CBC application rates on nutrient loss. The temporal variations in nutrient concentrations under different treatments are shown in Figure 4.

Total nitrogen leaching

As shown in Figure 4a, the TN concentration in the leachates of the CK treatment continuously decreased throughout the experimental period. In contrast, the TN concentrations in the four amendment treatments exhibited a rapid

Table 2. Pore structural parameters of pristine biochar (BC) and $Ca(OH)_2$-modified biochar (CBC)

Parameter	Pore volume (cm^3/g)	Average pore size(nm)	Specific surface area(m^2/g)
BC	0.053266	3.8164	53.035
CBC	0.063863	4.4235	52.33

Table 3. Physicochemical properties of CBC and fermented chicken manure

Parameter	pH	N/%	P/%	K/%	Organic carbon /%	ash content /%
CBC	10.45	8.23	2.48	15.93	41.55	7.06
Fermented chicken manure	6.5	3.73	2.47	1.85	27.5	0

decline during the initial stage followed by a slight increase, reaching minimum values during days 4–6. Among all treatments, the S_2 treatment showed the lowest TN concentration, with a minimum value of 17.33 mg/L recorded during days 5–6, whereas the highest TN concentration (28.07 mg/L) was observed in the $S_{4.5}$ treatment during days 1–2.

Compared with the CK treatment, the addition of CBC combined with fermented chicken manure effectively reduced nitrogen loss. The cumulative TN losses were 141.49, 140.62, and 139.42 mg/L for S0.5, S_1, and S_2, respectively, indicating that increasing the CBC dosage within a certain range improved nitrogen retention. However, when the application rate reached 4.5%, the cumulative TN loss slightly increased to 142.33 mg/L, suggesting that excessive CBC addition weakened its nitrogen retention effect.

