Food and Energy Security

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ORIGINAL ARTICLE OPEN ACCESS

Crop Residue Biochar Rather Than Manure and Straw Return Provided Short Term Synergism Among Grain Production, Carbon Sequestration, and Greenhouse Gas Emission Reduction in a Paddy Under Rice-Wheat Rotation

Xin Xia[1,2] | Zheng Zhao[1,2] | Yuanjun Ding[1,2] | Xiao Feng[1,2] | Shuotong Chen[1,3] | Qianqian Shao[1,4] | Xiaoyu Liu[1,2] | Kun Cheng[1,2] | Rongjun Bian[1,2] | Jufeng Zheng[1,2] | Lianqing Li[1,2] | Genxing Pan[1,5]

[1]Institute of Resources, Ecosystem and Environment of Agriculture, Nanjing Agricultural University, Nanjing, China | [2]Jiangsu Collaborative Center of Solid Waste Resource and Utilization, Nanjing Agricultural University, Nanjing, China | [3]College of Environmental Science and Engineering, Yangzhou University, Yangzhou, China | [4]Bureau of Water Conservancy, Gongyi County, Zhengzhou Municipality, China | [5]School of Environment and Resources, Zhejiang University of Science and Technology, Hangzhou, China

Correspondence: Genxing Pan (gxpan@njau.edu.cn; pangenxing@aliyun.com)

Received: 11 May 2024 | **Revised:** 14 August 2024 | **Accepted:** 26 September 2024

Funding: This work was supported by National Natural Science Foundation of China, 41371298, 41771332, 42077082.

Keywords: crop productivity | crop residue | food and environment | organic carbon sequestration | paddy methane emission | rice and wheat rotation | soil amendment | soil health

ABSTRACT

Return of crop residues directly as straw, animal manure, or biochar are recommended management options for biowaste recycling and soil organic carbon (SOC) maintenance in agriculture. However, to address the soil health challenges associated with soil degradation and climate change, it is critical to determine if or which of these different forms of crop residues could deliver a synergic improvement in SOC storage, emission reduction, and crop productivity following field application. In this study, maize straw in the form of air-dried biomass (CS), manure via cattle digestion (CM), and biochar via pyrolysis (CB) was respectively amended once at a dose of $10\,t\,C\,ha^{-1}$, in comparison to no maize straw addition (CK), in a paddy field under rice-wheat rotation. Changes in soil properties, SOC storage, greenhouse gas (GHG) emissions, and rice/wheat yield were examined over two consecutive rice/wheat rotation cycles following soil amendment. The total rice grain yield considerably increased by 6% under CM and CB, while it reduced by 6% under CS compared to CK. Soil nutrient content persistently increased under CM and CB by 4.2%~17% and 11%~26% for total nitrogen, 26%~61% and 20%~53% for available P, and 2%~82% and 30%~115% for available K, respectively. Topsoil SOC storage increased considerably by 8% under CM and 20% under CB, while remained unchanged under CS, compared to CK. The total methane (CH_4) and nitrous oxide (N_2O) emissions were considerably increased by 7 folds and 15% under CS and 3.5 folds and 61% under CM, respectively, compared to CK. In contrast, these emissions considerably decreased under CB by 33% for CH_4 and 29% for N_2O. Consequently, the C emission efficiency considerably reduced under CS and CM but increased under CB over the two rotation cycles monitored. Moreover, the soil quality index (SQI) considerably improved under CM and CB but remained unchanged under CS compared to CK. Among the different forms of straw return, manure, and biochar, straw amendments differed considerably in their effects on C sequestration, GHG emissions, and crop productivity. Only biochar from crop residues synergistically improved these functions in the short-term following application to paddy soil.

1 | Introduction

In an effort to ensure food security, global agriculture faces serious challenges, including accelerated land and soil degradation, climate change, and environmental pollution (OECD-FAO 2023). Agricultural development has gained considerable attention because of the negative environmental consequences of intensive cultivation and overfertilization (Poore and Nemecek 2018; IPBES 2019; Balogh 2022). Increasing soil organic carbon (SOC) in the form of soil organic matter (SOM) is widely recommended to improve soil health, sustain food production, and mitigate climate change (Amelung et al. 2020; Lal 2020b; Lehmann et al. 2020). Particularly, a global action to boost soil C sequestration for climate and food security has been suggested through the "4 per 1000" initiative launched post Paris Agreement (Minasny et al. 2017; Rumpel, Lehmann, and Chabbi 2018). From the perspective of a circular economy (D'Amato et al. 2017), residue recycling in crop production can be considered a nature-based solutions (NbS) (UNEP 2022) for increasing SOC and crop productivity. However, the reality and potential trade-offs should be addressed for sound policy decisions (Hunt, Celestina, and Kirkegaard 2020).

Crop residue recycling and reuse are considered primary options for promoting SOC storage and climate resilience (Paustian et al. 2016; Minasny et al. 2017). Major efforts have been made to promote crop residue recycling in farmlands (Chen et al. 2016; Ghimire et al. 2017; Zhao et al. 2018; Liu et al. 2023). Traditionally, crop residue can be recycled as direct straw return, and manure is transformed via cattle digestion. While these practices tend to disappear with rapid industrialization, urbanization, and intensive application of synthetic chemical fertilizers in developing countries (Cui et al. 2018), their efficacy in increasing SOC storage may often be low, although variable (Lal 2016). Direct incorporation of crop residues may induce the potential risk of enhancing biological nitrogen (N) immobilization (Olk et al. 2006) and increasing methane (CH_4) emissions from paddy soil (Ma et al. 2008; Bhattacharyya et al. 2012). The incorporation of unprocessed crop residues into the soil can induce some soil-borne diseases and harmful insect pests (Yu et al. 2023) and potentially constrain the penetration of crop roots (Wang et al. 2019). In contrast, manure is well known for its superior performance in increasing SOC, with improved soil structure, plant availability of soil nutrients (Meng, Ding, and Cai 2005; Feng et al. 2022b), and microbial activity (Dong et al. 2014; Zhou et al. 2016).

Recently, the application of biochar to soil, a novel recycling approach involving the thermal conversion of crop residues (Lehmann and Joseph 2015), has been advocated to enhance SOC sequestration and crop productivity (Jeffery et al. 2011; Liu et al. 2012, 2018b; Chen et al. 2018; Nguyen, Trinh, and Bach 2020; Liu and Pan 2021). Soil application of biochar is well known for its promising effect on crop productivity (approximately 10% of global mean) (Jeffery et al. 2011; Liu et al. 2013), with notable improvement in soil fertility (Ding et al. 2016), possibly owing to the improvement of soil structure, water availability (Omondi et al. 2016; Wu et al. 2022), microbial activity (Zhou et al. 2017), and nutrient availability, particularly P (Tesfaye et al. 2021). Biochar is widely known for its role in reducing greenhouse gas (GHG) emissions from amended fields (Zhang et al. 2010; Cayuela et al. 2014; Schimmelpfennig et al. 2014; Jeffery et al. 2016; Liu et al. 2020). In addition to the continuous increase in SOC with long-term stability (Wang, Xiong, and Kuzyakov 2016), biochar can provide sustainable improvements in soil health by improving microbial C use efficiency (Lehmann and Joseph 2015). However, the widespread application of biochar has been a subject of debate because of its longevity and cost benefits (Clare et al. 2015; Chen et al. 2023). Therefore, sound knowledge of the comparative merits of biochar and unprocessed crop residues or livestock-derived manure from animal digestion should be provided for robust crop production.

