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Biochar Enhances Paddy Productivity, Carbon Sequestration, and Reduces Greenhouse Gas Emissions in the Middle Yangtze River Region

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Abstract: Biochar's benign effects on agricultural production have been demonstrated. Still, no consistent conclusions have been drawn on the impact of biochar-amended paddy fields on carbon sequestration, gas emission reduction, and efficiency enhancement in typical cropping areas in the middle Yangtze River. A field experiment using five dosages of biochar (CK, BC1.5, BC3, BC4.5, and BC6) at 0, 1.5, 3, 4.5, and 6 kg·m^{-2} was conducted at the Hubei Irrigation Experiment Center Station, Jingmen City, Hubei Province, China, to investigate the effects of biochar on carbon sequestration, greenhouse gas emissions, and agricultural efficiency in paddy in the middle Yangtze River Region. This study showed that the optimal biochar dosage was 4.5 kg·m^{-2} (BC4.5). Biochar significantly improved soil properties, increased rice yield by 26.4–61.4%, and enhanced water use efficiency (WUE) and economic profit (EP) by 32.0–83.7% and −8.0–48.6%, respectively. Biochar increased soil carbon sequestration (SCS) and carbon pool management index (CPMI) by 23.0–198.3% and 22.9–71.5%, respectively. Biochar also reduced greenhouse gas emission intensity (GHGI), global warming potential (GWP), and emissions of CO_2, CH_4, and N_2O. Furthermore, structural equation modeling (SEM) indicated that soil organic carbon (SOC), in addition to the "biochar" influence factor, was a key positive influence factor for SCS, CPMI, and EP. Another major positive factor for GWP was silt, and for WUE it was saturated hydraulic conductivity, while TN and SOC were the major negative variables for GHGI. In summary, biochar demonstrated outstanding carbon sequestration and emission reduction impacts while ensuring crop production growth and efficiency improvement. The results provide a research basis for safeguarding food security and mitigating climate warming in the middle Yangtze River region.

Keywords: biochar amendment; soil carbon sequestration; greenhouse gas emissions; agricultural efficiency

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1. Introduction

As an important global food source, rice feeds about 50% of the world's population [1], and its planting area accounts for 11% of global agricultural land [2]. As one of the essential sources of global warming, greenhouse gas emissions from paddy fields account for over 10% [3]. China, the world's largest rice producer (with an annual output of over 200 million tons) [4], generates over 7.7 Tg of CH_4 and 138 Gg of N_2O annually [5]. Long-term rice cultivation leads to an absence of soil organic matter [6], exacerbating the function of carbon sources in rice fields. The middle Yangtze River is essential for rice farming in China and globally. With the continuous evolution of agricultural technology, the region's rice industry is poised for even more significant expansion and enhancement. As a result, focusing on rice fields in the middle Yangtze River is critical for addressing the greenhouse effect. Fortunately, biochar has attracted great attention from the scientific community in this field due to its versatile properties.

Biochar is a high-carbon refractory decomposition material obtained from agricultural waste (such as straw, sawdust, and garbage) through anaerobic high-temperature decomposition and carbonization [7,8]. Biochar is an ideal choice for soil improvement and environmental remediation due to its high porosity [9], high thermal stability, strong adsorption [10], larger specific surface area [11], and abundant functional groups [12]. This paper focuses on assessing the impact of biochar on soil properties, agricultural efficiency, carbon sequestration, and greenhouse gas emissions reduction.

For soil properties, biochar has been recognized for improving soil aggregate structure, porosity [9], water-holding capacity [2], soil pH, and available nutrients [13,14]. Biochar enhances crop yield by 10–16% [15] and raises rice production by 10.73% [16].

For agricultural efficiency, biochar improves the efficiency of water and fertilizer resource utilization, which is a continuous process with increasing production. Biochar enhances soil nutrient content (alkali-hydrolyzed nitrogen, available phosphorus, and available potassium) and effective water content [17,18], promoting plants to absorb more nutrients and water to strengthen yield [19], and ultimately achieving higher water and fertilizer use efficiency. Compared with individual fertilization, adding biochar boosts nitrogen and phosphorus utilization efficiency by 20–53% and 38–230%, respectively [15], and water use efficiency by 20.93–58.47% [20].

