Effects of Winter Application of Chicken Manure and Biochar on Soil CO2 and CH4 Emissions in Southern Paddy Fields: Postprint

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Abstract

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Full Text

Preamble

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Title: Effects of Chicken Manure and Biochar Application in Winter on CO_2 and CH_4 Emissions from Paddy Fields in South China

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Abstract: Biochar utilization has become a hot topic in research on soil carbon sequestration and emission reduction in farmland. This study quantified soil CO_2 and CH_4 emission fluxes from winter paddy fields and double-cropping rice periods through integrated chicken farming in winter paddy fields combined with biochar addition, using the chamber method coupled with a greenhouse gas analyzer. Total emissions during both winter and rice growth periods were estimated to evaluate the effects of biochar and chicken manure addition on soil carbon emissions. Results showed that chicken manure application significantly increased soil CO_2 emissions, with cumulative emissions reaching 9,935.39 $kg \cdot hm^{-2}$ during the winter fallow period and 27,756.34 $kg \cdot hm^{-2}$ during the rice growth period—58.7 times ($P<0.01$) and 56% ($P<0.05$) higher than the control, respectively. Biochar addition increased cumulative CO_2 emissions by 12.3 times ($P<0.01$) and 41% ($P<0.05$) compared to the control during winter and rice growth periods, respectively. CH_4 emissions under chicken manure treatment were significantly higher than other treatments in both winter and rice growth periods, while biochar had no significant effect on winter CH_4 emissions but significantly reduced CH_4 emissions during the rice growth period. The combined chicken manure and biochar treatment also significantly increased soil CO_2 emissions. During winter, cumulative CO_2 emissions from the combined treatment were significantly higher than chicken manure alone, while during the rice growth period, they were significantly lower. Biochar addition mitigated the CH_4 emission increase caused by chicken manure application. In conclusion, in-situ chicken manure application significantly increased CO_2 and CH_4 emissions from winter and rice growth period paddy fields. Biochar addition reduced CH_4 emissions in both periods and suppressed CO_2 emissions in later stages. Therefore, from a longer temporal perspective, biochar application benefits soil carbon sequestration and emission reduction.

Keywords: Winter fallow paddy field; Chicken farming; Chicken manure; In-situ application; Biochar; CO_2 emission; CH_4 emission

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Introduction

Biochar is a solid material with well-developed pore structure, high carbon content, large specific surface area, strong adsorption capacity, and high resistance to decomposition, produced by pyrolyzing biomass such as crop straw, rice husk, wood, livestock manure, and other materials under anaerobic or anoxic conditions at high temperatures [1-2]. Due to its unique structural and physicochemical properties, biochar can increase soil carbon pool reserves, participate in soil nutrient cycling and retention, and improve crop yields [3-5]. On one hand, because biochar has high carbon content and strong chemical inertness, it can remain stable in soil for thousands of years after application, thereby reducing carbon emissions from biomass burning or direct field return, slowing terrestrial ecosystem carbon cycling, and representing an effective new approach to mitigate climate change [6]. On the other hand, some researchers are optimistic about biochar’ s environmental benefits, believing that the biochar-soil system has the potential to sequester atmospheric carbon dioxide (CO_2) and reduce greenhouse gas emissions such as soil methane (CH_4) and nitrous oxide (N_2O) [7-9].

However, controversy remains regarding whether biochar addition increases soil carbon pool reserves or promotes soil carbon emissions. Studies in forest soils suggest that biochar's effectiveness as a long-term soil carbon pool has been overestimated, as this effect is partially offset by its ability to promote decomposition of original soil organic matter, leading to increased soil carbon emissions [10]. Other research indicates that biochar application to semi-arid farmland soils has no significant short-term effect on CO_2 and N_2O emissions [11]. Research on biochar in China started later than abroad and has focused on applications in soil improvement and crop yield enhancement [12-14]. With biochar technology development and increased environmental awareness, the impact of biochar on greenhouse gas emissions from farmland soils has gradually gained attention. However, few studies have reported on greenhouse gas emissions from paddy soils after in-situ manure return combined with biochar application.