Soil health has been increasingly investigated to improve food production and human health (Lehmann et al. 2020). Soil health is generally defined as the capacity of the soil to perform its functions and provide ecosystem services, such as providing crop productivity, conserving biota, buffering water and nutrients, and storing organic carbon (OC) for climate stabilization, as well as land surface and landscape stabilization, continuously in spatial and temporal scope (Lehmann et al. 2020; Zhao et al. 2023). While the global decline in SOC storage has been accelerating with extensive land use changes (Amelung et al. 2020), SOM, as OC associated with soil components, is well known as the key driver of soil fertility/health for the sustainable development of agriculture (Lehmann et al. 2020). Soil health status should be understood in terms of local ecosystems and site-specific production conditions (Janzen, Janzen, and Gregorich 2021). Therefore, soil health changes under management intervention can be assessed with production capacity in line with other major ecosystem services (Zhao et al. 2023). For example, yield changes in line with SOC increases, microbial manipulation, and input efficiency for rice production have been depicted as short-term soil health changes following biochar amendment (Wang et al. 2018; Lu et al. 2020). In this regard, the multifunctionality of management practices has been considered to develop a soil quality index (SQI) (Liu et al. 2023). Similarly, the soil health status with soil-landscape changes in a hilly rural area was assessed using a radar diagram with key indicators of SOC storage, aggregation, microbial abundance, and available nutrients (Zhao et al. 2022). Although farm production affected by crop residues against adverse environmental feedback has been highlighted, soil health status under crop residue amendment should be addressed for any potential trade-offs between production and GHGs emissions, as well as between SOC storage and nutrient retention and availability in terms of C emission efficiency and nutrient use efficiency. However, the impact of crop residue amendments on soil health has not yet been assessed in terms of multifunctionality.

Rice is one of the most important staple crops globally, providing calories to more than half of the world's population. Over the last few decades, rice cultivation areas have dramatically increased in Asia, Africa, Latin America, and Europe (Bin Rahman and Zhang 2023). However, rice production has been a serious concern because of its high GHG emissions, CH_4 rather than nitrous oxide (N_2O), from paddy fields (Brodt et al. 2014; Linquist et al. 2018). Global paddy emits ca. $0.04\,Gt\,CH_4\,year^{-1}$, accounting for 1.7% of the global anthropogenic GHG emissions (IPCC 2022). With the recently launched Global Methane Pledge

(GMP 2023), CH_4 emission reduction has become a cut-edging paradigm for sustainable rice agriculture. China ranks first in countries producing rice, contributing approximately 30% to global rice production (FAO 2023). It is estimated that China emitted approximately 10 Tg CH_4 per annum by 2020 (Duan et al. 2023). Compared with dry croplands, China's rice paddies have a higher SOC storage and sequestration potential (Pan et al. 2004; Wei et al. 2021) through rational tillage and residue incorporation. Residue return or manure application into rice fields is incentivized, with the ban on straw field burning, to enhance SOM and soil fertility; however, the considerable increase in CH_4 emissions would offset SOC sequestration and N_2O emission reduction (Liu et al. 2014; Zhang et al. 2019; Kan et al. 2023). Recently, the industrial production and soil amendment of crop residue biochar in rice farms has offered an opportunity to reduce N_2O emissions and, to a lesser extent, CH_4 emissions from paddy fields (Zhang et al. 2010, 2012), particularly when replacing direct straw return with rice fields (Qin et al. 2016). Critical issues continue to emerge with the use of different forms of crop residue amendments, such as direct straw return, manure, or biochar. First, how do the overall effects on SOC accumulation, GHG emissions (particularly CH_4), and crop productivity differ among the different forms? Second, can manure and biochar, instead of direct straw return, provide a synergistic improvement in the above-mentioned effects in rice/wheat-rotated paddies? Addressing these issues is critical for developing sound strategies and technical options to achieve China's C neutrality targets by 2060.

Therefore, we hypothesized that all forms of crop residue, such as unprocessed biomass, animal-converted manure, and pyrolyzed biochar, could contribute to SOC sequestration, whereas manure and biochar would synergistically improve soil fertility, crop productivity, and emission reduction, particularly of CH_4, in rice-based agriculture. To test this, data derived from a field experiment with a rice-wheat rotation system were used to assess short-term changes in soil fertility, crop yield, and GHG emissions following soil amendment with the above-mentioned crop residue forms in a paddy field in the Tai Lake region of China. The objective of this study was to provide potential technical solutions for the safe recycling of crop residues in agriculture to contribute to China's C Neutrality target.

2 | Materials and Methods

2.1 | Site Condition

A field experiment involving crop-residue soil amendment was conducted at a rice and wheat production farm in the Tai Lake region of China. The farm is located in Kangbo Village (31°35′11.96′′ N, 120°54′51.86′′ E), Changshu Municipality, Jiangsu, China. The lower reaches of the Yangtze River Delta experience a subtropical monsoon climate, with a mean annual temperature of 18.2°C and precipitation of 1558 mm over 2015–2017. The paddy soil developed on clayey lacustrine deposits and was classified as Gleyic Stagnic Anthrosol (IUSS Working Group WRB, 2015). The soil texture was clay loam with sand (48%), silt (33%), and clay (19%). Crop cultivation in this area has been managed under summer rice-winter wheat rotation for hundreds of years. As a routine practice, crop straw is harvested mechanically with stubs left approximately 20 cm above the ground and turned into a plow layer prior to the next crop production. Before the experiment, the properties of topsoil (0–15 cm) were: pH (H_2O) of 7.3, bulk density of 0.95 g cm^{-3}, SOC of 28.5 g kg^{-1}, total nitrogen (TN)of 2.0 g kg^{-1}, available P (Olsen-P) of 23.6 mg kg^{-1}, and available K (exchangeable K) of 79.7 mg kg^{-1}.

2.2 | Experimental Design

The experimental design involved a one-time soil amendment with different forms of crop straw. The amendment rate was consistent at 10 t OC ha^{-1} as per the total crop straw amount of 20 t ha^{-1} per annum (rice and wheat yield of 18 t ha^{-1}, shoot to grain ratio of 1.14, and OC content of 47%, on average, for the region) (Sun et al. 2018). Maize straw was amended in the following forms: (1) air-dried unprocessed biomass (CS), (2) manure from dairy cattle fed with maize straw (CM), and (3) biochar from pyrolyzed maize straw (CB). These residue amendments were compared with the control treatment (CK) without maize straw amendment.

Maize straw was collected from a nearby household farm, air-dried, and chopped to approximately 2 cm before use. Maize-derived manure was collected from a household farm where dairy cows were fed a diet of fresh maize straw, while maize-derived biochar was produced via pyrolysis of maize straw in a vertical kiln with a temperature range of 350°C–550°C provided by Sanli New Energy Company, Henan, China. Considering the OC content (Table S1), field amendment was performed once in a dry mass at 20.4, 34.8, and 19.6 t ha^{-1} for the CS, CM, and CB treatments, respectively.

For the field experiment, the treatment was conducted in four replicated plots arranged in a Latin square design (Figure S1). The treatment plot was 19.5 m^2 (6.5 m × 3 m) and was separated by a protection row 30 cm in width. In early June 2015, following the wheat harvest and removal of aboveground residues, the required amount of amendment material in a certain maize residue form was weighed and spread onto the soil surface of the plot. The soil was then tilled to a depth of approximately 15 cm and subsequently homogenized using a wooden rake to ensure that the amended material was thoroughly incorporated into the plow layer soil.

2.3 | Field Management

During the rice growing season, an Indica (Oryza sativa L. cv., Zhongyou 1176) seedling was transplanted in late June, with three seedlings per hill and 27 hills per m^2. Following the local conventional management practice for rice production, all treatment plots were kept flooded for 1 month following transplantation and subsequently drained for 1 week, followed by intermittent irrigation until rice harvest in early November. In winter, wheat (Triticum aestivum L. cv. Yangmai No.16) seeds were sown by hand at a rate of 262.5 kg ha^{-1} in late November. Wheat was grown without irrigation until harvest in early June. The climatic conditions over the two rice–wheat rotation cycles during the experimental period are shown in Figure S2.