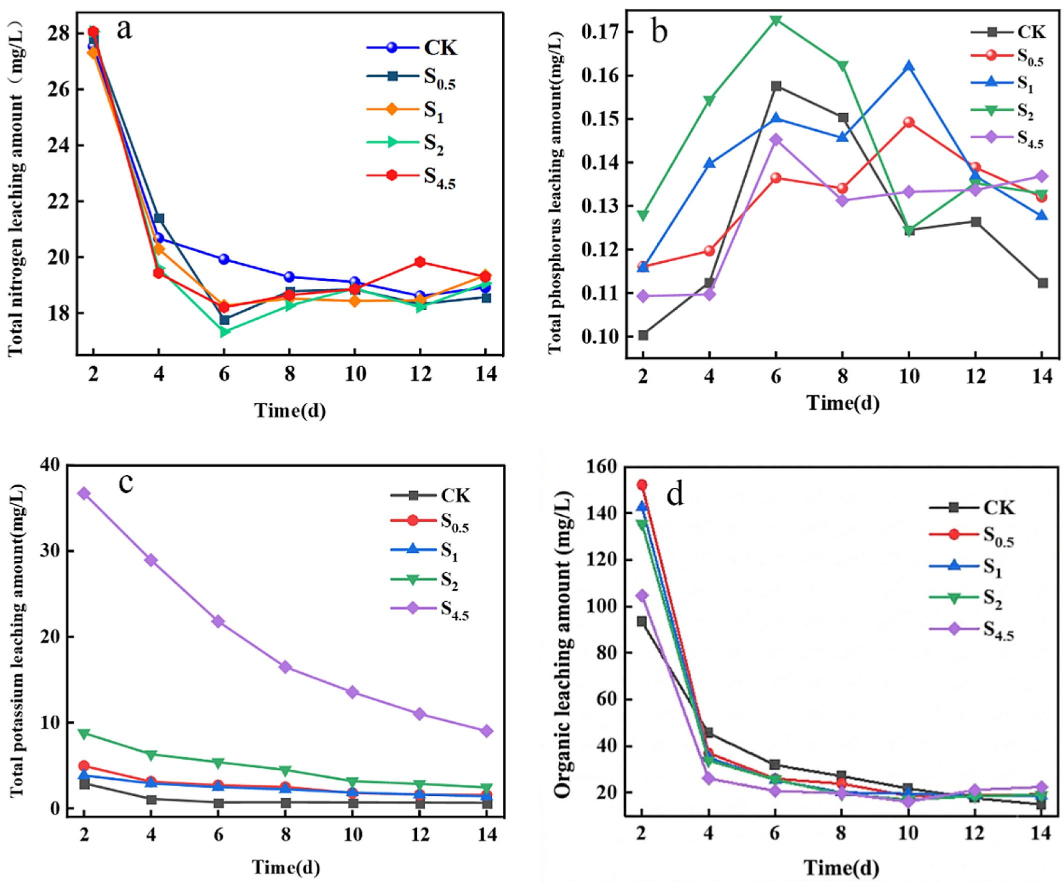

Figure 4. Temporal variations in TN, TP, TK, and organic matter concentrations in soil leachates under different treatments

Overall, the S_2 treatment exhibited the strongest ability to reduce nitrogen leaching, with a total TN loss of 139.42 mg/L, representing the lowest value among all treatments.

Total phosphorus leaching

The TP concentration in soil leachates generally exhibited an increasing trend during the first six days, followed by a gradual decline (Figure 4b). The TP concentrations in all treatments increased during the early stage of the experiment, indicating the release of phosphorus from the soil and amendment materials. The highest TP concentration was observed in the S_2 treatment during days 5–6, whereas the lowest value occurred in the CK treatment during days 1–2.

After day 6, the TP concentration in the CK treatment continuously decreased, while the amended treatments showed slight fluctuations before gradually declining. These results indicate that CBC application altered phosphorus migration behavior and affected phosphorus release and retention in the soil.

The cumulative TP losses are presented in Table 4. Compared with the CK treatment (0.884 mg/L), the cumulative TP losses in the $S_{0.5}$, S_1, and S_2 treatments increased to 0.926, 0.978, and 1.010 mg/L, respectively. However, the $S_{4.5}$ treatment showed a lower cumulative TP loss (0.899 mg/L), which was close to that of the CK treatment.

Overall, the TP leaching pattern exhibited an initial increase followed by a decrease. Although moderate CBC application promoted phosphorus release, excessive CBC addition appeared to suppress phosphorus loss, resulting in relatively lower cumulative TP concentrations in the $S_{4.5}$ treatment.

Total potassium leaching

As illustrated in Figure 4c, the concentration of TK in the leachates generally exhibited a continuous decreasing trend throughout the experimental period. In the CK treatment, the TK concentration gradually stabilized at approximately 0.65 mg/L after day 4. For the $S_{0.5}$, S_1, and S_2 treatments, the potassium concentrations approached stable values after day 10, with equilibrium concentrations of approximately 1.5, 1.4, and 2.4 mg/L, respectively.

In contrast, the $S_{4.5}$ treatment maintained a decreasing trend even at the end of the experiment, indicating that potassium release had not yet reached equilibrium. It was estimated that the TK concentration in the $S_{4.5}$ treatment would gradually stabilize after approximately 20 days, with a potential range of 6–10 mg/L.

Comparison between the $S_{0.5}$ and S_1 treatments revealed that moderate additions of CBC enhanced potassium retention in soil and reduced potassium leaching. However, excessive CBC application promoted potassium release and migration. In particular, the $S_{4.5}$ treatment exhibited substantially higher potassium concentrations than the other treatments during the entire experimental period, indicating that excessive CBC application may weaken the capacity of the soil amendment to retain potassium and thereby accelerate potassium loss.

Organic matter leaching

The variation in organic matter concentration in soil leachates is shown in Figure 4d. The organic matter concentration in the CK treatment continuously decreased throughout the experiment, whereas the amended treatments exhibited a decreasing trend during the initial stage followed by a slight increase after day 10.

Compared with the four amendment treatments, the CK treatment maintained a relatively stable decline, whereas the addition of CBC and fermented chicken manure significantly altered the dynamics of organic matter release. With increasing CBC application rates, the retention capacity for organic matter gradually improved. The $S_{4.5}$ treatment showed the lowest organic matter concentration of 13.36 mg/L on day 10, indicating the strongest retention effect among all treatments.