Southern China has over 20 million hectares of winter fallow fields across 15 provinces, with Hunan Province alone having at least 1.2 million hectares [15]. Such large-scale land idleness inevitably leads to tremendous waste of spatial resources. Current primary utilization methods for winter fallow fields in southern China include planting green manure crops such as milk vetch (*Astragalus sinicus*), ryegrass (*Lolium multiflorum*), alfalfa (*Medicago sativa*), and oats (*Avena sativa*), as well as winter crops like rapeseed (*Brassica campestris*) and potato (*Solanum tuberosum*) [15-18]. This utilization approach offers numerous benefits such as improved soil fertility [19], but its direct economic returns are not obvious, affecting farmers' adoption enthusiasm. Introducing rotational chicken farming to winter paddy fields can utilize green manure to supplement chicken feed while increasing soil available carbon and nitrogen [20]. On one hand, ecological local chickens can be marketed before the Spring Festival, substantially improving economic benefits of winter paddy fields. On the other hand, chicken manure and biochar application can regulate soil physicochemical properties, improve soil quality, and input large amounts of organic carbon into the soil.

Therefore, this study quantified soil CO_2 and CH_4 emission fluxes from winter paddy fields and double-cropping rice periods through integrated winter chicken farming combined with biochar addition, evaluated the effects of biochar and chicken manure on soil carbon emissions, and explored their mechanisms to provide a scientific reference for deepening understanding of the environmental benefits of biochar and chicken manure organic fertilizer.

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1 Materials and Methods

1.1 Study Area Description

The experiment was conducted from December 2015 to November 2016 at the Yunyuan Experimental Base of Hunan Agricultural University in Changsha, Hunan Province. The experimental area has a mild climate with abundant precipitation, concurrent rainfall and heat, and distinct four seasons. The annual average temperature is 17.2°C, and the average annual precipitation is 1,361.6 mm. From late November to mid-March of the following year, the average temperature in Changsha is below 0°C, with January being the coldest month (monthly average 4.4-5.1°C), allowing safe overwintering and slow growth of winter crops. The previous cropping system was early rice-late rice-winter fallow, and the soil texture is alluvial soil.

1.2 Experimental Materials

The chicken breed used was the local Changsha variety "Tu 2.5" with an average weight of 0.5 kg. The conventional early rice variety was "Zhongjiazao 17," and the late rice variety was "Xiangwanxian 12." Biochar was rice husk biochar provided by the Changsha Biomass Energy Utilization Research Center, produced through oxygen-limited carbonization at high temperature (300-450°C). The basic physicochemical properties of the tested soil and biochar are shown in Table 1 .

Table 1 Basic physical and chemical properties of tested soil and biochar

Property	Soil	Biochar
Organic carbon (g · kg^{-1})	[value]	[value]
Organic matter (g · kg^{-1})	[value]	[value]
Total N (g · kg^{-1})	[value]	[value]
Total P (g · kg^{-1})	[value]	[value]
Total K (g · kg^{-1})	[value]	[value]
Water-soil ratio	2.5:1	–

1.3 Experimental Design and Field Management

Four treatments were established: one control and three treatments, each with three replications, totaling 12 plots of 3$×9 = 27m^{2}$. Plots were arranged in a randomized complete block design.

Treatments: 1. **Biochar only (B):** Biochar was applied at 30 t · hm^{-2} and mixed with surface soil (0-15 cm). 2. **Chicken farming (C):** Rotational chicken farming was conducted in winter paddy fields with in-situ chicken manure return. Each plot contained one chicken cage housing 30 local chickens in a 3$×3m^{2}$ area. During the experiment, cages were moved every 8 days: after 8 days at the first position, the cage was moved to the second position for another 8 days, then to the third position, and so on. Each position housed chickens for 16 days total, creating a rotational grazing system. Due to the short interval and slow chicken growth, manure distribution was considered uniform across plots. Simultaneously, five chickens were raised in another cage, and manure weight was measured every 3 days until the end of chicken farming. Statistics showed the equivalent application of fresh chicken manure was 7.3 kg · m^{-2}. 3. **Chicken farming + biochar (CB):** Biochar was applied at 30 t · hm^{-2} and mixed with surface soil (0-15 cm), combined with rotational chicken farming and in-situ manure return at the same rate as treatment C. 4. **Control**

(CK): After rice harvest, the paddy field remained as winter fallow without any treatment.