For crop production, fertilizer applications followed the conventional practices of local farmers, which are outlined in Table S2, with urea for N-only and compound fertilizer for NPK. For rice, the total input of chemical fertilizer per hectare was 200 kg N, 130 kg P_2O_5, and 56 kg K_2O. The fertilizer applications were split into basal and topdressing posts, except for K, which was only top-dressed. For wheat, the total fertilizer input per hectare was 265 kg N, 75 kg P_2O_5, and 30 kg K_2O. Urea was applied as a basal and heading fertilizer, and a compound fertilizer was applied as a jointing fertilizer.

Throughout the crop seasons, rice and wheat residues were removed after harvest from all treatment plots, including the CK. All other farming practices, such as weed control, irrigation methods, and fertilizer application modes, were performed as per the local conventional farming practices with a rice-wheat rotation system, as documented by Xiong et al. (2021). All practices were consistent across the two rice–wheat rotation cycles throughout the experimental period.

2.4 | Crop Yield Measurement and Plant Sampling

At harvest, a random 2 m × 1 m quadrat was selected from the treatment plot. All the plants within the quadrats were collected and weighed. The grains were then manually threshed and homogenized to form a grain sample. Ten shoots were randomly selected. The shoots and grains were oven-dried at 105°C for 30 min and 70°C for 24 h to calculate the moisture content. The crop aboveground biomass and grain yield in dry base were estimated in kg per hectare.

2.5 | Soil Sampling and Analysis

Following the crop harvest, a composite sample of topsoil (0–15 cm) was collected from five random cores in the treatment plot using an Eijkelkamp soil core sampler. The collected composite samples were placed in plastic bags, sealed, and shipped to the laboratory within 2 days of sampling. On arrival, a portion of the fresh soil sample was sieved through a 2-mm sieve to measure the soil microbial biomass. The other major portion was air-dried and ground to pass through a 2-mm nylon sieve. Subsequently, a small portion of the air-dried sample was ground and passed through a 0.15-mm sieve for SOC and TN analysis. The soil physicochemical properties were determined according to the protocol described by Lu (2000). Soil particulate OC was measured according to the method by Cambardella and Elliott (1992). Ten grams of soil and 30 mL of 5 g L^{-1} sodium hexametaphosphate were placed in a 50 mL centrifuge tube. The slurry was shaken for 16 h and decanted onto a 0.53 μm sieve. The material retained on the sieve was collected as particulate organic carbon (POC) and oven-dried at 50°C for 72 h. The OC content of bulk soil and POC were determined using a wet digestion method with H_2SO_4—$K_2Cr_2O_7$ as per the protocol described by Lu (2000). Microbial biomass C (MBC) and N (MBN) were measured using fumigation as per Vance et al. (1987) using a conversion factor of 0.45. Subsequently, microbial quotient (MQ) was calculated as follows (Zhou et al. 2017):

$$\mathrm{MQS} = \mathrm{MBC} / \mathrm{SOC} \tag{1}$$

where MBC is the soil microbial biomass C in mg kg^{-1} soil and SOC is the content of topsoil OC in g kg^{-1} soil.

2.6 | Greenhouse Gas Emission Monitoring

Following Zhang et al. (2010), N_2O and CH_4 fluxes from the soil were monitored using the static closed-chamber method across two consecutive rice/wheat cycles. A PVC flux collar was installed in each plot before rice transplantation and wheat sowing during the rice and wheat seasons. A groove (5 cm deep) was placed on the top edge of the collar and filled with water to seal the rim of the chamber during gas collection. The flux chambers had dimensions of 50 cm × 50 cm × 50 cm or 50 cm × 50 cm × 100 cm, depending on the crop height. To minimize air temperature fluctuations, each chamber was covered with a layer of sponge and aluminum foil. Gas samples were collected using a gas-tight syringe at 0, 10, 20, and 30 min after chamber closure from 8:00 to 10:00 am on the measurement day. After collection, the gas sample was immediately injected into a special borosilicate glass vial (No. 5, Japan Maruemu Corporation). Gas sampling was generally conducted in 1 week interval, while additional sampling was performed following a fertilizer application event or during the midseason drainage of the rice season. However, less frequent gas sampling was conducted during winter, when wheat growth was low (Figure S3).

The concentrations of CH_4 and N_2O in the sampled gas were analyzed simultaneously using a gas chromatograph (Agilent 7890A) equipped with a flame ionization detector and an electron capture detector. The detailed protocol has been described by Zhang et al. (2012). Sample sets were rejected unless they yielded a linear regression value of $r^2 > 0.90$. The total emissions of CH_4 and N_2O over the entire rice or wheat growing season were sequentially accumulated from the emission fluxes averaged for every two adjacent intervals of the measurements (Zou et al. 2005).

A flux of CH_4 or N_2O was estimated using the following equation:

$$F\left(\mathrm{mg\ m^{-2}\ h^{-1}}\right) = \rho \times h \times \mathrm{d}c / \mathrm{d}t \times 273 / (273 + T) \tag{2}$$

where F is the GHG emission flux (mg m^{-2} h^{-1}); ρ is the density at the standard state of CH_4 or N_2O; h is the height of the static chamber (0.5 m or 1.0 m depending on the crop height); dc/dt is the rate of accumulation of the gas (1×10^{-6} L L^{-1} min^{-1}); and T is the mean temperature inside the chamber at the time of sampling (°C).

The overall global warming potential (GWP) and emission efficiency of crop production under treatment were estimated according to Zhang et al. (2016).

$$\mathrm{GWP}\ \left(\mathrm{kg\ CO_2 - eq\ ha^{-1}}\right) = \mathrm{CH_4} \times 29.8 + \mathrm{N_2O} \times 273 \tag{3}$$

where CH_4 and N_2O represent the total emissions (kg ha^{-1}) of CH_4 and N_2O gases, respectively, accumulated from the measured fluxes throughout the growth period of a crop. The numbers 29.8 and 273 denote the warming forcing factors of

CH_4 and N_2O molecules, respectively, according to IPCC AR6 (IPCC 2022).

2.7 | Soil Quality/Health Assessment

To address crop production against GHGs emissions, C emission efficiency was calculated using the following equation:

$$\text{C emission efficiency}\left(t\ \text{grain}\ t^{-1}\ \text{CO}_2\ \text{eq}\right) = Y / (\text{GWP}/1000) \tag{4}$$

where, GWP is the value in kg CO_2-eq ha^{-1} from Equation (3), Y is the yield (t grain ha^{-1}) of the crop under treatment, and 1000 is the conversion factor.

To assess the treatment effects on crop productivity against nutrient input, the fertilized nitrogen efficiency (NE), also called partial N productivity (PNP), was estimated as follows:

$$\text{NE} = Y / \text{N} \tag{5}$$

where NE represents the harvested grain in kg against per kg of total N fertilized; Y is the grain yield in kg ha^{-1} of the crop under treatment, and N is the total N input with fertilizers in kg ha^{-1}. To assess SOC sequestration, changes in SOC storage were calculated using the SOC content data measured over two rotation cycles (Pan et al. 2004):

$$D_{\text{SOC}} = \text{SOC} \times \text{BD} \times H / 10 \tag{6}$$

$$\Delta D_{\text{SOC}} = D_{\text{SOCtr}} - D_{\text{SOCck}} \tag{7}$$

$$\text{SOCpreserved} = D_{\text{SOCtr}} - D_{\text{SOC original}} \tag{8}$$

where Dsoc is the topsoil OC density (Mg C ha^{-1}), SOC is the measured SOC content (g kg^{-1}), BD is the soil bulk density (g cm^{-3}), and H is the topsoil thickness (cm) (15 cm in this study). ΔD_{soc} is the relative change of SOC density of treatment over CK; D_{soctr} and D_{SOCck} represent the SOC density of a treatment and of CK, respectively. Number 10 is the conversion factor. The $D_{\text{SOC original}}$ is the SOC density before the amendment.

