



Effects of different application ratios of biochar-organic compound fertilizers and chemical fertilizers on soil nutrition content and yield of maize

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ABSTRACT

Overuse of traditional chemical fertilizers may result in environmental pollution and a decrease in the quality of farm produce. By contrast, applying biochar-organic compound fertilizers can enhance soil structure, increase soil fertility, and mitigate pollution levels. This study explores the intricate mechanisms of the combined application of biochar-organic compound fertilizers and chemical fertilizers on soil chemical properties and corn growth. The aim is to elucidate the theoretical foundations supporting the widespread adoption of biochar-organic compound fertilizers. A total of 6 treatments were set up, among which the CK treatment did not apply fertilizer, the CF treatment used bovine excrement organic fertilizer combined with chemical fertilizer, the T1 to T4 treatments used biochar-organic compound fertilizers and replaced 40%, 60%, 80%, and 100% bovine excrement organic fertilizer combined with chemical fertilizer. The results showed that applying biochar-organic compound fertilizers enhanced the slow-release properties of soil available nutrients, increased corn yield, and improved grain quality. Notably, when biochar-organic compound fertilizers were employed instead of 100% bovine excrement organic fertilizer, the yield surpassed that of other treatments, exhibiting a remarkable 9.30% increase compared to the CF treatment. Through comprehensive analysis, it was determined that using biochar-organic compound fertilizer to replace 60% of bovine excrement organic fertilizer is a scheme that can balance both fertilizer efficacy and cost and is recommended to farmers. This research can contribute to promoting the green transformation of agriculture and help achieve the goal of "carbon neutrality".

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1. INTRODUCTION

Maize plays a significant role globally in food, livestock feed, and industrial sectors. It is widely cultivated in China, and its yield and quality directly affect food security and the agricultural economy (Zhong et al., 2024). As a crop with high fertilizer requirements and a sensitive response to soil nutrients, maize growth relies on efficient fertilization management (Moi et al., 2022). However, simply applying chemical fertilizers is no longer sufficient to meet the planting requirements. In China alone, the application of chemical fertilizers represents approximately 30% of the worldwide total, with an efficiency rate of less than 40% (Liu et al., 2023). This situation results in an annual loss of approximately 10 million tons of nitrogen due to leaching or volatilization (Eisa et al., 2025). Concurrently, nitrogen-based fertilizers stand out as the primary culprits behind greenhouse gas emissions,

posing a direct threat to the sustainability of farmland ecosystems (Hu et al., 2024). Given this context, biochar-based fertilizers and biochar-organic compound fertilizers have emerged as pivotal intervention measures in the agricultural sector's transition towards environmental sustainability. These functional fertilizers revolve around the central role of biochar and are esteemed for their synergistic functionalities of "carbon sequestration, emission reduction, soil enhancement, and gradual nutrient release".

Biochar, a porous carbonaceous material resulting from the pyrolysis process conducted at temperatures ranging between 300°C to 700°C with biomass such as straw, rice husk, or wood under restricted oxygen conditions (Li et al., 2023), boasts distinctive physicochemical properties like a notable specific surface area (BET) ranging between 200 m² g⁻¹

to 500 m² g⁻¹, a substantial porosity of 40% to 60%, and a wealth of surface functional groups (Gao et al., 2016). This is outfitted with several functionalities, including heavy metal absorption, microbial community regulation, improved soil water retention, and an extended nutrient release cycle (Hu et al., 2024). Despite its multifaceted benefits, biochar encounters challenges in its adoption as an organic fertilizer due to its relatively low nutrient content. The impact of applying low quantities of biochar on enhancing soil-available nutrients proves to be insubstantial, sometimes showing negligible differences compared to untreated controls. Practical improvements in the content of available nutrients are only observed at significantly high application rates, such as applying 20 t ha⁻¹ at one time, a level that surpasses the economic feasibility of conventional fertilizers, however, an excessively high application rate, such as 60 t ha⁻¹, would cause the nutrients in the soil to be firmly adsorbed (Hou et al., 2025). In recent years, the momentum towards achieving “carbon neutrality” in China has catalyzed accelerated research and advancement in the arena of biochar-organic compound fertilizers. These efforts focus on mixing biochar with chemical or organic fertilizers based on changes in raw materials and processing methods. Notable methods include embedding nutrients such as nitrogen, phosphorus, and potassium into the pores of biochar through physical adsorption or chemical bonding to establish a system for gradual nutrient release. Additionally, blending biochar with chemical fertilizers intensifies organic matter accumulation and bolsters microbial activity (Rombel et al., 2022).

In Europe and America, biochar-organic compound fertilizers are primarily utilized in organic agriculture and carbon trading. Conversely, in developing countries, greater emphasis is placed on their capacity to boost crop productivity and remediate problematic soils. Notably, in China, the scope of application for biochar-organic compound fertilizers has evolved from initial acid soil reclamation to encompass water-conserving practices in arid regions, the restoration of farmland contaminated by heavy metals, and the cultivation of high-value crops, for instance, the application of biochar-organic compound fertilizers in tobacco cultivation can increase the accumulation of dry matter in tobacco plants and enhance the yield of tobacco leaves (Cao, 2019). Research indicates that biochar-organic compound fertilizers can ameliorate the toxicity of constraining factors in calcareous and acidic soils while enhancing the bioavailability of soil nutrients (Zhang et al., 2022). Moreover, through leveraging the hydrophilic nature of oxygen-rich functional groups, biochar-organic compound fertilizers stimulate the formation of soil aggregates, enhancing soil fertility and water retention (Chen et al., 2020). By a slow-release mechanism, these fertilizers facilitate the optimal synchronization of soil nutrient levels with crop fertilization requirements, ultimately leading to elevated and sustainable crop yields (Wang et al., 2023). Furthermore, the inclusion of biochar-organic compound fertilizers exerts a suppressive effect on nitrifying and denitrifying bacterial communities, thereby curbing the generation of N₂O in soil and reducing nitrogen loss by 20% to 30% via the absorption of oxygen-containing functional