After day 10, a slight increase in organic matter concentration was observed in the amended treatments. This phenomenon may be attributed to the gradual decomposition of the amendment and the sustained release of dissolved organic substances, which indirectly supplied additional organic matter to the soil solution.

Overall, the application of CBC combined with fermented chicken manure effectively reduced organic matter loss and enhanced the retention of soil organic carbon.

According to Table 4, the cumulative TN loss was lowest in the S_2 treatment (139.42 mg/L), whereas the minimum cumulative TP and organic matter losses were observed in the $S_{4.5}$ treatment, reaching 0.899 mg/L and 224.62 mg/L, respectively. The lowest cumulative TK loss occurred in the S1 treatment (16.21 mg/L). These results indicate that different application rates of CBC exerted varying effects on nutrient retention, and no single treatment simultaneously minimized the losses of all nutrients.

Effects of CBC on soil physicochemical properties

The effects of different application rates of CBC combined with fermented chicken manure on soil physicochemical properties after the leaching experiment are illustrated in Figure 5. The measured parameters included soil pH, NH_4^+-N, NO_3^--N, available phosphorus, available potassium, and soil organic matter. Overall, the incorporation of the compound soil amendment improved soil fertility to varying degrees compared with the control treatment.

Soil pH

The variation in soil pH under different treatments is presented in Figure 5a. Compared with the control treatment, the addition of CBC and fermented chicken manure increased soil pH values at all sampling depths. The pH values of the treated soils were generally above 7.0, indicating that the acidic soil was effectively neutralized after amendment application.

The influence of CBC on soil pH was most pronounced in the upper soil layer. At the depth of 5 cm, the treated soils exhibited higher pH values than the control, suggesting that the amendment had a greater effect on the surface soil. However, with increasing soil depth, the relationship between CBC application rate and pH value became less obvious. Among all treatments, the $S_{4.5}$ treatment exhibited the highest pH value of 7.75 at the depth of 20 cm. Overall, soil pH increased by approximately 14.77% compared with the initial soil condition.

These results demonstrate that the application of CBC combined with fermented chicken manure effectively alleviated soil acidity and improved the chemical environment of acidic farmland soils.

NH_4^+-N and NO_3^--N

The distributions of ammonium nitrogen and nitrate nitrogen under different treatments are shown in Figure 5b and Figure 5c, respectively. Compared with the control treatment, the addition of CBC significantly increased the contents of inorganic nitrogen in the soil profile.

For ammonium nitrogen, relatively low application rates of CBC exhibited more pronounced effects in the upper soil layers (0–10 cm). However, with increasing soil depth and amendment dosage, the NH_4^+-N content gradually increased. The highest ammonium nitrogen concentration was observed in the $S_{4.5}$ treatment at the depth of 20 cm, reaching 29.02 mg/kg.

The nitrate nitrogen content was also enhanced by CBC addition throughout the soil profile. Compared with the control treatment, all amended treatments showed higher NO_3^--N concentrations. The increase was particularly evident in the 0–15 cm soil layer, indicating that the compound amendment effectively promoted nitrate retention in the soil. Among all treatments, the highest NO_3^--N content (180.8 mg/kg) was recorded in the $S_{0.5}$ treatment at the depth of 20 cm.

Overall, the results indicate that the combined application of CBC and fermented chicken manure improved the availability and retention of inorganic nitrogen in acidic soils. Different amendment dosages resulted in different distribution patterns of NH4+-N and NO_3^--N within the soil profile, suggesting that the response of soil nitrogen forms to CBC application varied with both amendment rate and soil depth.

Available phosphorus

The effects of different treatments on soil available phosphorus are presented in Figure 5d.