To assess the change in soil fertility with the treatments, the SQI under a given treatment was estimated based on the minimum data set (MDS) of soil measurements, following Liu et al. (2018a) and Zhao et al. (2022):

$$\text{SQI} = \sum_{i=1}^{k} W_i f(x_i) \tag{9}$$

where SQI is the normalized value of soil fertility under treatment, W_i represents the weight of the ith indicator, $f(xi)$ represents the score of the ith indicator, and k represents the total number of measured variables used in the MDS.

The amendment effect intensity in % of soil quality, C emission efficiency, or fertilized nutrient efficiency was estimated using the following equation:

$$\text{AEI}\,(\%) = \left(\frac{Q_{\text{Amendment}} - Q_{\text{CK}}}{Q_{\text{CK}}}\right) \tag{10}$$

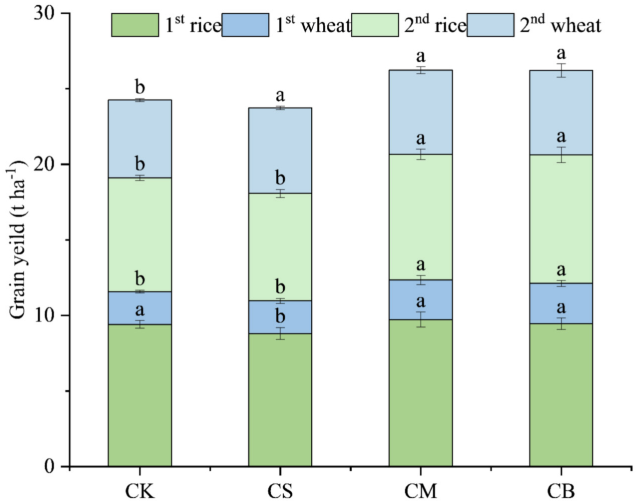

FIGURE 1 | Grain yield of rice (green) and wheat (blue) over the first (darker colored) and second (shallow colored) rotation cycle. The vertical bars represent the standard deviations of the means ($n = 4$).

Finally, following Guillaume et al. (2020), Zhao et al. (2022), and Li et al. (2023), the performance of soil ecosystem functions could be assessed using the ecosystem multifunctionality index (EMF), which was calculated with the equation:

$$\text{EMF} = 0.5 \times \sum_{i=1}^{n} (P_i)^2 \sin\left(\frac{2\pi}{n}\right) \tag{11}$$

where EMF is the normalized value of EMF under treatment, P_i is the score of ith indicator, and n is the total number of soil function indicators.

2.8 | Statistics

All data are expressed as mean plus/minus the standard deviation. Data were processed using Excel 2019, and statistical analyses were performed using SPSS 22.0. Means were compared using the least significant difference test, whereas variance among treatments was examined using one-way analysis of variance, with a significant difference defined as $p < 0.05$. Origin 2023b software was used to plot figures.

3 | Results

3.1 | Crop Yield

Data on the grain yield of rice and wheat over two consecutive rotation cycles are shown in Figure 1. Overall, the total grain yield remained unchanged under CS but increased considerably by approximately 8% under CM and CB, compared to CK. On average, in the two seasons, rice grain yield decreased by 6.0% under CS, and increased by 6.6% under CM and 6.1% under CB, compared to CK. Wheat grain yield considerably increased in all the amendment treatments, by 6.7% under CS and approximately 12% under CM and CB, compared to CK. In particular, the yield of the 1st wheat was as low as 2.1 t ha^{-1} under CK due to the prolonged waterlogging under heavy rainfall during the spiking-to-harvest period (Figure S2). However, the yield increased by over 20% under CM and CB treatments, although it did not change under CS. Overall, for the four crop seasons over the experimental duration, crop yield was reduced slightly under CS but increased considerably under CM and CB (by 8%), compared to CK. In addition, the harvest index of rice remained unchanged over the two seasons, whereas that of wheat was lower in the 1st season than in the 2nd season (Table S3). However, there was no variation in the harvest index values among the treatments for a single crop season.

3.2 | Soil OC and Nutrient Status

The edaphic properties of the topsoil sampled at crop harvest across the two rotation cycles are presented in Table S4. The changes in key properties are shown in Figure 2. First, the soil pH was lower in the rice season than in the wheat season, by 0.07–1.0 units. Compared to CK, topsoil pH (H_2O) was unchanged under CS and CM (except 0.2 units higher for the 1st rice season) but considerably increased under CB, by 0.1–0.3 units, across all the crop seasons of the consecutive rice/wheat rotation cycles. Second, topsoil SOC (Figure 2a) was almost consistent ($29.1 \pm 0.42\,g\,kg^{-1}$) under CK, while the amendment treatments showed remarkable seasonal variations across the crop seasons. For the 1st rotation cycle, topsoil SOC generally increased under all the amendment treatments compared to CK, with an increase of 8.2% under CS, 12% under CM, and 33% under CB in the 1st wheat season. For subsequent rotation cycles, the change in SOC compared to CK was either insignificant (2nd rice) or small (2nd wheat) under CS and CM. The SOC content under CB increased by approximately 30% compared to that under CK across all the crop cycles monitored.

Third, there were notable changes in soil nutrient retention among the treatments across the crop seasons. The changes in total soil N among the treatments were similar to the changes in SOC (Figure 2b). The changes in soil available P (overall CV of 19%) and K (overall CV of 31%) were different among the treatments and across the crop seasons. Compared to CK, available P remained unchanged under CS but increased under CM and CB across the crop seasons (Figure 2c), being greater in the 1st rotation cycle than in the 2nd cycle. Available K, in the range of $80–185\,mg\,kg^{-1}$, varied widely across crop cycles and among treatments. Different from available P, topsoil available K greatly increased under CM (by over 50%) and CB (by over 100%), but moderately increased under CS (by approximately 40%) in the 1st rotation cycle. It remained unchanged under CS, slightly increased (by 2 ~ 14%) under CM, and greatly increased under CB (by 30 ~ 50%) in the 2nd crop rotation cycle. The content of MBC (Table S4), varying in the range of $675 \sim 936\,mg\,kg^{-1}$, was generally higher in the rice seasons than in the wheat seasons across the two rotation cycles. Compared to CK, MBC was generally higher (10 ~ 20%) under CS and CM but remained unchanged under CB for the 1st rice, 1st wheat, 2nd rice, and 2nd wheat seasons. The change in MBC among the treatments was smaller during the late crop season following the amendment. The estimated MQ (%) was considerably lower under CB than under the other treatments across the crop seasons (Table S3).