For carbon sequestration, numerous studies have demonstrated that biochar increases soil organic carbon (SOC) and promotes soil carbon accumulation [21–23]. In particular, SOC is retained more in paddy field soil that floods for a long time [24]. However, the SOC is decomposed after rice field harvesting and drying, producing extra greenhouse gases and exacerbating climate warming. This issue may be successfully alleviated by adding biochar to the soil. Because of its difficult decomposition and macromolecular structure, biochar firmly fixes SOC in the soil and is not released into the atmosphere [1,25]. According to reports, biochar application in the range of 10–40 $t \cdot ha^{-1}$ enhances SOC (16–77%) and DOC (4–70%) [14,26]. However, the application of biochar in fertile soil cannot achieve the same good performance. The effectiveness of biochar on soil carbon sequestration in rice fields in the middle Yangtze River remains to be determined.

For greenhouse gas emissions reduction, biochar has an increase [22] or decrease [27–29] in CH_4 and N_2O emissions of rice fields, which mainly depends on soil properties, rice types, and tillage management [2,24]. Methane synthesis and oxidation processes contribute to CH_4 emissions from rice fields [30], while N_2O emissions are mainly determined by nitrification and denitrification processes [27]. DOC is proportional to methane production [13,27], and SOC provides energy for nitrification and denitrification processes. Therefore, high SOC and DOC in biochar-amended paddy fields may promote soil CH_4 and N_2O emissions. Furthermore, CH_4 and N_2O are linked to redox potential and soil microbial activity. According to previous studies, biochar can expand the redox potential range of rice fields from −386–248 mV to −420–247 mV [31], affecting greenhouse gas production. By influencing microbial development, biochar lowers CH_4 and N_2O emissions [32]. For example, the adsorption of NH_4^+ in soil by biochar increases soil pH, weakens the activity of methane-producing bacteria and N_2O reductase [29,33], enhances the abundance of methane-oxidizing bacteria and ammonia-oxidizing bacteria [22], and reduces CH_4 and N_2O emissions. Exploring the effects of biochar on greenhouse gas emissions from paddies in the middle Yangtze River is even more scarce and important.

Currently, biochar is discussed individually or in pairs in many regions in terms of improving water and fertilizer use efficiency, promoting soil carbon sequestration, and reducing greenhouse gas emissions. However, there is a dearth of inquiry in this part of the key rice-growing region of agriculture (the middle Yangtze River). Therefore, we conducted field biochar experiments in typical rice planting areas in the Yangtze River Basin to comprehensively analyze the impact of biochar on carbon sequestration, emission reduction, and efficiency enhancement. The objectives of this study were to (1) examine how biochar affects soil characteristics and greenhouse gas emissions; (2) quantitatively evaluate the variation of carbon sequestration, emission reduction, and efficiency enhancement in biochar-amended rice; and (3) establish an SEM of the influences of biochar and soil factors on carbon sequestration, emission reduction, and efficiency enhancement and identify essential factors. This study aimed to explore whether applying biochar to rice fields may increase efficiency and achieve carbon sequestration and emission reduction in the environment.

2. Materials and Methods

2.1. Study Area

The study area is located at the Hubei Irrigation Experiment Center Station (112.09° E, 30.91° N), Jingmen City, Hubei Province, China, which belongs to the Jianghan Plain in the Yangtze River Basin. The subtropical monsoon climate is characterized by warm, humid conditions and annual sunshine of 1300–1600 h. The average annual precipitation is 947 mm, and the annual evaporation is 1300–1800 mm. The average annual temperature is 17 °C, with a frost-free period of approximately 260 days. During the experimental period (from 19 May to 17 September 2022 and 27 May to 3 September 2023), an automatic weather station in the experimental station recorded meteorological data.