Table 4. Cumulative losses of total nitrogen, total phosphorus, total potassium, and organic matter under different treatments

Parameter	CK	S_0.5	S_1	S_2	$S_{4.5}$
Total nitrogen leaching amount/ mg/L	144.0715	141.4907	140.6241	139.4186	142.326
Total phosphorus leaching amount/ mg/L	0.88447	0.92640	0.97765	1.01035	0.89925
Total potassium leaching amount(mg/L)	7.404	18.138	16.208	33.345	137.450
Organic Leaching amount(mg/L)	252.028	295.790	279.769	272.072	224.616

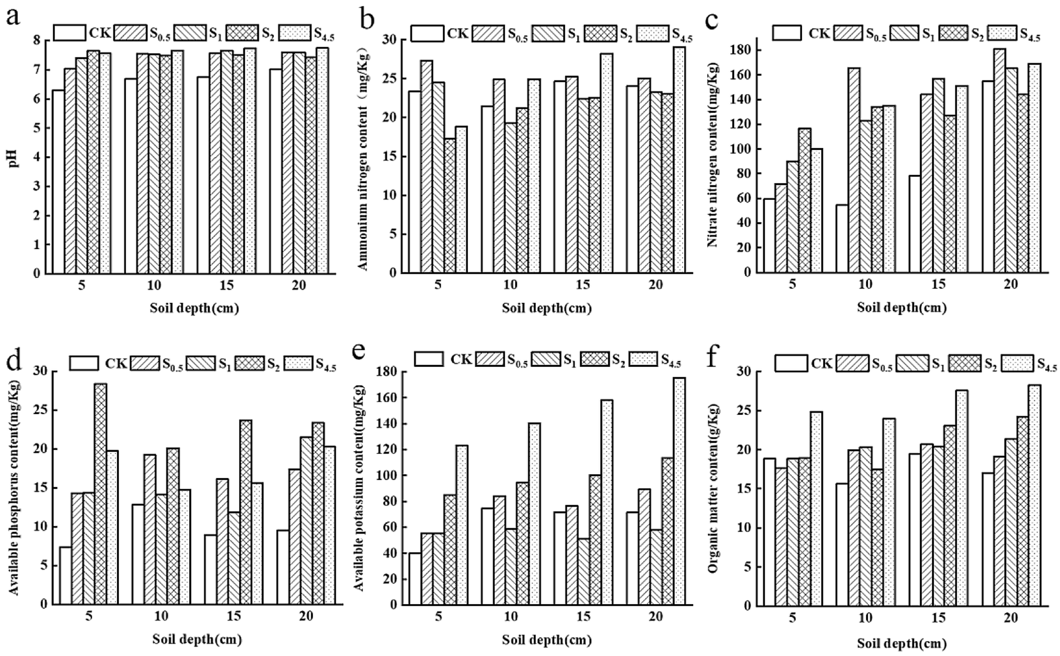

Figure 5. Changes in soil physicochemical properties under different treatments

Compared with the control treatment, the addition of CBC combined with fermented chicken manure significantly increased the available phosphorus content throughout the soil profile. However, the enhancement effect was not positively correlated with the application rate of CBC.

Among all treatments, the S_2 treatment exhibited the most pronounced increase in available phosphorus. The available phosphorus contents at all sampling depths under S_2 were higher than those of the other treatments. The maximum value of 28.38 mg/kg was observed at the depth of 5 cm. In contrast, although the $S_{4.5}$ treatment also improved soil phosphorus availability compared with the control treatment, its promoting effect was lower than that of the S_2 treatment.

Overall, the results suggest that moderate CBC application was more effective in increasing soil available phosphorus, whereas excessive amendment dosage did not further enhance phosphorus availability.

Available potassium

The variations in soil available potassium under different treatments are shown in Figure 5e. Compared with the control treatment, all amended soils exhibited higher available potassium contents. Moreover, the increase in available potassium generally became more pronounced with increasing CBC application rates.

Among the treatments, $S_{4.5}$ showed the highest available potassium content throughout the soil profile. The maximum value of 175.4 mg/kg was recorded at the depth of 20 cm. Relative to the control treatment, the available potassium content increased by approximately 1.31 times after the combined application of CBC and fermented chicken manure.

These findings demonstrate that the compound soil amendment effectively enhanced soil available potassium by the addition of the CBC, owing to the abundant potassium constituents contained within the CBC.