groups like carboxyl and phenolic hydroxyl groups (Liu, 2019). While the merits of biochar-organic compound fertilizers are evident, their widespread adoption still confronts several technical challenges. The intricate coupling mechanisms governing the interaction among biochar-organic compound fertilizers, soil, and crops remain unclear, as does the spatio-temporal dynamic understanding of nutrient fluctuations. Analysis of the dynamic regulatory pathways through which biochar-organic compound fertilizers influence the alignment of soil nutrient storage capacity (evidenced by the fluctuating nitrogen, phosphorus, and potassium levels) with crop demands, and the quantification of ecological and economic benefits in terms of the fertilization ratio, is lacking. No studies have quantified the optimal substitution ratio of biochar-organic fertilizers for bovine manure in maize systems. Consequently, this study focuses on biochar-organic compound fertilizers, investigating the effects of varying ratios of these fertilizers in comparison with chemical fertilizers on soil chemical attributes, crop yield, and quality. The aim is to determine the optimal substitution ratio, provide a theoretical basis for the broad application and promotion of biochar-organic compound fertilizers, offer reasonable suggestions for farmers' scientific fertilization, and contribute to the realization of green and sustainable agricultural development.

2. MATERIALS AND METHODS

2.1. Experimental materials

The research was performed between May and October 2024 in the experimental field of the Yantai Institute, affiliated with China Agricultural University. The experimental field is located in the central part of the Shandong Peninsula (37°26'2"N, 121°31'14"E), characterized by a warm temperate continental monsoon climate. According to the data from the Meteorological Bureau of Yantai City, the average annual precipitation is 672.5 mm, mostly occurring from June to September. The average annual temperature is 11.8 °C, complemented by an average relative humidity of 68% and an annual sunshine duration reaching 2698.4 h. The pH value of the soil in the experimental area is 6.7, and the soil texture is sandy. The soil bulk density of the 0–20 cm plough layer is 1.36 g cm⁻³, with an organic matter content of 1.38%, alkaline hydrolyzable nitrogen content of 67.69 mg kg⁻¹, the available phosphorus content of 120.68 mg kg⁻¹, and available potassium content of 145.70 mg kg⁻¹. The experimental crop selected for this study is the maize (*Zea mays* L.) variety Denghai Xixing Wucaixiannuo, with a growth period of 80 days. Maize is cultivated with a gap of 20 cm separating the plants and 50 cm separating the rows. The organic fertilizer from bovine excrement used in the experiment was provided by Yantai Changsheng Dairy Farm. The Biomass and Circular Agriculture Research Center of the Yantai Institute of China Agricultural University provided the biochar-organic compound fertilizers. The raw material used for making biochar is apple wood, and it undergoes continuous pyrolysis at a temperature of around 600°C for one hour. The nutrient contents of bovine excrement, organic fertilizers, and biochar-organic compound fertilizers are shown in Table 1.

Table 1. Nutrient content of organic fertilizers

Classification	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Bovine excrement organic fertilizers	2.45	0.76	1.92
Biochar-organic compound fertilizers	1.98	0.81	1.94



Figure 1. Pictures a and b are photos of field experiments, picture c is a photo of laboratory soil property analysis, and picture d is a photo of laboratory plant sample analysis

2.2. Experimental design

The experiment consists of 6 treatments, each repeated 3 times. Treatment 1: CK, no fertilizer applied; Treatment 2: CF, bovine excrement organic fertilizer + chemical fertilizer; Treatment 3: T1, 40% substitution of bovine excrement organic fertilizer + chemical fertilizer; Treatment 4: T2, 60% substitution of bovine excrement organic fertilizer + chemical fertilizer; Treatment 5: T3, 80% substitution of bovine excrement organic fertilizer + chemical fertilizer; Treatment 6: T4, 100% substitution of bovine excrement organic fertilizer + chemical fertilizer. Each plot is 30 m² in size. Before sowing maize, organic fertilizer and chemical fertilizer are applied once as base fertilizer to the farmland and combined with soil tillage to mix the fertilizers into the soil. The target yield for maize is set at 10,500 kg ha⁻¹. This target value is derived by combining the region's average corn yield and farmers' expected yield. Among chemical fertilizers, the urea content in nitrogen fertilizers is 46%, calcium superphosphate in phosphate fertilizers is 18%, and potassium sulfate in potassium fertilizers is 50%. Although the amounts of different fertilizers used vary, the total nutrient content they provide is the same. The amounts of organic fertilizer and chemical fertilizer for different treatments are detailed in Table 2.