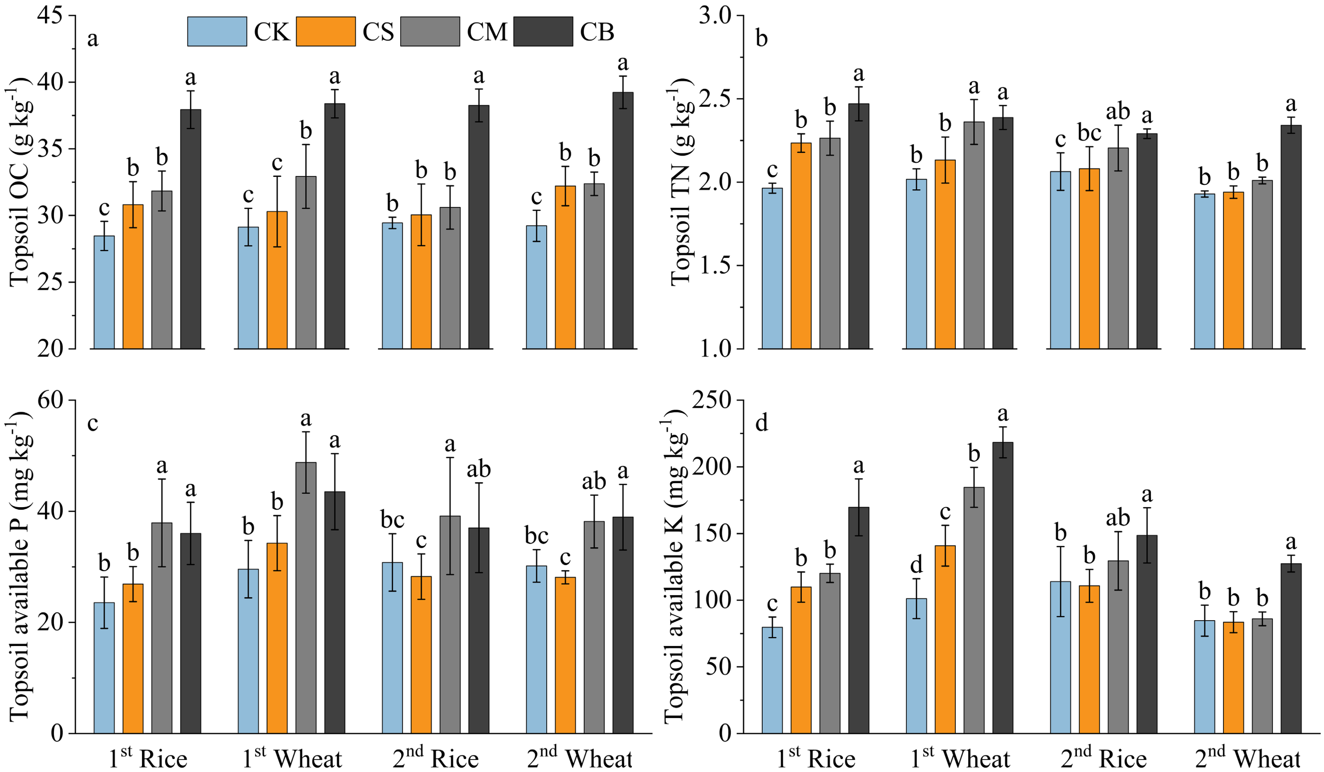

FIGURE 2 | The change of topsoil OC, total N, available P, and available K under different treatments during 2015–2017 rice-wheat rotations. OC, organic carbon; MBC, soil microbial biomass carbon. Different lowercase letters in a single column indicated significant difference among treatments at $p < 0.05$.

3.3 | Greenhouse Gases Emissions

The flux dynamics of the non-CO_2 potent gases, N_2O and CH_4, monitored over the two rotation cycles are presented in Figure S3 and the calculated total seasonal emissions under the treatments are summarized in Table 1.

Varying in a wide range of 0~300 μg N_2O-N $m^{-2} h^{-1}$, N_2O-N emission fluxes showed peaks following fertilizer application across the crop seasons, particularly following midseason drainage in rice seasons (Figure S3a). Total seasonal N_2O emissions were higher in the first rotation cycle than in the second, except for the CB treatment in the 1st rice season. Compared to CK, seasonal total N_2O emissions were unchanged under CS but considerably increased under CM by 74% for rice and 100% for wheat in the 1st rotation cycle. For the 2nd rotation cycle, the total emissions considerably increased by approximately 25% under CS and CM treatments for rice and wheat in the 2nd rotation cycle. However, the total seasonal emissions of N_2O substantially reduced under CB across all the crop seasons, by 60% for the 1st rice and approximately 20% for the following crop seasons, across the two rotation cycles. In the four crop seasons monitored, total N_2O emissions considerably increased by 15% under CS and 60% under CM, but reduced by 22% under CB.

Notable fluxes of CH_4 occurred during the rice-growing season, which followed a mode of flooding, drainage, intermittent irrigation, and moisture in the seedling, elongation, spiking, and ripening stages (Figure S2). The total seasonal CH_4 emission was either low (≤ 2.5 kg ha^{-1}) in the wet 1st wheat season with high rainfall or negative (−0.4~−0.1 kg ha^{-1}) in the 2nd wheat season, but varied in a tremendous range of 37~1730 kg ha^{-1} across the treatments over the two rice seasons. Compared with the 2nd rice season, the total CH_4 emissions were folds higher in the 1st rice season under the conditions of residue return of the preceding wheat crop before the experiment. For the 1st rice following the amendment, total CH_4 emission increased by 9 folds under CS and 4.5 folds under CM but decreased by 35% under CB, compared to CK. For the 2nd rice, the third crop season following amendment, the total CH_4 emissions remained unchanged under CS, increased under CM by 35%, and decreased by 24% under CB. In the four crop seasons, the total CH_4 emissions were 6 folds under CS, 4 folds under CM, and 0.7 folds under CB, similar to those under CK.

Over the two consecutive rotation cycles, the total GWP calculated according to Equation (2) was highly affected by the residue amendment treatments (Figure 3). The total GWP was 11.6 t CO_2 eq ha^{-1} under CK, increased to 74.2 CO_2 eq ha^{-1} under CS and 44.7 CO_2 eq ha^{-1} under CM, but reduced to 7.9 CO_2 eq ha^{-1} under CB. Rice CH_4 emissions dominated the overall GWP of the studied crop system under the amendment treatments.

3.4 | Crop Production and Soil Health Indices

In this study, crop production performance was assessed for the 4 crop seasons totally, while soil quality changes were assessed after the 4 crop seasons across the treatments. C emission efficiency of grain production, calculated with Equation (4), ranged from 0.34 to 3.52 t grain t^{-1} CO_2eq, while fertilized nutrient efficiency (NE), calculated with Equation (5), ranged from 24.9 to 27.5 kg grain kg^{-1} of input. SOC preservation, calculated using Equations (6–8), ranged from 1.7 to 10.9 t OC ha^{-1} after the 4 crop seasons. Furthermore, the overall soil fertility index (SQI), calculated with Equation (9) using the data in Figure S4 and Tables S4–S6, ranged from 0.34~0.58 across the treatments. Evidently, N efficiency (NE), SOC preservation, and the overall soil quality improved under CM and CB, and C emission efficiency was greatly reduced under CM. In other words, the system's functioning was improved with CB treatment by 58% for C emission efficiency, 57% for overall soil quality, 5 folds for C preservation, and 8% for N input efficiency (Figure 4).

The changes in the aforementioned indicators were digested and evaluated as per Equation (10) as the effect sizes. Resultantly, a negative effect on C emission efficiency was observed under

TABLE 1 | Seasonal total emissions (kg ha^{-1}) of N_2O-N and CH_4-C calculated with the fluxes monitored over the crop seasons of the two consecutive rice-wheat rotation cycles following the one-time residue amendment.

Treatment	1st Rice	1st Wheat	2nd Rice	2nd Wheat	Overall
N_2O emission					
CK	1.75 ± 0.21b	1.81 ± 0.20b	1.64 ± 0.23b	1.28 ± 0.06b	6.48 ± 0.40c
CS	1.79 ± 0.15b	2.09 ± 0.20b	2.05 ± 0.31a	1.51 ± 0.11a	7.43 ± 0.12b
CM	3.06 ± 0.53a	3.76 ± 0.64a	2.15 ± 0.16a	1.45 ± 0.16a	10.42 ± 0.93a
CB	0.73 ± 0.11c	1.56 ± 0.18b	1.23 ± 0.19c	1.08 ± 0.10c	4.60 ± 0.31d
CH_4 emission					
CK	171.72 ± 25.25c	1.73 ± 0.25b	49.62 ± 2.32b	−0.33 ± 0.20a	222.70 ± 26.52c
CS	1729.60 ± 248.32a	2.52 ± 0.46a	56.38 ± 4.74b	−0.20 ± 0.26a	1788.30 ± 247.60a
CM	941.60 ± 221.70b	1.70 ± 0.21b	69.31 ± 7.23a	−0.15 ± 0.07a	1012.50 ± 216.20b
CB	112.170 ± 21.33c	0.96 ± 0.18c	37.44 ± 3.01c	−0.36 ± 0.17a	150.21 ± 18.48d

Note: CK, control; CS, CM and CB, one-time amendment at 10 t OC ha^{-1} respectively of air dried, manured and pyrolyzed maize straw. Overall, the sum of the 4 crop seasons monitored. Different lowercase letters in a single column indicated significant difference among the treatments at $p < 0.05$.