Soil organic matter

The changes in soil organic matter content after different treatments are illustrated in Figure 5f. Compared with the control treatment, the application of CBC and fermented chicken manure substantially increased soil organic matter contents at all sampling depths.

A clear increasing trend in soil organic matter was observed with increasing CBC application rates. Among all treatments, $S_{4.5}$ exhibited the greatest enhancement effect. The maximum soil organic matter content reached 28.29 g/kg at the depth of 20 cm, representing an increase of approximately 47.13% compared with the control treatment.

Furthermore, the promoting effect of the amendment became more evident in deeper soil layers. Particularly at the depth of 20 cm, the differences among treatments were more pronounced than those observed in the upper soil layers. The results indicate that increasing the amount of CBC contributed to greater accumulation of soil organic matter.

Overall, the combined application of $Ca(OH)_2$-modified biochar and fermented chicken manure effectively improved soil fertility by increasing the contents of available phosphorus, available potassium, and soil organic matter. However, the responses of different nutrients to increasing amendment dosage varied considerably, indicating that different soil properties exhibited different sensitivities to CBC application.

DISCUSSION

Effects of compound soil amendment on nutrient losses

The nutrient component characteristics of acidic soil in Sichuan Province, China was conducted, and it was revealed that the acidic soil is generally deficient in nutrients, with strong spatial heterogeneity being observed, indicating that nutrient loss from the acidic soil is also considerably severe. Therefore, the prevention of nutrient loss and nutrient supplementation should be given priority attention when the compound soil conditioner are being evaluated.

The results of the soil column experiment demonstrated that the compound soil amendment consisting of CBC and fermented chicken manure effectively influenced the migration and loss of soil nutrients. Different application rates of CBC exhibited different effects on the leaching behaviors of nitrogen, phosphorus, potassium, and organic matter, indicating that the retention capacity of nutrients was strongly associated with amendment dosage. Among all treatments, the S_2 treatment showed the lowest cumulative TN loss, suggesting that a moderate amount of CBC was beneficial for reducing nitrogen leaching. Biochar has been reported to possess abundant pore structures (as shown in Figure 3a) and oxygen-containing functional groups (as shown in Figure 3c), which provide adsorption sites for nutrient ions and improve nutrient retention in soils. In addition, the porous structure of biochar may increase water-holding capacity and prolong the residence time of nutrients, thereby reducing nitrogen losses during the leaching process. Similar results have been reported by Qian et al. (2023), who found that biochar-based amendments effectively enhanced nutrient retention and reduced nutrient leaching in degraded soils.

The variation in phosphorus loss exhibited a different pattern from that of nitrogen. Although the cumulative TP loss increased slightly under low and moderate CBC application rates, the $S_{4.5}$ treatment exhibited the lowest phosphorus loss among all treatments. According to previous studies, calcium-rich biochar may facilitate the transformation of soluble phosphorus into relatively stable phosphorus forms through interactions between calcium ions and phosphate ions. Therefore, the reduced phosphorus loss observed in the $S_{4.5}$ treatment may be associated with the increased calcium content introduced by $Ca(OH)_2$ modification. Similar phenomena have also been reported in acidic soils amended with calcium-containing biochar materials. However, because the concentrations of calcium ions and phosphorus fractions were not determined in the present study, the underlying mechanisms require further investigation.

In contrast to nitrogen and phosphorus, the potassium loss shows certain differences. Because of the abundant potassium constituents contained within the CBC, the cumulative TK loss in the $S_{4.5}$ treatment was markedly higher than that in the other treatments. A moderate amount of CBC appeared to reduce potassium loss, whereas excessive amendment application may promote the release and downward migration of potassium ions. Similar observations have been reported in previous studies, which indicated that excessive biochar addition may alter soil pore structures and enhance the mobility of soluble potassium.