Field Management: Chickens were caged in the field on December 3, 2015, and removed on January 28, 2016. Feed formula was 50% corn flour + 10% rice bran + 35% alfalfa grass powder + 5% premix. Rice cultivation used seedling transplanting. Other management practices such as water and pest control were consistent across treatments. Phosphorus fertilizer was applied as base fertilizer at once. Nitrogen fertilizer was applied as base fertilizer:tillering fertilizer:panicle fertilizer at a 4:2:4 ratio. Potassium fertilizer was applied as base fertilizer:panicle fertilizer at a 7:3 ratio. For B and CK treatments, N, P, and K fertilizer rates followed conventional farmer practice in Changsha: 165 $kg \cdot hm^{-2}$ N, 75 $kg \cdot hm^{-2}$ P_2O_5, and 135 $kg \cdot hm^{-2}$ K_2O per rice season. For C and CB treatments, chemical N and K were reduced by 20% (132 $kg \cdot hm^{-2}$ N and 108 $kg \cdot hm^{-2}$ K_2O), while P remained unchanged (75 $kg \cdot hm^{-2}$ P_2O_5).

1.4 Gas Measurement Methods

1.4.1 Gas Flux Measurement Soil CO_2 and CH_4 exchange fluxes were measured using an Ultraportable Greenhouse Gas Analyzer (CH_4, CO_2, H_2O) (Los Gatos Research, USA, Model 915-0011-1000) combined with a circulating transparent static chamber. The analyzer can measure linear concentration changes of CO_2 and CH_4 inside the static chamber in situ. During measurement, the linear change displayed on mobile communication devices allowed real-time judgment of chamber sealing to ensure data accuracy. The static chamber was made of transparent organic glass (30 cm × 30 cm) with inlet and outlet holes. Each plot had a base with the same dimensions as the chamber, featuring grooves on four sides. During installation, the base edge was embedded 3 cm deep into the soil. For measurement, the static chamber was placed on the base, and water was added to the grooves to ensure airtightness. Each plot was measured for five minutes between 8:00 AM and 12:00 PM. Soil temperature (0–5 cm) was measured simultaneously.

Winter chicken farming period: The base was fixed in the first 9 m^2 chicken-raising area of each plot. The first measurement was taken when the chicken cage was moved to the second 9 m^2 area after 8 days, on December 11, 2015. The measurement interval was approximately 8 days, with six measurements total.

Rice growth period: Measurements were taken at mid-stage of each growth period: early rice seedling (May 8), tillering (May 18), booting (June 13), heading (July 1), and maturity (July 15); late rice seedling (August 1), tillering (August 15), booting (September 6), heading (September 20), filling (October 10), and maturity (November 3). An Onset HOBO temperature recorder (Model: U23-001) was used to simultaneously measure soil temperature (0–5 cm) and air temperature inside the static chamber.

1.4.2 Calculation of Gas Flux and Cumulative Emissions The net exchange flux of CH_4 and CO_2 was calculated using the formula:

$$F = \frac{dc}{dt} \times \frac{P \times V}{A \times R \times T}$$

where: F is CO_2 flux ($\mu mol \cdot m^{-2} \cdot s^{-1}$) or CH_4 flux ($\mu mol \cdot m^{-2} \cdot s^{-1}$); dc/dt is the rate of change of CO_2 or CH_4 concentration (ppm) over time t (s); P is standard atmospheric pressure (101.2237 kPa); V is the effective volume of the chamber (m^3), i.e., transparent chamber volume minus total plant volume inside the base and volume of the fan and temperature recorder inside the chamber wall; R is the gas constant ($8.3144\ J \cdot mol^{-1} \cdot K^{-1}$); A is the area covered by the transparent chamber (m^2); and T is the average temperature inside the transparent chamber during measurement (K = 273.15 + °C).

Cumulative emissions of CO_2 and CH_4, E_c ($kg \cdot hm^{-2}$), were calculated as [21]:

$$E_c = \sum_{i=1}^{n-1} \frac{F_i + F_{i+1}}{2} \times (t_{i+1} - t_i) \times a$$

where n is the number of observations during the winter and rice growth periods; F_i and F_{i+1} are CO_2 and CH_4 fluxes at the ith and $(i+1)$th measurements ($\mu mol \cdot m^{-2} \cdot s^{-1}$); t_{i+1} and t_i are the time intervals between the ith and $(i+1)$th measurements (days); and a is a conversion coefficient for the rice growth period (since the measurement days were fewer than the total rice growth days from sowing to harvest, this coefficient converts to the full growth period length), here taken as 194/176.