2.3. Sample collection and determination methods

Systematic collection of soil samples from 0 to 20 cm deep and mature leaves was conducted during important maize

growth stages, including seedling, tillering, tasseling, and grain filling/maturity stages. The plant and the soil samples were collected using the five-point sampling method, then mixed and subjected to three repeated experiments. A portion of the fresh soil samples collected was employed to assess soil enzyme activity, while the remaining fraction underwent air-drying and purification procedures. Subsequently, these soil samples were sequentially sieved through 1 mm and 0.25 mm screens to facilitate the determination of soil organic matter, alkali-hydrolyzable nitrogen, available phosphorus, and available potassium content. Soil urease activity was quantified utilizing a sodium phenolate-sodium hypochlorite colorimetric method (Wang et al., 2019). The activity of soil acid phosphatase was measured using phenylate disodium phosphate colorimetry (Shao & Li, 2016). The measurement of soil organic matter involved employing the potassium dichromate oxidation-external heating methodology. Additionally, alkali-hydrolyzable nitrogen, available phosphorus, and available potassium content were determined through alkali-hydrolyzable diffusion, sodium bicarbonate leaching coupled with molybdenum-antimony spectrophotometry, and ammonium acetate leaching utilizing a flame photometer, respectively (Bao, 2000). Freshly collected leaf samples were divided, with one portion dedicated to assessing chlorophyll content and another subjected to drying processes. The latter underwent initial deactivation at 105 °C for 30 min, followed by drying at 80 °C to reach a constant weight. These dried samples were then ground and sieved through a 1 mm mesh to quantify the leaves' total nitrogen, phosphorus, and potassium content. The leaves' total nitrogen, phosphorus, and potassium content was determined by employing the Kjeldahl method, spectrophotometry, and a flame photometer, respectively (Bao, 2000). Furthermore, chlorophyll content in the leaves was assessed utilizing a spectrophotometer (Hu et al., 2018). The model of the spectrophotometer is 752pro. For the determination of available phosphorus, a wavelength of 660nm is used, while wavelengths of 663nm and 645nm are employed for the determination of chlorophyll content. During the harvesting phase, the number of corn spikes per plot was meticulously documented, following which ten spikes of average size were selected for laboratory analysis. These selected spikes were threshed, and the number of grains per ear was determined. Subsequently, the spikes were naturally air-dried until achieving a moisture content of approximately 14%, following which the 1000-grain weight was measured. Yield calculations were subsequently performed based on a specific Equation 1. Moreover, post-harvest corn samples were utilized to ascertain the crude protein content, and a determination was carried out using the Kjeldahl method (Zhao & Cang, 2015).

2.4. Data statistical analysis

Excel 2021 facilitated data collation, and SPSS 25.0 was used for performing one-way ANOVA, significance tests, and correlation analysis. Conduct post-hoc tests using the LSD method and Duncan's Multiple Range Test.

$$\text{Yield (kg ha}^{-1}\text{)} = \frac{\text{number of spikes per hectare} \times \text{number of grains per spike} \times 1000 - \text{grain weight (g)} \times 0.85}{10^6} \dots\dots\dots [1]$$

Note: 0.85 in the formula is the yield measurement coefficient.

Table 2. Application rates of organic and chemical fertilizers for different treatment groups

Treatment	Biochar-organic compound fertilizers (kg ha ⁻¹)	Bovine excrement organic fertilizer (kg ha ⁻¹)	Urea (kg ha ⁻¹)	Calcium superphosphate (kg ha ⁻¹)	Potassium sulfate (kg ha ⁻¹)
CK	0	0	0	0	0
CF	0	4500	1048	22.5	380.28
T1	1800	0	1150	218.7	431.76
T2	2700	0	1126	145.8	414.30
T3	3600	0	1101	72.9	396.84
T4	4500	0	1077	0	379.38

Table 3. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on soil available nutrient content

Stage	Treatment	Soil available nutrient content (mg kg ⁻¹)		
		Alkali-hydrolyzable nitrogen	Available phosphorus	Available potassium
Seedling	CK	67.40 ± 0.61e	125.37 ± 0.57d	155.40 ± 0.91f
	CF	88.89 ± 0.10d	126.84 ± 0.95d	268.32 ± 0.56d
	T1	116.81 ± 0.91a	160.64 ± 0.96a	341.39 ± 0.65a
	T2	103.71 ± 0.81b	146.88 ± 0.69b	315.38 ± 0.40b
	T3	94.29 ± 0.75c	130.09 ± 0.76c	281.91 ± 0.89c
	T4	89.06 ± 0.35d	126.77 ± 1.05d	265.32 ± 0.50e
Tillering	CK	61.23 ± 0.62e	119.69 ± 0.68f	150.80 ± 0.74f
	CF	88.52 ± 0.70c	121.80 ± 0.69e	239.78 ± 0.68e
	T1	104.53 ± 0.54a	151.75 ± 1.03a	323.41 ± 0.56a
	T2	92.29 ± 0.61b	139.56 ± 0.58b	291.09 ± 0.62b
	T3	92.15 ± 0.57b	126.15 ± 1.16c	264.14 ± 0.74c
	T4	86.14 ± 0.70d	124.22 ± 0.50d	251.46 ± 0.62d
Tasseling	CK	52.52 ± 0.45f	103.42 ± 0.48f	116.69 ± 0.81f
	CF	71.17 ± 0.50e	105.98 ± 0.69e	182.44 ± 0.83e
	T1	90.63 ± 0.79a	121.71 ± 0.59a	215.16 ± 0.49a
	T2	82.23 ± 0.51b	115.24 ± 0.38b	213.58 ± 0.64b
	T3	80.76 ± 0.21c	110.30 ± 0.59c	208.94 ± 0.60c
	T4	78.74 ± 0.18d	109.63 ± 0.97d	205.11 ± 0.71d
Grain filling and maturity	CK	40.52 ± 0.50e	92.67 ± 0.51e	110.99 ± 0.87e
	CF	55.95 ± 0.46d	93.57 ± 0.48e	162.73 ± 0.67d
	T1	65.47 ± 0.81c	102.03 ± 0.24d	177.56 ± 0.63c
	T2	67.00 ± 0.52b	103.72 ± 0.63c	182.91 ± 0.37b
	T3	68.92 ± 0.49a	105.52 ± 0.66b	183.98 ± 0.67b
	T4	69.74 ± 0.59a	106.82 ± 0.39a	189.98 ± 0.72a