2.2. Experimental Design and Field Management

The field biochar experiment was conducted from 19 May to 17 September 2022, and 27 May to 3 September 2023. Biochar levels of 0, 1.5, 3, 4.5, and 6 $kg{\cdot}m^{-2}$ were set and labeled as CK, BC1.5, BC3, BC4.5, and BC6. Biochar was applied in both 2022 and 2023. Liaoning Jinhefu Agricultural Development Co., Ltd., Anshan, China, produced the biochar used in this experiment from paddy straw. Each treatment was repeated four times, resulting in twenty experimental microplots (1 m^2). The planted crop was rice, variety 'Zuanliangyouchaozhan'. The irrigation method was a traditional flood system. Except for the mid-season drainage period and the last week before harvest, the field water level was maintained at 5 mm to 50 mm above the soil surface throughout the whole rice season. Before rice transplanting, the biochar was thoroughly mixed with 15–20 cm of soil in the tillage layer and then started to soak the field. Fertilizers applied in the field included nitrogen fertilizer (urea 180 kg N ha^{-1}), phosphate fertilizer (superphosphate 115 kg P_2O_5 ha^{-1}), and potassium fertilizer (potassium sulfate 72 kg K_2O ha^{-1}). As base fertilizers, 50% nitrogen, 100% phosphorus, and 100% potassium fertilizers were applied. At the tillering stage, the remaining 50% nitrogen fertilizer was administered as topdressing. Drainage operations were not carried out in paddy fields within 3–5 days after application of fertilizers. The soil properties and biochar parameters of this experiment are shown in Table 1.

Table 1. Basic soil property of the paddy field and the property of biochar.

Parameters	Soil	Biochar
Sand (%)	21.16 ± 1.08	–
Silt (%)	64.11 ± 4.79	–
Clay (%)	14.73 ± 0.38	–
Bulk density ($g{\cdot}cm^{-3}$)	1.59 ± 0.033	–
Organic matter content ($g{\cdot}kg^{-1}$)	7.31 ± 0.27	–
pH	6.65 ± 0.09	9.14 ± 0.10
C mass fraction (%)	–	68.60 ± 3.12
H mass fraction (%)	–	2.13 ± 0.18
N mass fraction (%)	–	1.28 ± 0.13
S mass fraction (%)	–	0.67 ± 0.05
Ash content (%)	–	25.18 ± 3.96
Particle size range (mm)	–	1.5–2.0

Note: The soil sampling depth was 10–20 cm. The number of samples used to obtain mean values and standard deviation was three.

2.3. Greenhouse Gases

CO_2, CH_4, and N_2O were collected by an artificial static dark chamber, which consisted of a cylindrical box and a stainless steel base (Figure 1). The chamber was made of PVC (5 mm thick), with a diameter of 32 cm and a height of 120 cm. The stainless steel base had a sealing groove with a width of 20 mm and a depth of 50 mm. An electric fan and thermometer was installed inside the top chamber to monitor the uniform air temperature during gas collection. The exterior of the chamber was covered with tinfoil to isolate the heat. Samples were obtained every 5–7 days between transplanting and harvesting. The gas samples were selected every 10 min for 30 min between 8:00 and 11:00. The depth of the water layer on the field surface and the air temperature within the box were recorded simultaneously. After sampling, CO_2, CH_4, and N_2O gases were analyzed using a meteorological chromatograph (Agilent 7890 A, Agilent Technologies, Santa Clara, CA, USA). The gas chromatograph was calibration tested for appearance, carrier gas flow rate, and column box temperature prior to testing.