1.4.3 Data Processing Data were organized using Microsoft Excel 2007. SPSS 18.0 software was used for one-way ANOVA, and Sigmaplot 12.5 was used for figure preparation.

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2 Results

2.1.1 CO_2 Flux

As shown in Figure 1 [Figure 1: see original paper], during the winter paddy field chicken farming period, CO_2 emission fluxes under C, CB, and B treatments were all higher than CK. In terms of variation range, C treatment flux varied from 3.30-10.77 $\mu mol \cdot m^{-2} \cdot s^{-1}$, CB treatment from 3.86-12.80 $\mu mol \cdot m^{-2} \cdot s^{-1}$, B treatment from 0.27-3.11 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and CK from 1.76-1.37 $\mu mol \cdot m^{-2} \cdot s^{-1}$. This indicates that adding chicken manure and biochar promoted winter paddy field soil respiration and increased soil CO_2 emissions.

Except for the early rice seedling stage, significant differences in paddy soil CO_2 flux among treatments were observed within the same growth stage ($P<0.05$). During the rice growth period, soil CO_2 flux varied greatly across treatments, with emission peaks appearing at the booting and maturity stages for early rice and at the tillering and heading stages for late rice. The highest value for early rice was 10.22 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (CB treatment at maturity), while the highest for late rice was 8.70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (CB treatment at heading). Even for the same treatment, the timing of maximum CO_2 emissions differed between early and late rice, indicating that rice varieties affect soil CO_2 emissions. However, at early rice tillering, booting, late rice seedling, and filling stages, C treatment showed the highest CO_2 flux values; at early rice heading, B treatment was highest; and at late rice booting, CK was highest. This suggests that different treatments have complex effects on soil CO_2 emissions across various rice growth stages.

2.1.2 CH_4 Flux

During the winter paddy field chicken farming period, as shown in Figure 2 [Figure 2: see original paper], soil CH_4 emission flux trends were generally consistent across treatments and showed no significant correlation with soil temperature. Both C and CB treatments were higher than CK, but overall, CH_4 flux variations were small and fluctuated around 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$, indicating low CH_4 emissions from winter paddy soils.

During the rice growth period, C treatment soil CH_4 flux showed large increases and decreases at early rice tillering and booting stages and late rice seedling stage, with significant differences from other treatments ($P<0.05$). Other treatments showed small variations during the rice growth period with no significant differences among them ($P>0.05$), and values concentrated within $±0.03mol·m^{{-2}·s}{-1}.HighsoilCH_{4}$ fluxes occurred during field flooding periods, demonstrating that CH_4 production and emission mainly occurred during flooded stages of rice growth.

2.2.1 Cumulative CO_2 and CH_4 Emissions During Winter Paddy Period

As shown in Figure 3 [Figure 3: see original paper], cumulative CO_2 emissions across treatments ranged from 166.43-12,263.24 $kg \cdot hm^{-2}$, while cumulative CH_4 emissions ranged from 0.45-44.53 $kg \cdot hm^{-2}$. Both CO_2 and CH_4 cumulative emissions showed extremely significant differences among treatments ($P<0.01$).

During the 50-day measurement period, compared with CK, cumulative CO_2 emissions under C, CB, and B treatments were 58.7 times, 72.7 times, and 12.3 times higher, respectively, with extremely significant differences ($P<0.01$). This indicates that adding chicken manure and biochar significantly promoted cumulative CO_2 emissions. In this study, fresh chicken manure addition was 73 $t \cdot hm^{-2}$, and biochar addition was 30 $t \cdot hm^{-2}$. Both chicken manure and biochar contain large amounts of organic carbon, indicating that adding exogenous organic carbon increased soil CO_2 emissions. Additionally, CB treatment cumulative CO_2 emissions were 2,327.85 $kg \cdot hm^{-2}$ higher than C treatment, which was comparable to the 2,214.05 $kg \cdot hm^{-2}$ from B treatment alone. This suggests that part of the CO_2 cumulative emissions in CB treatment consisted of labile carbon decomposition and release from biochar itself.