Note: Different lowercase letters in the same column indicate significant differences between treatments ($P < 0.05$, similarly hereinafter)

3. RESULTS

3.1. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on soil available nutrient content

As per the data presented in Table 3, the levels of alkali-hydrolyzable nitrogen in the soil of maize seedlings treated with biochar-organic compound fertilizers at substitution rates of 40%, 60%, 80%, and 100% in place of bovine excrement organic fertilizers were recorded to be 131.41%, 116.67%, 106.07%, 100.19%, and 126.65%, respectively, relative to those in soils amended solely with bovine excrement organic fertilizers. The levels of available phosphorus in the soil of maize seedlings treated with biochar-organic compound fertilizers at substitution rates of 40%, 60%, 80%, and 100% in place of bovine excrement organic fertilizers were recorded to be 126.65%, 115.80%,

102.56%, and 99.94%, respectively, relative to those in soils amended solely with bovine excrement organic fertilizers. The levels of available potassium in the soil of maize seedlings treated with biochar-organic compound fertilizers at substitution rates of 40%, 60%, 80%, and 100% in place of bovine excrement organic fertilizers were recorded to be 127.23%, 117.54%, 105.06%, and 98.88% respectively, relative to those in soils amended solely with bovine excrement organic fertilizers. The results indicated a trend where, at the seedling, tillering, and tasseling stages, a proportional increase in the utilization of biochar-organic compound fertilizers instead of bovine excrement corresponded to a subsequent decrease in the levels of alkali-hydrolyzable nitrogen, available phosphorus, and available potassium in the soil. Moreover, as the maize growth period advanced, a decline in the availability of nutrients was

observed across all treatment plots. The most prominent reduction in alkali-hydrolyzable nitrogen content occurred during the transition from the tasseling stage to the filling/maturity stage, where the decrease in alkali-hydrolyzable nitrogen for CF, T1, T2, T3, and T4 treatments accounted for 46.21%, 49.00%, 41.49%, 46.67%, and 46.58% of the total decline, respectively. By the filling/maturity stage of maize development, the alkali-hydrolyzable nitrogen content in T1, T2, T3, and T4 treatments remained at 117.02%, 119.75%, 123.18%, and 124.65% in comparison to that in the CF treatment. Conversely, in contrast to alkali-hydrolyzable nitrogen, available phosphorus and potassium levels exhibited a more pronounced decline from the tillering to the tasseling stage. Specifically, for available phosphorus, a reduction of 47.55%, 51.25%, 56.35%, 64.51%, and 73.13% was noted for CF, T1, T2, T3, and T4 treatments, respectively; for available potassium, a reduction by 54.30%, 66.07%, 58.51%, 56.37%, and 61.52% was noted for CF, T1, T2, T3, and T4 treatments, respectively. As maize reached the filling/maturity stage, the available phosphorus levels in T1, T2, T3, and T4 treatments were 1.09, 1.11, 1.13, and 1.14 times higher than those in the CF treatment, respectively. The available potassium levels were 1.09, 1.12, 1.13, and 1.17 times higher than those in the CF treatment, respectively.

3.2. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on soil organic matter content

During the seedling stage of maize, the organic matter content of the soil in the T1 treatment was found to be 98.99% of that in the CF treatment. However, the disparity between the T2 and CF treatments was not statistically significant. Notably, the organic matter content in the T3 and T4 treatments exhibited an increase, reaching 1.02 times and 1.06 times that of the CF treatment, as illustrated in Figure 2. This observation suggests that an escalating proportion of biochar-organic compound fertilizer in lieu of bovine excrement organic fertilizer leads to an augmentation in soil organic matter content. As the maize plants continued to grow, a general decline in the organic matter content of all treated soils was observed. Nevertheless, the soil treated with biochar-organic compound fertilizers consistently maintained a higher organic matter content compared to that treated with bovine excrement organic fertilizers. Notably, the most pronounced decline in soil organic matter content was observed during the tillering and tasseling stages of

growth. Specifically, in the tasseling stage, the soil organic matter content in the CK, CF, T1, T2, T3, and T4 treatments decreased by 6.29%, 20.05%, 18.82%, 11.43%, 12.34%, and 13.30%, respectively, relative to the tillering stage. Subsequently, by the filling/maturity stage, the organic matter content in the T1, T2, T3, and T4 treatments surpassed that of the CF treatment by 4.10%, 9.14%, 12.58%, and 14.24%, respectively.

3.3. Effect of Combined Application of Biochar-organic Compound Fertilizers and Chemical Fertilizers on Soil Urease and Acid Phosphatase Activities