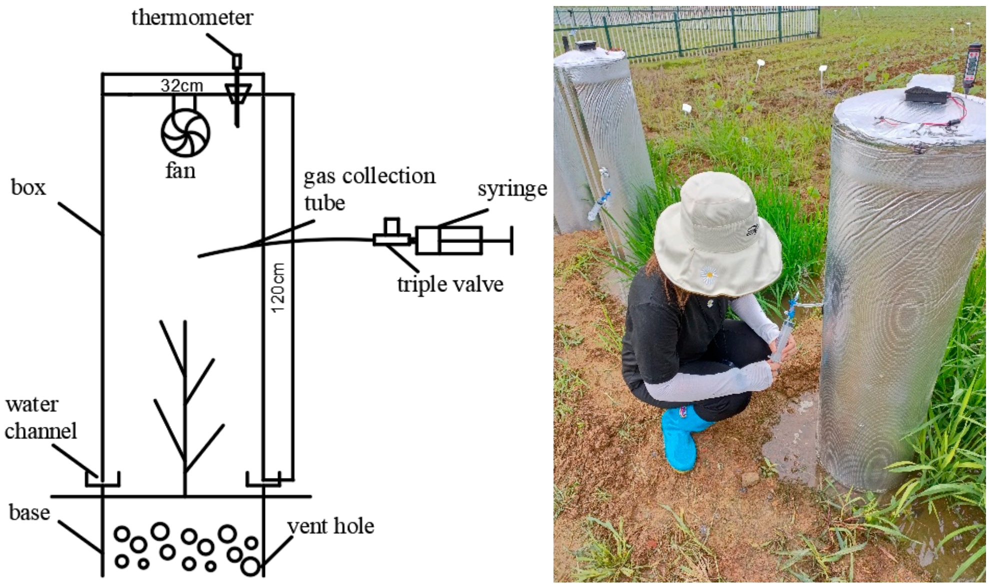

Figure 1. Static chamber for greenhouse gas collection and the actual collection diagram.

2.4. Experimental Observation Indicators

At the rice regreening stage, tillering stage, heading stage, milk stage, and harvest stage, soil samples were collected from each test plot to assess soil properties. There were three replicates for each soil sample. There were three soil sampling depths (15–20 cm, 35–40 cm, 55–60 cm). The undisturbed soil samples were used to measure soil bulk density (ρ_b), saturated moisture content (θ_s), field capacity (θ_f), wilting coefficient (θ_r) [34], and soil moisture characteristic curve (SWCC) [34]. A portion of fresh soil samples was acquired to measure soil ammonia nitrogen (NH_4^+-N), soil nitrate nitrogen (NO_3^--N) and soil dissolved organic carbon (DOC) [35]. The remaining fresh soil samples were air-dried to measure the soil particle size distribution, hydraulic conductivity (Ks) [36], unsaturated water diffusion rate (D), soil acidity (pH), soil total nitrogen (TN) [35], and soil organic carbon (SOC). Finally, the soil porosity (P), specific water capacity (C), and unsaturated soil hydraulic conductivity (Kh) were measured by an indirect calculation approach. Following ripening, each experimental field was completely harvested for yield measurement, and the yield (Y) was obtained.

2.5. Carbon Sequestration, Emission Reduction, and Efficiency Enhancement Calculation

(1) Carbon sequestration

The influence of biochar on the carbon sequestration capacity of rice was determined by the carbon pool management index (CPMI) and soil carbon sequestration (SCS). Soil nitrogen retention (SNR) was used to evaluate the impact of rice nitrogen retention. The subsequent formulas were used for calculation.

$$\begin{aligned} CPMI &= 100 \times CPI \times AI \\ CPI &= SOC/SOC_0 \\ AI &= A/A_0 \\ A &= ROC/IOC \end{aligned} \tag{1}$$

$$\begin{aligned} SCS &= SOCD_E - SOCD_A \\ SOCD &= SOC \times \rho_b \times h_{20} \end{aligned} \tag{2}$$

$$\begin{aligned} SNR &= SND_E - SND_A \\ SND &= TN \times \rho_b \times h_{20} \end{aligned} \tag{3}$$