As shown in Figure 3, cumulative CH_4 emissions across treatments followed the order C > CB > CK > B, with extremely significant differences between C and CB ($P<0.01$). C treatment CH_4 cumulative emissions were 2.4 times higher than CB treatment, indicating that biochar inhibited CH_4 emissions in upland soils.

2.2.2 Cumulative CO_2 and CH_4 Emissions During Rice Growth Period

As shown in Figure 4 [Figure 4: see original paper], C and CB treatments had higher cumulative CO_2 emissions than CK with significant differences ($P<0.05$). Specifically, C treatment was 56% higher than CK, and CB treatment was 41% higher. Although B treatment was 17% higher than CK, the difference was not significant. CB treatment was 726.11 $kg \cdot hm^{-2}$ lower than C treatment with significant difference ($P<0.05$), indicating that biochar addition in winter paddy fields could reduce soil CO_2 cumulative emissions during the rice growth period compared with chicken manure alone. Biochar addition increased soil CO_2 cumulative emissions during winter (Figure 3) but reduced them after a longer period.

Similar to the winter fallow period (Figure 3), biochar treatments showed significantly lower cumulative CH_4 emissions than non-biochar treatments. CB treatment reduced CH_4 by 746% compared to C treatment, and B treatment reduced CH_4 by 1,303% compared to CK, with extremely significant differences ($P<0.01$). Although CB treatment CH_4 cumulative emissions were higher than CK, the difference was not significant. This demonstrates that biochar addition inhibited CH_4 production and emission regardless of flooding conditions.

2.3 Cumulative CO_2 and CH_4 Emissions from Early and Late Rice

As shown in Figure 5 [Figure 5: see original paper], soil CO_2 cumulative emissions were higher for late rice than early rice across all treatments: CK late rice was 1.04 times higher than early rice, C treatment was 83% higher, CB treatment was 69% higher, and B treatment was 1.16 times higher, all reaching significant differences ($P<0.05$). This was likely mainly related to the longer growth period of late rice.

Soil CH_4 cumulative emissions under C, CB, and CK treatments were higher for early rice than late rice, while B treatment showed the opposite pattern, though differences were not significant. Specifically, CK early rice was 46% higher than late rice, C treatment early rice was 38% higher, and CB treatment early rice was 1.08 times higher, all reaching significant differences ($P<0.05$). Early rice paddies were flooded for extended periods, creating anaerobic conditions that maintained relatively high CH_4 emission rates.

2.4 Relationship Between CO_2 Flux and Soil Temperature at 5 cm Depth

Figure 6 [Figure 6: see original paper] shows the relationship between soil temperature and CO_2 flux during the annual measurement period. Only CK and B treatments could be well fitted with 5 cm soil temperature using a nonlinear exponential model, while C and CB treatments showed no significant correlation with 5 cm soil temperature. The r^2 value between CK and 5 cm soil temperature was greater than that between B treatment and 5 cm soil temperature, indicating that biochar addition and in-situ chicken manure return affected the mechanism of soil-atmosphere CO_2 exchange, making influencing factors more complex.

Discussion

Soil organic carbon mineralization is the main pathway for soil CO_2 emissions. Organic material application is an important measure for regulating soil organic carbon. It not only directly increases carbon input and changes soil organic carbon availability but also significantly affects soil carbon pool transformation processes, thereby influencing soil carbon sequestration and greenhouse gas emissions [22]. The availability and physicochemical properties of applied organic materials are key factors affecting soil carbon sequestration and emission reduction. Many studies have examined the effects of organic material application on soil CO_2 emissions, generally concluding that it promotes emissions, though the enhancement effect depends on organic material properties, soil temperature, moisture, and texture [23]. Currently, few studies have investigated the effects of biochar application alone or combined with organic materials on soil CO_2 and CH_4 emissions.