The analysis of Table 4 reveals a biphasic pattern in the soil urease and acid phosphatase activities across the entire growth period of maize. Initially, these activities increased and subsequently decreased, with the peak soil urease activity observed during the tasseling stage and the peak soil acid phosphatase activity noted during the tillering stage of maize development. This may be related to the significant increase in the demand for nitrogen and phosphorus during the tasseling stage and the tillering stage. The root system thrives and secretes abundantly, along with appropriate temperature, humidity, and substrate supply, which stimulates the extensive synthesis of urease and acid phosphatase by root-associated microorganisms. In comparison to the CF, the enzymatic activity of urease in treatments T1, T2, T3, and T4 exhibited significant enhancements by 9.90%, 49.00%, 133.17%, and 153.47% respectively, at the tasseling stage. The activity of acid phosphatase exhibited significant enhancements by 4.46%, 13.69%, 19.75%, and 41.72% respectively, at the tillering stage. These findings suggest a positive correlation between the proportion of biochar-organic compound fertilizers used as a replacement for bovine excrement and the activities of soil urease and acid phosphatase ($R_{urease} = 0.976$, $R_{phosphatase} = 0.977$). Upon further examination, it was observed that the urease activity in treatments CF, T1, T2, T3, and T4 began to decline in the filling/maturity stage, with reductions of 18.81%, 22.07%, 37.87%, 58.60%, and 55.47% relative to the tasseling stage, respectively. Despite a slight decrease in soil phosphatase activity from the tasseling stage to the filling/maturity stage across all treatments, the soil phosphatase activity in treatments T1, T2, T3, and T4 remained elevated compared to the CF at both the tasseling and maturity stages, evidenced by the respective increases of 1.03 times, 1.14 times, 1.17 times, and 1.23 times.

Table 4. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on soil urease and acid phosphatase activities

Treatment	Soil urease activity (mg (g d) ⁻¹)				Soil acid phosphatase activity (mg (g d) ⁻¹)			
	Seedling	Tillering	Tasseling	Filling and maturity	Seedling	Tillering	Tasseling	Filling and maturity
CK	0.64 ± 0.04d	0.87 ± 0.06e	1.56 ± 0.08f	1.47 ± 0.10d	1.95 ± 0.09e	2.35 ± 0.07f	1.98 ± 0.06d	1.47 ± 0.10d
CF	1.02 ± 0.08b	1.43 ± 0.08c	2.02 ± 0.06e	1.64 ± 0.05c	2.36 ± 0.06d	3.14 ± 0.07e	2.63 ± 0.09c	2.31 ± 0.04c
T1	0.84 ± 0.05c	1.14 ± 0.04d	2.22 ± 0.04d	1.73 ± 0.06c	2.46 ± 0.07d	3.28 ± 0.09d	2.59 ± 0.06c	2.39 ± 0.06c
T2	0.96 ± 0.05b	1.35 ± 0.04c	3.01 ± 0.09c	1.87 ± 0.05b	2.62 ± 0.06c	3.57 ± 0.07c	2.77 ± 0.05b	2.64 ± 0.05b
T3	1.15 ± 0.09a	1.76 ± 0.10b	4.71 ± 0.07b	1.95 ± 0.05b	2.92 ± 0.08b	3.76 ± 0.07b	2.85 ± 0.05b	2.71 ± 0.09ab
T4	1.23 ± 0.08a	1.92 ± 0.10a	5.12 ± 0.10a	2.28 ± 0.05a	3.19 ± 0.09a	4.45 ± 0.07a	2.98 ± 0.07a	2.83 ± 0.10a

Table 5. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on the contents of total nitrogen, phosphorus, and potassium in maize leaves

Stage	Treatment	Leaf nutrient content (%)		
		Total nitrogen	Total phosphorus	Total Potassium
Seedling	CK	1.97 ± 0.04c	0.3802 ± 0.0052e	2.38 ± 0.04d
	CF	2.12 ± 0.05b	0.4408 ± 0.0118cd	2.64 ± 0.02c
	T1	2.36 ± 0.06a	0.5103 ± 0.0075a	3.17 ± 0.03a
	T2	2.28 ± 0.06a	0.4813 ± 0.0066b	2.93 ± 0.06b
	T3	2.16 ± 0.03b	0.4476 ± 0.0068c	2.68 ± 0.04c
	T4	2.13 ± 0.03b	0.4329 ± 0.0063d	2.62 ± 0.02c
Tillering	CK	2.27 ± 0.04d	0.2861 ± 0.0067f	2.78 ± 0.04d
	CF	2.65 ± 0.04b	0.4011 ± 0.0019e	3.34 ± 0.03b
	T1	2.40 ± 0.04c	0.4819 ± 0.0044a	3.26 ± 0.02c
	T2	2.64 ± 0.03b	0.4735 ± 0.0027b	3.35 ± 0.06b
	T3	2.71 ± 0.05b	0.4389 ± 0.0015c	3.42 ± 0.01a
	T4	3.45 ± 0.05a	0.4264 ± 0.0048d	3.43 ± 0.02a
Tasseling	CK	2.74 ± 0.03e	0.2835 ± 0.0048d	3.18 ± 0.07f
	CF	3.08 ± 0.04d	0.3807 ± 0.0059c	3.54 ± 0.03e
	T1	3.10 ± 0.07d	0.3893 ± 0.0040bc	3.74 ± 0.03d
	T2	3.39 ± 0.04c	0.3916 ± 0.0068bc	4.00 ± 0.03c
	T3	3.68 ± 0.03b	0.3985 ± 0.0093ab	4.24 ± 0.03b
	T4	3.87 ± 0.03a	0.4079 ± 0.0101a	4.32 ± 0.02a
Filling and maturity	CK	1.48 ± 0.04e	0.2491 ± 0.0091d	1.24 ± 0.02d
	CF	1.82 ± 0.04d	0.3445 ± 0.0050c	1.27 ± 0.01c
	T1	1.88 ± 0.04d	0.3668 ± 0.0073b	1.32 ± 0.03c
	T2	2.12 ± 0.04c	0.3705 ± 0.0055b	1.63 ± 0.04b
	T3	2.26 ± 0.05b	0.3726 ± 0.0066b	1.70 ± 0.05a
	T4	2.39 ± 0.02a	0.3848 ± 0.0047a	1.75 ± 0.02a