CS (84%) and CM (71%), whereas a positive effect on C emission efficiency was observed under CB (58%) (Figure 5a). A positive effect on soil OC preservation (Figure 5b), NE (Figure 5c), and SQI (Figure 5d) was observed under CM and CB. The AEI (%) were observed to be 8% under CM and 20% under CB for soil OC storage, more than 8% for NE under CM and CB, 23% under CM, and 57% under CB for SQI. CS had no effect on soil OC preservation, NE, or SQI.

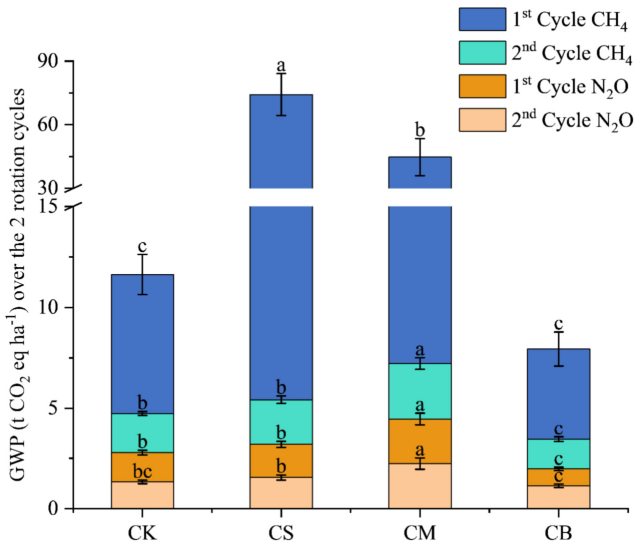

FIGURE 3 | The overall GWP (t CO_2 eq ha^{-1}) of the carbon emissions under the treatments over the 2 crop rotation cycles.

To better assess EMF, the above indicators were standardized and integrated, an ecosystem services radar map was created, and the value of EMF was calculated using Equation (11). A positive effect of increasing EMF was observed under CB (~600%), with no change under CS and CM (Figure 6).

4 | Discussion

4.1 | Variation in Crop Productivity and GHG Emission With Residue Amendment Forms

Maximizing crop productivity is a prerequisite for global agriculture to ensure global food security with a rapidly growing population but limited available resources (Licker et al. 2010; Tilman et al. 2011; van Ittersum et al. 2013; Cui et al. 2018). However, management to increase crop yield has often been debated regarding its consequences on

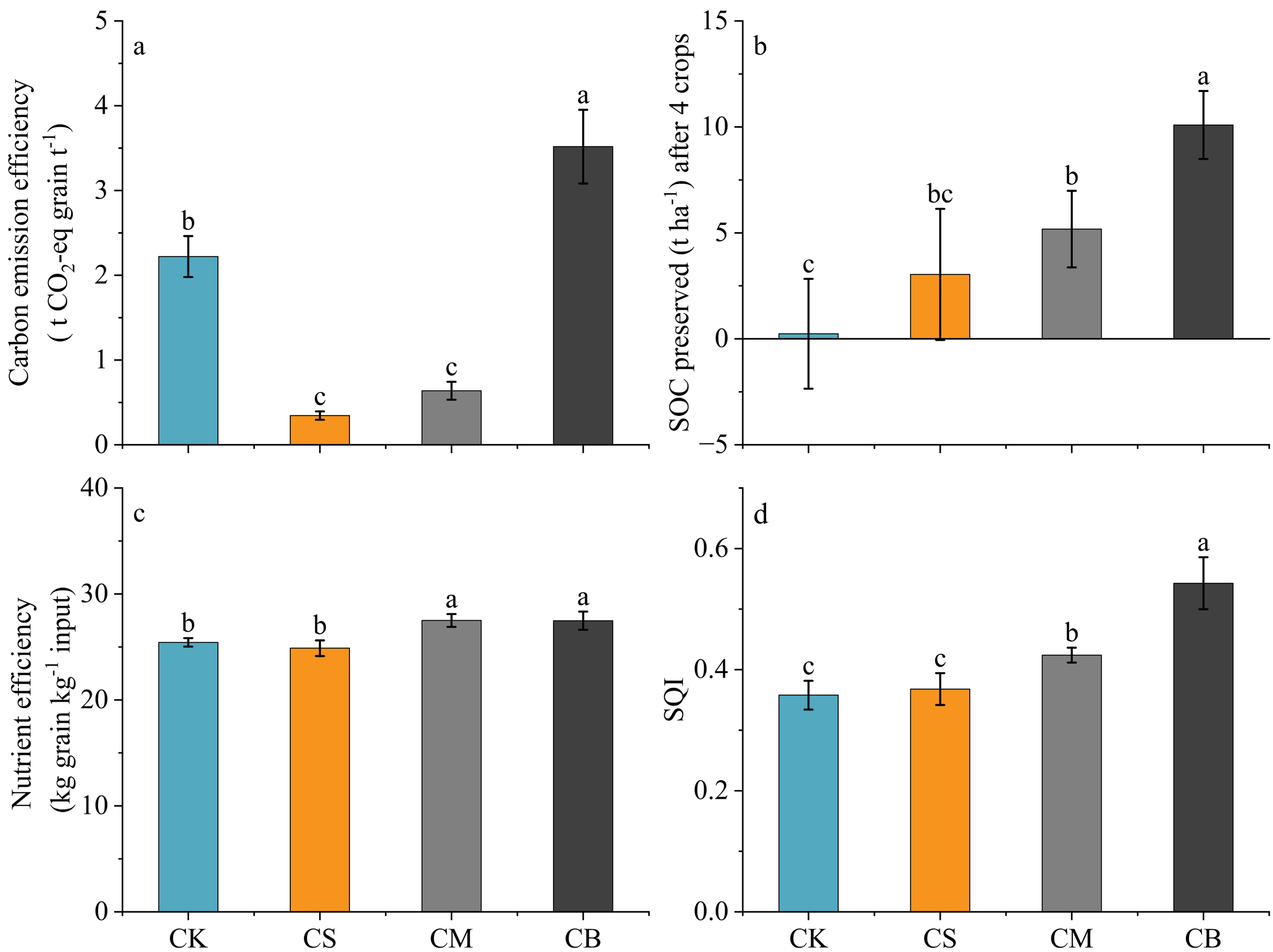

FIGURE 4 | The change of carbon emission efficiency (t grain t^{-1} CO_2 eq) (a), SOC preserved (t ha^{-1}) after 4 crops (b), Nutrient efficiency (kg grain kg^{-1}) (c) or SQI (d) under different treatments. SQI, soil quality index.