Research on the effects of applying decomposed chicken manure on soil respiration shows that chicken manure significantly promotes soil CO_2 emissions [24-25]. This study used fresh chicken manure and similarly demonstrated that chicken manure application to paddy soils significantly increased CO_2 emissions during both winter farming and rice growth periods. Biochar addition, however, showed different results across time scales. Some studies indicate that biochar application reduces soil organic carbon mineralization by 25.5% [26], with soils without biochar showing significantly higher CO_2 emissions than biochar-treated soils [27]. Other researchers found that rice husk biochar addition promoted soil mineralization [28]. These contradictory conclusions may relate to inconsistent study time scales. This study also used rice husk biochar and found that biochar addition significantly increased winter paddy field CO_2 emissions. However, the difference in cumulative CO_2 emissions between the combined chicken manure and biochar treatment and chicken manure alone was comparable to the emissions from biochar alone, suggesting that biochar addition did not significantly promote mineralization of original soil organic carbon or added chicken manure organic carbon. Instead, decomposition of labile organic carbon contained in biochar itself increased soil CO_2 emissions. Soil carbon net mineralization or loss is positively correlated with unstable substances in biochar [29-30]. Additionally, ^{14}C research shows that CO_2 emissions after biochar application approximately equal the amount of organic carbon decomposition and inorganic carbon release from biochar [31], with C released as CO_2 accounting for only 0.1%-0.8% of total biochar C [32]. Therefore, considering only carbon emissions induced by biochar and comparing them with the large amount of inert organic carbon it contains and its long residence time in soil, short-term biochar-induced CO_2 emissions are minimal [31]. During the rice growth period, the combined chicken manure and biochar treatment showed significantly lower cumulative CO_2 emissions than chicken manure alone, while biochar alone showed no significant difference from CK. This indicates that after stabilization in soil, added biochar suppressed CO_2 emissions. This suppression may occur because biochar addition promotes formation of soil humus and helps form organic macromolecules such as carbohydrates, esters, and aromatics that are difficult for microorganisms to utilize. This process reduces microbial utilization of organic carbon, decreasing mineralization of original soil organic carbon and exogenous chicken manure organic carbon, thereby reducing soil CO_2 emissions [33-34]. These results are consistent with soil incubation studies showing that biochar addition promotes soil organic carbon mineralization in the early stage but produces inhibitory effects in the later stage [35-36]. In summary, although biochar addition alone or combined with chicken manure and other organic materials promotes soil CO_2 emissions in the short term, this is only a short-term priming effect [37]. In the long term, biochar addition is beneficial for soil carbon sequestration and emission reduction.

Soil CH_4 is produced by methanogens, which require strong anaerobic conditions for survival and reproduction. Therefore, enhancing soil permeability and reducing anaerobic conditions can decrease methanogen populations while increasing methane-oxidizing bacteria, thereby reducing soil CH_4 emissions or even making soil a CH_4 sink. Biochar’ s special physicochemical properties can achieve this [38-39]. Additionally, biochar’ s adsorption of NH_4^+ reduces competition for methane-oxidizing bacteria, thereby increasing CH_4 oxidation probability [40-41]. Some researchers believe that biochar application increases soil redox potential and C/N ratio, stimulating methane-oxidizing bacterial activity [42]. This study similarly found that biochar addition to paddy fields significantly reduced CH_4 emissions regardless of whether soil moisture was low during winter or during prolonged flooding in the rice growth period. Biochar also significantly reduced CH_4 emissions when combined with chicken manure, demonstrating a significant CH_4 reduction effect.

Conclusions

1) Compared with the control, chicken manure addition significantly promoted soil CO_2 and CH_4 emissions. Biochar addition inhibited CH_4 emissions, significantly increased CO_2 emissions during the winter paddy period, but increased CO_2 emissions without significant differences during the rice growth period.
2) Biochar combined with chicken manure significantly increased soil CO_2 emissions compared with the control during both winter and rice growth periods. CH_4 cumulative emissions were significantly higher than the control during winter but showed no significant difference during the rice growth period. Compared with chicken manure alone, the combined treatment significantly increased soil CO_2 cumulative emissions during winter but significantly reduced them during the rice growth period. CH_4 emissions were significantly lower than chicken manure alone in both periods.
3) In summary, biochar addition to soil inhibits CH_4 production and emission with significant effects. Compared with the large amount of inert organic carbon contained in biochar, short-term biochar-induced CO_2 emissions are minimal. Therefore, in the long term, biochar application to farmland soil has obvious benefits for soil carbon sequestration and emission reduction.

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Note: Figure translations are in progress. See original paper for figures.