3.4. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on the contents of total nitrogen, phosphorus, and potassium in maize leaves

In comparison with the seedling stage of maize, the concentrations of total nitrogen and total potassium in the leaves across all treatments exhibited an initial increase followed by a subsequent decrease over the entire growth cycle of maize, with peak values observed during the tasseling stage. Notably, at the tasseling stage, the concentrations of total nitrogen in the leaves for treatments CF, T1, T2, T3, and T4 recorded increases of 45.28%, 31.36%, 48.68%, 70.37%, and 81.69%, respectively, compared to the seedling stage, while that of total potassium recorded increases of 34.09%, 17.98%, 36.52%, 58.21%, and 64.89%, respectively. Conversely, the total phosphorus content in maize leaves displayed a consistent downward trend throughout the growth cycle, with reductions of 21.85%, 28.12%, 23.02%, 16.76%, and 11.11% observed in the filling and maturity stages when compared to the seedling stage for treatments CF, T1, T2, T3, and T4, respectively. A meticulous analysis of Table 5 reveals a gradual decrease in the concentrations of total nitrogen, total phosphorus, and total potassium in leaves during the seedling stage, alongside an increasing proportion of biochar-organic compound fertilizers substituting bovine excrement. In contrast, the concentrations of total nitrogen, total phosphorus, and total potassium in leaves during the tillering stage, tasseling stage, and filling/maturity stage displayed a positive correlation with the proportion of biochar-organic compound fertilizers replacing bovine excrement organic fertilizers.

3.5. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on leaf chlorophyll content, maize quality, and yield

Based on the findings presented in Table 6, it is evident that during the seedling stage, the chlorophyll content in leaves was found to be the most elevated in the CF, surpassing the levels in the CK, T1, T2, T3, and T4 treatments by margins of 1.27, 1.15, 1.15, 1.11, and 1.08 times, respectively. As the growth period progressed, the chlorophyll content in all treated leaves exhibited a continuous increase during the tillering and tasseling stages, following which it began to decline during the filling/maturity stages. Despite the incremental rise in chlorophyll content in leaves corresponding to the augmented proportion of biochar-organic compound fertilizers replacing bovine excrement, the chlorophyll content in leaves treated with T1 consistently remained lower than that in CF across the entirety of the maize growth phase. Specifically, the chlorophyll content in leaves treated with T1, T2, T3, and T4 stood at 98.87%, 101.42%, 126.06%, and 127.20% of the levels observed in leaves treated with CF, respectively. In terms of yield, the T4 treatment yielded the highest output, exceeding those in the CK, CF, T1, T2, and T3 treatments by factors of 1.68, 1.09, 1.13, 1.10, and 1.03, respectively. Furthermore, the crude protein content in maize grain and maize bulk density were notably highest in the T4 treatment, followed in descending order by T3, T2, CF, T1, and CK, with significant differences observed between the different treatments.

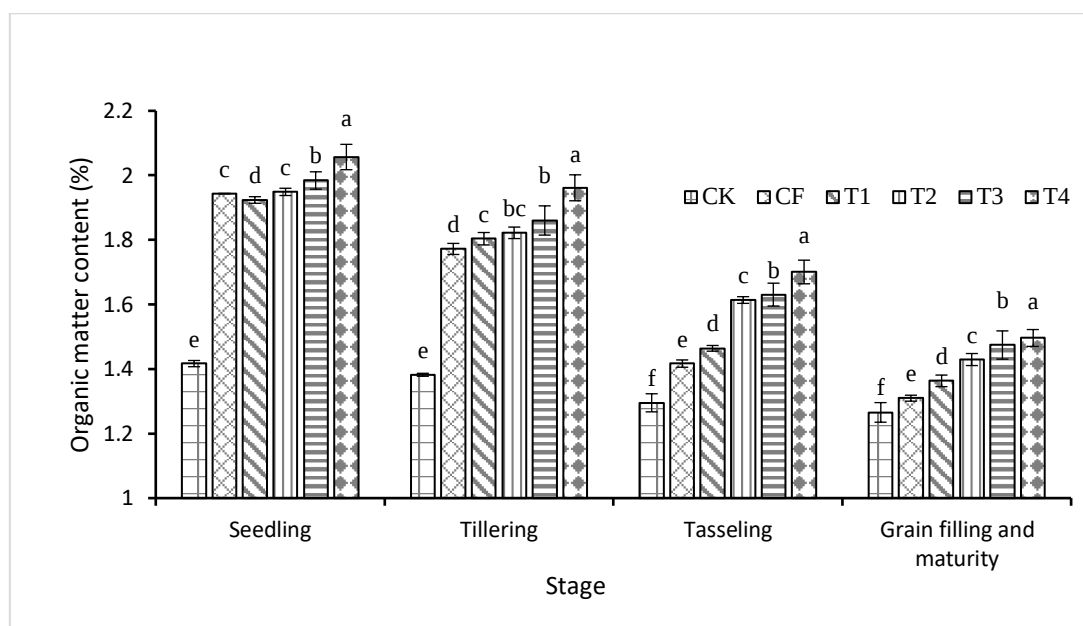


Figure 2. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on soil organic matter content

Table 6. Effect of combined application of biochar-organic compound fertilizers and chemical fertilizers on leaf chlorophyll content, maize quality, and yield