The cumulative loss of organic matter generally decreased with increasing CBC application rates. Among all treatments, the $S_{4.5}$ treatment exhibited the lowest TOC loss. This result indicates that the combined application of CBC and fermented chicken manure contributed to the conservation of organic carbon in soil. The porous structure of biochar can provide favorable habitats for microorganisms and adsorb dissolved organic compounds, thereby slowing the loss of organic matter. In addition, biochar itself contains relatively high amounts of stable carbon, which may further contribute to carbon sequestration and organic matter accumulation in soils.

Overall, the results indicate that the compound soil amendment effectively regulated nutrient migration and improved nutrient retention in acidic farmland soils. However, the responses of different nutrients to increasing CBC application rates were not consistent. Moderate application rates appeared to be more favorable for reducing nitrogen and potassium losses, whereas higher amendment dosages contributed more significantly to phosphorus retention and organic matter conservation. Therefore, appropriate optimization of amendment dosage is essential to achieve balanced nutrient management and maximize soil improvement efficiency.

Effects of compound soil amendment on soil physicochemical properties

The present study demonstrated that the combined application of CBC and fermented chicken manure improved soil physicochemical properties to varying degrees. Significant increases in soil pH, inorganic nitrogen, available potassium, and soil organic matter were observed after amendment application, indicating that the compound soil amendment effectively enhanced soil fertility and alleviated soil degradation.

The addition of CBC increased soil pH throughout the soil profile, and the overall pH values of the treated soils were approximately 14.77% higher than those of the initial acidic soil. These findings are consistent with previous studies showing that alkaline biochar materials can neutralize soil acidity and increase soil pH through the release of alkaline ions and the enhancement of soil buffering capacity. However, the magnitude of pH improvement was relatively limited and no obvious linear relationship was observed between pH and amendment dosage. Previous studies have suggested that the decomposition of organic fertilizers may generate low-molecular-weight organic acids during microbial metabolism, which could partially offset the alkalinity introduced by biochar. Therefore, the relatively moderate increase in soil pH observed in the present study may be associated with the interaction between alkaline components and organic acid production during the decomposition process. Since the concentrations of organic acids were not determined in this study, further investigations are needed to clarify the mechanisms involved.

The contents of NH_4^+-N and NO_3^--N increased significantly after the application of the compound amendment. Biochar possesses a highly porous structure and abundant surface functional groups, which can provide adsorption sites for nitrogen species and improve nutrient retention. In addition, previous studies have reported that biochar amendments can enhance soil aeration and create favorable conditions for microbial activities involved in nitrogen transformation. Consequently, the combined application of CBC and fermented chicken manure may contribute to improving the availability and utilization efficiency of soil nitrogen. Similar results have been reported by Mäder et al. (2002), who found that organic amendments promoted nitrogen retention and increased plant nitrogen uptake.

Available phosphorus showed a different response pattern compared with other nutrients. Although all amendment treatments increased phosphorus availability relative to the control treatment, the S_2 treatment exhibited the highest available phosphorus content, whereas the $S_{4.5}$ treatment showed a comparatively weaker enhancement effect. Previous studies have indicated that calcium-rich materials may promote the formation of relatively stable phosphorus compounds in acidic soils (Chen et al., 2014), thereby reducing phosphorus mobility and bioavailability. Therefore, the lower available phosphorus observed under the $S_{4.5}$ treatment may be associated with the increased calcium content introduced by $Ca(OH)_2$ modification and the transformation of soluble phosphorus into less available forms. Similar findings have been reported by Chen et al. (2014) and Jeffery et al. (2011). However, because calcium concentrations and phosphorus fractions were not analyzed in the present study, the exact mechanism remains unclear and requires further verification.

The enhancement of available potassium exhibited a positive relationship with CBC application rates. The $S_{4.5}$ treatment showed the highest potassium content among all treatments, indicating that increasing biochar dosage contributed to potassium accumulation in the soil profile. This result may be attributed to biochar itself contains considerable amounts of potassium, which can be gradually released into the soil. Similar trends have been reported by previous studies investigating the effects of biochar amendments on nutrient availability in agricultural soils (Mäder et al., 2002; Agegnehu et al. 2017).