environmental risks, particularly climate change (Sadowski and Baer-Nawrocka 2018; Balogh 2022). In this study, the total grain yields of rice and wheat in two consecutive rotation cycles varied considerably among the residue treatments following the amendment (Figure 1). Overall, in the four crop seasons, the direct return of unprocessed straw (CS) caused no yield change but a 4.4-fold increase in GWP, primarily due to the increase in rice CH_4 emissions (Figure 3). Crop residue manure treatment (CM), enhanced grain yield gain by 8.1% and GWP by almost 3 folds. Comparatively, residual biochar (CB) treatment led to an 8.0% yield increase, which is in line with a 32% reduction in GWP. In terms of balancing food productivity and GHG mitigation, CS showed a net negative effect, CM showed a seesaw effect, and CB guaranteed a double gain in yield and GHG mitigation. The sale price of grain was 3 CNY per kg in China's food market (https://www.grainmarket.com.cn/), and the emission price with voluntary C trading was 75 CNY per ton of CO_2 eq (https://www.jiangsu.gov.cn/art/2024/3/17/art_84324_11178969.html) in 2023. Accordingly, the farmers' revenue per hectare from the production in all four crop seasons would potentially be a net loss of 680 $ under CS, a net gain of 580 $ under CM, and a net gain of 800 $ under CB. Thus, considering the potential trade-offs between food production and GHG emissions (Balogh 2022) or the land use competition between food and environmental services (Sadowski and Baer-Nawrocka 2018), crop residue in unprocessed form could be considered a non yield-beneficial but climate-negative practice, whereas manure was shown to be beneficial with potentially great climate impact trade-offs. Crop residue biochar would not compromise crop productivity with climate change mitigation and has been advocated for by the FAO (https://www.fao.org/climate-change/action-areas/access-to-climate-finance/fast/en). Moreover, the concurrent yield and C gain would align with China's National Climate Change Adaptation Strategy 2035 (http://big5.www.gov.cn/gate/big5/www.gov.cn/zhengce/zhengceku/2022-06/14/5695555/files/9ce4e0a942ff4000a8a68b84b2fd791b.pdf), which aims to greatly reduce GHG emissions while sustaining crop productivity and farmers' revenues in China's agriculture. Thus, soil amendment with thermo-converted biochar rather than manure or direct straw return could be a strategic solution for recycling large amounts of crop residues in the food production sector of China.

CH_4 emissions have been considered a critical or cutting paradigm in rice agriculture (Bin Rahman and Zhang 2023), as rice cultivation contributes 1.7% to global GHG emissions and up to 25% to global anthropogenic CH_4 emissions (Whalen 2005; IPCC 2013, 2022). The incorporation of crop residue or organic

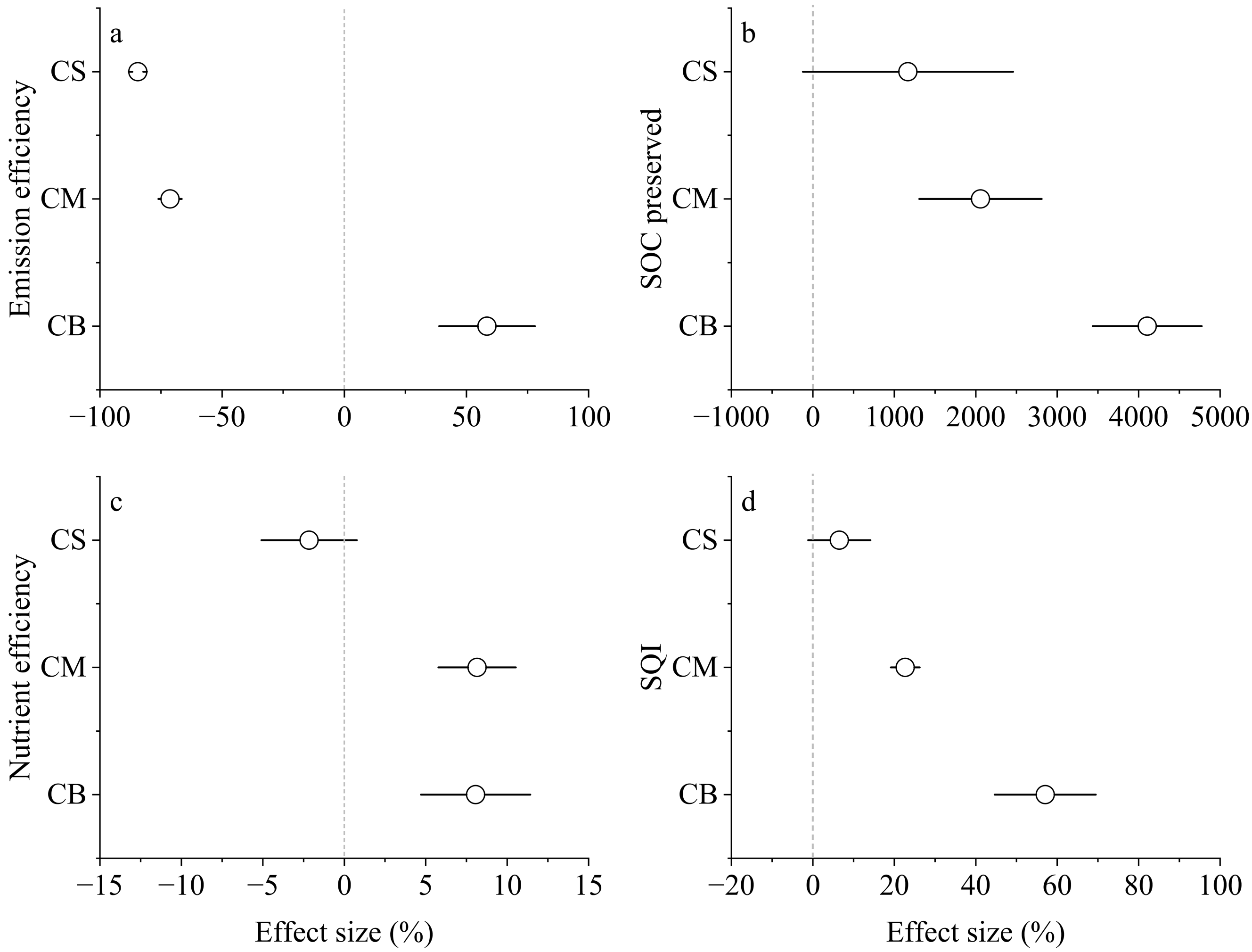

FIGURE 5 | The amendment effect intensity in% of emission efficiency (a), SOC preserved (b), Nutrient efficiency (c) or SQI (d) under different treatments. SQI, soil quality index.

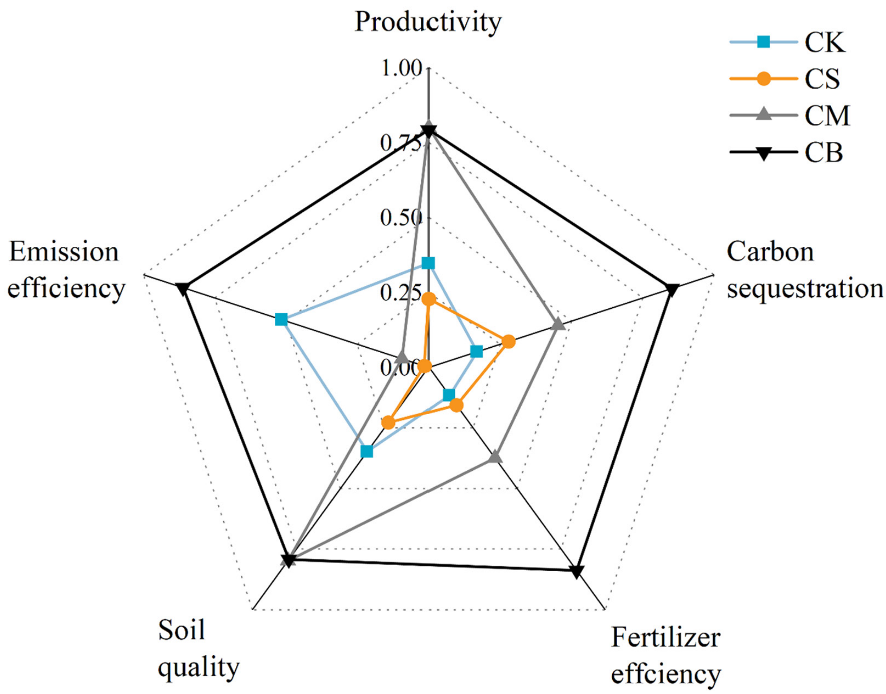

FIGURE 6 | The change of ecosystem multifunctionality (EMF) under different treatments.

fertilizers, which are highly available as degradable C and reactive N (Rath et al. 1999), enhances CH_4 emissions in rice cultivation (Conrad 2007; Yuan, Pump, and Conrad 2014; Malyan et al. 2016). In this study, crop residue directly incorporated or used as manure, caused an increase in CH_4 emission in rice fields by 9 folds and 4.5 folds in the 1st season and 14% and 40% in the 2nd season, following amendment (Table 1). In contrast, the application of biochar as a pyrolyzed residue resulted in a 35% reduction and 24% reduction in the 1st and 2nd rice seasons, respectively. These results indicate that a one-time amendment of crop residues could affect CH_4 production and emissions over the years following the amendment. Fortunately, a one-time amendment of the residual biochar prevented this considerable increase in rice CH_4 emissions over the two rice seasons following the treatment.