Treatment	Chlorophyll content in leaves (mg g ⁻¹)				Yield (kg ha ⁻¹)	Grain crude protein (%)	Maize bulk density (g L ⁻¹)
	Seedling	Tillering	Tasseling	Filling and maturity			
CK	2.16 ± 0.09d	3.05 ± 0.03e	4.04 ± 0.02e	2.18 ± 0.04d	6397.8 ± 35.5e	9.26 ± 0.06f	704.5 ± 3.9e
CF	2.74 ± 0.04a	3.90 ± 0.03c	4.17 ± 0.04d	3.53 ± 0.03bc	9838.8 ± 33.7c	9.80 ± 0.03d	750.6 ± 3.1c
T1	2.38 ± 0.05c	3.82 ± 0.04d	4.20 ± 0.05d	3.49 ± 0.06c	9520.8 ± 39.1d	9.71 ± 0.02e	733.6 ± 3.6d
T2	2.39 ± 0.08c	3.89 ± 0.03c	4.34 ± 0.03c	3.58 ± 0.03b	9808.0 ± 23.0c	9.92 ± 0.04c	754.4 ± 3.0c
T3	2.46 ± 0.03bc	4.15 ± 0.02b	4.56 ± 0.04b	4.45 ± 0.02a	10426.2 ± 24.7b	10.35 ± 0.03b	762.6 ± 2.5b
T4	2.53 ± 0.03b	4.97 ± 0.03a	4.98 ± 0.03a	4.49 ± 0.05a	10754.3 ± 38.0a	10.96 ± 0.03a	771.4 ± 1.6a

4. DISCUSSION

This study investigates the effects of varying ratios of biochar-based organic fertilizers and chemical fertilizers on soil nutrient content and corn growth performance. As a pivotal technology for the green transformation of agriculture, the core mechanism of biochar-based organic fertilizers is rooted in the unique chemical properties of biochar and its synergistic interaction with chemical and organic fertilizers (F. Li et al., 2025). With an increasing substitution ratio of biochar-based organic fertilizers, the biochar content in the fertilizer also rises, leading to more pronounced improvement effects (Feng et al., 2024). Notably, when biochar-based organic fertilizers replace 60% of bovine excrement organic fertilizers, the soil improvement and yield increase effects are already comparable to those of the CF treatment, and a higher substitution ratio further enhances this effect. Although the yield of the T4 treatment is higher, the T2 treatment may be more economically viable because the higher yield is insufficient to cover the cost of fertilizers.

The maintenance effect of biochar-based organic fertilizer on soil available nutrient content is attributed to the synergistic mechanism between biochar and chemical fertilizers (Lan et al., 2024). This study verified the effectiveness of the biochar-based organic fertilizer and provided a detailed account of the changes in soil nutrients

during the different growth stages of corn. As illustrated in Table 3, during the corn seedling stage, the soil available nutrient content exhibits a negative correlation with the substitution ratio of biochar-based organic fertilizer. The increase is linked to the higher application rates of chemical fertilizers. This phenomenon is associated with the distinct properties of organic and chemical fertilizers. Chemical fertilizers rapidly replenish soil nutrients, whereas biochar-based organic fertilizers minimize the leaching of available nutrients, thereby maintaining soil nutrient availability at a relatively high level over an extended period (Tuo et al., 2025). Additionally, the short-term efficacy of chemical fertilizers results in a decrease in total nitrogen, total phosphorus, and total potassium content in corn leaves during the seedling stage as the substitution ratio of biochar-based organic fertilizer for cow manure organic fertilizer increases (N. Li et al., 2025).

The high specific surface area and well-developed pore structure of biochar serve as an effective physical carrier for nutrient adsorption and slow-release processes (Xing et al., 2022). The high specific surface area and well-developed pore structure of biochar enable it to adsorb ammonium nitrogen (NH₄⁺) and nitrate nitrogen (NO₃⁻), augmenting nitrogen retention capabilities and mitigating losses. This characteristic underlies the utility of biochar-organic

compound fertilizers in enhancing soil nitrogen levels, a phenomenon corroborated by extant research findings (Zhao et al., 2022). Moreover, application of biochar-organic compound fertilizers has been found to elevate the concentrations of available phosphorus and potassium in the soil. During the Filling and maturity periods, the contents of available phosphorus and available potassium in the T4 treatment were 14.16% and 16.75% higher than those in the CF treatment, respectively. Primarily, biochar harbors elevated levels of these nutrients on its surface, which are subsequently released into the soil upon application. Furthermore, the introduction of biochar-organic compound fertilizers fosters a conducive environment for phosphorus- and potassium-solubilizing microorganisms (Khalisha et al., 2022), bolstering their activity and facilitating the conversion of fixed soil nutrients into bioavailable forms (Wang et al., 2024).

Although bovine excrement organic fertilizers also have the effect of a slow-release fertilizer and the ability to improve soil quality (Nurmegawati et al., 2019). Since biochar comprises a blend of non-aromatic hydrocarbon and aromatic hydrocarbon components resulting from pyrolysis processes, its soil degradation transpires sluggishly. Particularly notable is the persistence of refractory carbon components, which can endure for extended periods ranging from hundreds to thousands of years (Wen et al., 2025). In contrast, bovine excrement organic fertilizer, sourced from animal excrement and subjected to fermentation and decomposition, comprises organic carbon components with unstable properties prone to rapid decomposition and mineralization under the influence of plant and microbial activity in the soil (Q. Zhang et al., 2024). Consequently, investigations reveal a pronounced disparity in the soil adsorption and fixation capacities between bovine excrement organic fertilizer and biochar-organic compound fertilizers, accounting for the discrepant soil nutrient levels favoring the latter (Pandey et al., 2020).