The content of soil organic matter increased continuously with increasing amendment dosage, and the greatest enhancement was observed under the $S_{4.5}$ treatment. The maximum increase reached approximately 47.13% compared with the control treatment. This improvement may be related to the abundant carbon sources supplied by fermented chicken manure and the stable carbon structure of biochar. Previous studies have demonstrated that the combined application of biochar and organic fertilizers effectively promotes carbon sequestration and enhances soil fertility, which is in agreement with the results obtained in this study.

Overall, because composite soil amendments contain a large amount of organic matter, they can quickly increase the content of humus and organic matter in the soil after being applied, enriching the carbon source in the soil (Jeffery et al., 2011). Therefore, under the condition of applying the same amount of organic fertilizer, the more CBC is applied, the higher the quality ratio of soil organic matter.

CONCLUSIONS

In this study, the nutrient component characteristics of acidic soil in Sichuan, China was analyzed and a compound soil amendment consisting of CBC and fermented chicken manure was prepared and its effects on nutrient leaching and soil physicochemical properties of acidic farmland soil were evaluated through soil column experiments. The main conclusions are summarized as follows:

1. The acidic soil areas generally have insufficient soil nutrients and exhibit strong spatial heterogeneity.
2. Improved $Ca(OH)_2$-modified biochar and fermented chicken manure can reduce the loss of N, P, K, and organic matter in soil to a certain extent by increasing soil pH and changing soil nutrient content.

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REFERENCES

1. Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., Paz-Ferreiro, J. (2013). Biochar's effect on crop productivity and the dependence on experimental conditions-A meta-analysis of literature data. *Plant and Soil 373*, 583–594. https://doi.org/10.1007/s11104-013-1806-x
2. Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S. (2010). Significant acidification in major Chinese croplands. *Science 327*, 1008–1010. https://doi.org/10.1126/science.1182570
3. Zhao, Y., Wang, P., Li, J., Chen, Y., Ying, X., Liu, S. (2009). The effects of two organic manures on soil properties and crop yields on a temperate calcareous soil under a wheat-maize cropping system. *European Journal of Agronomy 31*, 36–42. https://doi.org/10.1016/j.eja.2009.03.001
4. Fenn, M.E., Poth, M.A., Johnson, D.W. (1996). Evidence for nitrogen saturation in the San Bernardino Mountains in southern California. *Forest Ecology and Management 82*, 211–230. https://doi.org/10.1016/0378-1127(95)03668-7
5. Yuan, J.H., Xu, R.K., Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology 102*, 3488–3497. https://doi.org/10.1016/j.biortech.2010.11.018
6. Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment 144*, 175–187. https://doi.org/10.1016/j.agee.2011.08.015
7. Lehmann, J., Joseph, S. (2015). Biochar for environmental management: An introduction. *In: Biochar for Environmental Management: Science, Technology and Implementation.* Routledge, London, 1–13. https://doi.org/10.4324/9780203762264
8. Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal 81*, 687–711. https://doi.org/10.2136/sssaj2017.01.0017
9. Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere 99*, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071
10. Manuel T., and Mariano M. (2021). Toward a circular economy approach for integrated intensive livestock and cropping systems. *ACS Sustainable Chemistry & Engineering 9*, 13471–13479. https://doi.org/10.1021/acssuschemeng.1c04014
11. Han, Z., Han, C., Shi, Z., Li, J., Luo, E. (2023). Rebuilding the crop-livestock integration system in China: Based on the perspective of circular economy. *Journal of Cleaner Production 393*, 136347. https://doi.org/10.1016/j.jclepro.2023.136347
12. Moshe H., Asher B., Maya O., Dror M., Torsten M., Yermiyahu Uri. (2015). Chapter two-the use of biostimulants for enhancing nutrient uptake. *Advances in Agronomy, 130,* 141–174. https://doi.org/10.1016/bs.agron.2014.10.001