Despite the potential supplementation of a small level of dissolvable OC following its application (Zhang et al. 2012; Korai et al. 2021), the major recalcitrant OC and poor microbial accessibility of C and N reduced microbial growth (Figure 2) and unfavored methanogenic archaea activity, as described Sass et al. (1991) and Rath et al. (1999). Moreover, high porosity and pore size (e.g., in macroaggregates, Feng et al. (2022)) could increase the abundance of pore water in oxygen, favoring microbial C degradation to CO_2 (Krüger, Frenzel, and Conrad 2001; Conrad 2007). In addition, soil pH was higher by 0.2–0.3 units than the other treatments (Table S4), potentially inhibiting the methanogenic archaea community in neutral conditions (Hütsch 1998; Wu et al. 2019). Against the debate on potential trade-offs using biochar in agriculture (Jeffery et al. 2016), we argue that soil amendment with crop residue biochar may indeed provide a powerful tool to commit to the Global Methane Pledge (GMP 2023) in rice agriculture because of its multiple functions, in addition to soil fertility and crop productivity improvement (Liu et al. 2018b; Liu and Pan 2021).

4.2 | Variation of SOC Sequestration and Soil Quality With Residue Amendment Forms

According to Lehmann et al. (2020), improving soil health and ecological safety is a global paradigm in the food supply chain. Concerning the major functions and ecosystem services provided by soil, soil health is provisioned with a focus on those that are either globally or locally demanded (Janzen, Janzen, and Gregorich 2021). Therefore, SOC sequestration is considered a prerequisite for maintaining soil health (Zhao et al. 2023). Calculated using Equations (4–6) using the data in Figure 2 and Table S3, we found a wide variation of SOC preservation among the residue treatments after four consecutive crop seasons following the amendment at a single rate of 10 t ha^{-1}. Although there was no increase in topsoil OC storage under direct residue incorporation, manure and biochar amendment led to an increase of 1.75 and 4.2 t OC per hectare, respectively, compared to the control. Such increases are much higher than the target OC sequestration rate demanded by the 4 per 1000 initiative (Minasny et al. 2017; Lal 2020a). If calculated from the residue input (Table S1), the sequestration efficacy of residue incorporation into soil C would be approximately 12% under CS, over 30% under CM, but over 70% under CB. Thus, much greater OC sequestration efficacy was achieved with the manure- and biochar-converted forms in response to the call by Lal (2016, 2020b). Meanwhile, total soil N was mined at 167 kg ha^{-1} under the unprocessed residue treatment (CS), but supplemented at 51 kg ha^{-1} under the manure treatment (CM), and 230 kg ha^{-1} under the biochar treatment. Soil N mining under CS, with a high C/N ratio (Table S1), could be attributed to the increased microbial OC decay (Nguyen and Marschner 2016) with the excavation of N resources (Kuzyakov, Friedel, and Stahr 2000; Schimel and Bennett 2004; Chen et al. 2014). Such microbial N competition could constrain crop N supply and affect crop growth

(Jin et al. 2020), which was observed as a slight decline in rice yield under CS (Figure 1). In contrast, biochar amendment enhanced OC sequestration and considerably increased N retention (Liu et al. 2018b), whereas lower OC sequestration and minimal N retention were observed under CM (Zhang et al. 2019). It is worth noting that soil N retention under the CB treatment (230 ± 67 kg N ha^{-1}) was similar to the N contained in the existing biochar (250 kg N ha^{-1} in the preserved 8.4 t C of biochar following the four crop productions, compared to CK, Table S1). As shown by the data in Figure 2, unprocessed residue caused no improvement in P and K availability, whereas biochar, rather than manure, considerably improved soil availability of P and K. In the four crop seasons, biochar induced a 58% improvement and manure a 20% improvement in soil quality. However, manure and biochar improved apparent N efficiency by 8%, but with direct incorporation with CS treatment, there was a minimal and small reduction. Using a single source of crop residue on a single farm, we showed that incorporation of different forms of crop residue shifted the soil nutrient supply through modified nutrient availability, contributing to soil health changes.

Considering the major functions of soil, soil health should be perceived as a more diverse ecosystem services involving SOC sequestration, crop productivity, GHG mitigation, N retention, and microbial activity. In all four crop seasons (Figures 4–6), direct residue incorporation had no net positive effect on soil health but had negative effects on GHGs, whereas manure had a net positive effect on soil health, with a trade-off from a negative effect on GHGs. Biochar had a net positive but synergistic effect on soil health (Figures 4–6). Thus, this study highlights a net negative effect on overall soil health by direct residue incorporation and a trade-off effect by manure between SOC storage and GHG mitigation of soil health, in a loamy, slightly calcareous paddy. Xia, Wang, and Yan (2014) and Yang et al. (2015) reported a trade-off between straw return and manure application in rice paddy fields. However, the synergistic effect of biochar amendment on soil health is consistent with previous findings (Lu et al. 2020; Wang et al. 2018). They reported a synergistic effect of biochar amendment on rice yield, fertilizer efficiency, SOC, and microbial activity over the years following a single biochar amendment in an acidic clayey paddy in an adjacent area. This is the first study to provide evidence from four consecutive crop seasons in two rotation cycles that crop residue amendment in the form of biochar could be promising for enhancing soil health, addressing the major demands for yield maintenance, SOC sequestration, reduction of reactive N, and mitigation of CH_4 emissions in rice agriculture (Figure 6). However, how SOC sequestration can be envisaged in C-pool dynamics in relation to the microbial community and functional diversity requires further study.

5 | Conclusions

This study provides new insights into changes in soil quality, crop productivity, GHG emissions, and SOC sequestration with different forms of crop residue amendments in rice paddies. Compared to direct straw incorporation and animal-converted manure application, straw recycled as pyrolyzed biochar in rice paddies exerted greater positive effects on crop yield sustainability and soil quality over the two rotation cycles of rice and wheat crops. While direct straw incorporation and manure amendments considerably increased CH_4 and N_2O emissions and thus reduced C emission efficiency, biochar amendment not only reduced CH_4 and N_2O emissions over the four crop seasons but also considerably increased SOC storage and enhanced C emission efficiency, contributing to a great improvement in ecosystem multi-functionality. Therefore, recycling crop straw as biochar for rice paddies could be considered a promising soil management tool to achieve synergistic improvements in soil health, crop productivity, and SOC sequestration while reducing GHG emissions in rice agriculture.

Author Contributions

X.X. performed the field experiment, soil and plant analysis, data acquisition, data processing, and MS drafting; Z.Z., Y.D., X.F., S.C., and Q.S. participated in the field experiments and soil/plant analysis; X.L., K.C., R.B., and J.Z. reviewed and discussed the experimental design and data analysis; L.L. supervised the experimental design; G.P. conceptualized, supervised, funded, and performed MS editing.

Acknowledgments

This study was supported by the National Science Foundation of China under grant numbers 42077082, 41771332, and 41371298 and funded by the corresponding author. We thank Mr. Qiang Wang, Mr. Sheng Tang, and Mr. Genfu Pan for their assistance with field experiment maintenance and field sampling.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data supporting the findings of this study are available from the corresponding author upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.