During the later stage of corn growth, higher doses of biochar-organic compound fertilizers correspond to increased soil nutrient availability. This escalation is attributed to the heightened biochar content in the soil, which serves as a physical carrier for available nutrients, temporarily sequestering them via physical and chemical adsorption mechanisms to curtail nutrient losses and engender slow-release benefits (Zhao et al., 2022). Moreover, the adsorption and slow-release properties of this biochar for nutrients provide an abundant source of nutrients for the growth and development of corn. From the tillering stage onwards, the concentrations of total nitrogen, total phosphorus, and total potassium in maize leaves positively correlated with the proportion of biochar-organic compound fertilizers replacing bovine excrement (O'Dell et al., 2019). Furthermore, the temporal patterns of decline in alkali-hydrolyzable nitrogen, available phosphorus, and available potassium content vary significantly, primarily influenced by maize's biological characteristics. Maize exhibits a peak nitrogen absorption phase spanning from the ear to filling-maturity stages, whereas phosphorus and potassium

absorption peaks occur from the tillering to tasseling stages (Singh et al., 2023).

The study's results, as depicted in Figure 1, indicate a strong positive relationship between the soil's organic matter content and the use of biochar-organic compound fertilizers as a substitute for bovine organic fertilizer. Notably, the soil organic matter content in plots treated with biochar-organic compound fertilizers consistently surpassed that of plots treated with bovine excrement organic fertilizer, beginning from the tillering stage of plant development. This observation suggests that biochar-organic compound fertilizers are characterized by their high carbon content and stability, with a significantly lower degradation rate compared to bovine excrement organic fertilizers, thereby contributing to a sustained enhancement of the soil organic carbon pool (N. Zhang et al., 2024). The augmentation of the soil organic carbon pool serves a dual purpose: it supplies a more abundant and enduring carbon source for soil microorganisms, and it establishes optimal pH and moisture conditions conducive to microbial growth. These factors are primarily responsible for the elevated number and activity of microorganisms in soils treated with biochar-organic compound fertilizers, as opposed to those treated with bovine excrement and organic fertilizers (Zhao & Cang, 2015). Soil urease and phosphatase activities predominantly originate from microorganisms, and the observed increase in microbial quantity and activity indirectly results in heightened urease and phosphatase activities (Kabir et al., 2023).

The available nutrients in the soil serve as the direct material basis for the synthesis of chlorophyll in corn. Meanwhile, organic matter indirectly enhances the utilization efficiency of available nutrients by increasing nutrient retention, activating microbial functions, and improving soil structure (Zhang et al., 2017). According to Table 6, despite the initial lower chlorophyll content in leaves treated with biochar-organic compound fertilizers compared to those treated with bovine excrement organic fertilizer during the seedling stage, a gradual increase in chlorophyll content was observed at the tillering stage. Notably, at the tasseling stage and the filling/maturity stage, the chlorophyll content in leaves treated with biochar-organic compound fertilizers showed a significant boost compared to those treated with bovine excrement organic fertilizer. This phenomenon suggests that the application of biochar-organic compound fertilizers effectively enhances the mineral elements essential for maize chlorophyll synthesis. Particularly, a significant enhancement is noted in the soil's alkali-hydrolyzable nitrogen content due to the application of biochar-organic compound fertilizers, consequently positively influencing the chlorophyll content. In general, a positive correlation exists between chlorophyll content and the photosynthetic efficiency of plants (Jang et al., 2022). The enhancement of corn's photosynthesis and the improvement of the soil's water and nutrient retention capabilities due to the application of biochar-organic compound fertilizers provide the material basis for the increase in yield (Liu et al., 2020). Nutrients such as phosphorus and potassium form a metabolic network through energy metabolism and transport systems, amplifying the nitrogen effect, and causing the crude

protein content of corn kernels to increase as the amount of biochar-organic compound fertilizers used rises (Du et al., 2020).

In summary, the combined application of biochar in biochar-organic compound fertilizers and chemical fertilizers forms a “quick-acting + slow-release” nutrient supply mode, which not only meets the rapid growth needs of maize at the seedling stage but also ensures the continuous nutrient supply in the middle and late stages, achieving the effect of maize yield increase (Susilowati et al., 2024). However, this experiment was conducted in a single climate zone and soil type, and the universality of its results in different climates and soil types needs further verification. Additionally, the preparation cost of biochar-organic compound fertilizers and the impact of long-term application on soil carbon pool balance have not been quantified, which may restrict the economic feasibility of their large-scale application (Li et al., 2024). In the future, it is necessary to combine multi-regional long-term positioning experiments to systematically evaluate the fertilization effects and economic benefits of different combined application ratios.

5. CONCLUSION

The use of biochar-organic compound fertilizers as an alternative to traditional bovine excrement organic fertilizers has shown significant potential in improving soil nutrient content. Such substitution facilitates enhanced uptake and utilization of crucial nutrients, including nitrogen, phosphorus, and potassium, by corn plants, consequently elevating both crop yield and maize quality. In terms of the fertilizer's effectiveness and the economic benefits it brings to farmers, the adoption of biochar-organic compound fertilizers at a 60% substitution rate for bovine excrement organic fertilizers holds the potential to deliver equivalent benefits in enhancing soil fertility and boosting crop yields, as compared to the exclusive use of bovine excrement-based organic fertilizers. Notably, the observable enhancement in soil fertility and crop performance becomes increasingly pronounced as the substitution ratio escalates. Moreover, future long-term studies will be required to evaluate the overall impact of biochar-organic compound fertilizers on soil nutrient availability and their effect on the succession of microbial communities.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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