13. Kumar, R.R., Park, B.J., Cho, J.Y. (2013). Application and environmental risks of livestock manure. *Journal of the Korean Society for Applied Biological Chemistry 56*, 497–503. https://doi.org/10.1007/s13765-013-3184-8
14. An, J., Ding, Z.M., Gao, C.C., Hu, F.Y., Wei, S.H. (2023). Analysis of the environmental risk of livestock manure pollution and resource treatment technology. *Huan Jing Ke Xue 44*, 4764–4774. https://doi.org/10.13227/j.hjkx.202209018
15. Shanmugam, P.M., Sangeetha, S.P., Prabu, P.C., Varshini S. V., Renukadevi A., Ravisankar N., Parasuraman P., Parthipan T., Satheeshkumar N., Natarajan S. K., Gopi M. (2024). Crop-livestock-integrated farming system: a strategy to achieve synergy between agricultural production, nutritional security, and environmental sustainability. *Frontiers in Sustainable Food Systems 8*, 1338299. https://doi.org/10.3389/fsufs.2024.1338299
16. Qian, S., Zhou, X., Fu, Y., Song B., Yan H., Chen Z., Sun Q., Ye H. Qin L., Lai C. (2023). Biochar-compost as a new option for soil improvement: Application in various problem soils. *Science of the Total Environment 870*, 162024. https://doi.org/10.1016/j.scitotenv.2023.162024
17. Cheng, Y., Wang, B., Yan, P., Shen J., Kang J., Zhao S., Zhu X., Shen L., Wang S., Shen Y., Chen Z. (2023). In-situ formation of surface reactive oxygen species on defective sites over N-doped biochar in catalytic ozonation. *Chemical Engineering Journal 454*, 140232. https://doi.org/10.1016/j.cej.2022.140232
18. Petric, I., Helić, A., Avdihodžić Avdić, E. (2012). Evolution of process parameters and determination of kinetics for co-composting of organic fraction of municipal solid waste with poultry manure. *Bioresource Technology 117*, 107–116. https://doi.org/10.1016/j.biortech.2012.04.046.
19. He, X., Jackson N., Shi R., Xu R. (2022). Application of chitosan- and alginate-modified biochars in promoting the resistance to paddy soil acidification and immobilization of soil cadmium. *Environmental Pollution 313*, 120175. https://doi.org/10.1016/j.envpol.2022.120175
20. Ute K., Nicole B., Andrea B., Helena M., Christian P. (2014). Column leaching tests on soils containing less investigated organic pollutants. *Journal of Geochemical Exploration 147*, 291–297. https://doi.org/ 10.1016/j.gexplo.2014.06.014
21. Jebarathanam P., Ganesan N., Shunmugavel R., Chokalingam M., Vijaya R. (2019). In vitro synthesis of bio-brick using locally isolated marine ureolytic bacteria, a comparison with natural calcareous rock. *Ecological Engineering 138*, 97–105. https://doi.org/10.1016/j.ecoleng.2019.07.017
22. Major, J., Rondon, M., Molina, D., Riha, S.J., Lehmann, J. (2012). Nutrient leaching in a Colombian savanna Oxisol amended with biochar. *Journal of Environmental Quality 41*, 1076–1086. https://doi.org/10.2134/jeq2011.0128
23. Xiao B., Hu K., Ren T., Li B. (2016). Moss-dominated biological soil crusts significantly influence soil moisture and temperature regimes in semiarid ecosystems. *Geoderma 263*, 35–46. https://doi.org/10.1016/j.geoderma.2015.09.012
24. Agegnehu, G., Srivastava, A.K., Bird, M.I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology 119*, 156–170. https://doi.org/10.1016/j.apsoil.2017.06.008
25. Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J.L., Harris, E., Robinson, B., Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution 159*, 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023
26. Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad Thies J. O., J., Luizão F. J., Petersen J., Neves E. G. (2006). Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal 70*, 1719–1730. https://doi.org/10.2136/sssaj2005.0383
27. Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science 296*, 1694–1697. https://doi.org/10.1126/science.1071148
28. Chen, T., Zhang, Y., Wang, H., Lu, W., Zhou, Z., Zhang, Y., Ren, L. (2014). Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sludge. *Bioresource Technology 164*, 47–54. https://doi.org/10.1016/j.biortech.2014.04.048
29. Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment 144*, 175–187. https://doi.org/10.1016/j.agee.2011.08.015