where CPI is the carbon pool index; AI is the carbon pool activity index; SOC is the soil organic carbon ($g \cdot kg^{-1}$); SOC_0 is the reference soil organic carbon content ($g \cdot kg^{-1}$); A is the activity of the sample carbon pool; A_0 is the reference soil carbon pool activity; and ROC and IOC are the active and inactive organic carbon ($g \cdot kg^{-1}$). ROC was determined by the potassium permanganate oxidation-colorimetric method [37], and the IOC was determined by the value of SOC minus ROC. $SOCD_A$ and $SOCD_E$ are the soil organic carbon densities before and after harvest ($kg \cdot m^{-2}$); SND_A and SND_E are soil nitrogen densities before and after harvest ($kg \cdot m^{-2}$). h_{20} is the thickness of the topsoil, which is 20 mm in this study; ρ_b is the soil bulk density ($g \cdot cm^{-3}$); TN is the total nitrogen content of the soil ($g \cdot kg^{-1}$).

(2) Emission reduction

The fluxes and cumulative emissions of greenhouse gases, global warming potential (GWP), and greenhouse gas emission intensity (GHGI) were calculated by the following equations [1,27,35]:

$$F = \rho \times H \times \frac{dc}{dt} \times \frac{273}{273 + T} \times \frac{P}{P_0} \tag{4}$$

$$E_C = 0.01 \times 24 \times \left[\frac{F_1 + F_n}{2} + \sum_{i=1}^{n} \left(\frac{F_i + F_{i+1}}{2} \right) \times (t_{i+1} - t_i) \right] \tag{5}$$

$$GWP = 27.9 E_{C-CH_4} + 273 E_{C-N_2O} \tag{6}$$

$$GHGI = \frac{GWP}{Y} \tag{7}$$

where F is the flux of CH_4 and N_2O ($mg \cdot m^{-2} \cdot h^{-1}$); ρ is the density of CH_4 (0.714 $kg \cdot m^{-3}$) or N_2O (1.964 $kg \cdot m^{-3}$) in the standard state; H is the effective height of the box (m); dc/dt is the change rate of CH_4 and N_2O concentration in the box during the sampling process ($ml \cdot m^{-3} \cdot h^{-1}$); T is the average temperature inside the sampling chamber (°C); P_0 is the standard atmospheric pressure; and P is the air pressure inside the sampling box. In this study, $P = P_0$; EC is the cumulative emissions of CH_4 and N_2O ($kg \cdot hm^{-2}$); $(t_{i+1} - t_i)$ is the time interval from i to $i + 1$ sampling (d); 27.9 or 273 is the GWP per unit mass of CH_4 and N_2O at a 100-year scale [38]; Y is the rice yield ($kg \cdot hm^{-2}$).

(3) Agricultural efficiency enhancement

Agricultural efficiency includes three aspects: water resources, fertilizer resources, and economy. The calculation formulas for water use efficiency (WUE) [19], fertilizer agriculture use efficiency [16], fertilizer partial productivity, economic profits (EP), and input–output ratio (ROI) were as follows:

$$\begin{aligned} WUE &= Y/ET \\ &= Y/(P + I + G + \Delta W - R - D - S) \\ &= Y/[P + I + G + (\theta \times h_{20} \times \rho_b) - R - D - S] \end{aligned} \quad (8)$$

$$\begin{aligned} FAE &= (Y_{BC} - Y_{CK})/(F + B_F) \\ FPFP &= Y_{BC}/(F + B_F) \end{aligned} \quad (9)$$

$$\begin{aligned} ROI &= SP/PI = (Y \times PR)/PI \\ EP &= SP - MI - BI = (Y \times PR) - MI - BI \end{aligned} \quad (10)$$

where ET is the water consumption (mm); P is the precipitation (mm); I is the irrigation (mm); G is the underground water supply amount (mm) (G was zero in this test.); ΔW is the change in soil water storage before and after planting (mm); R is the surface runoff (mm) (R was zero in this test); D is the drainage (mm); S is the soil leakage amount (mm) (S was zero in this test.); θ is the soil moisture content ($cm^3 \cdot cm^{-3}$); FAE is the fertilizer's agricultural utilization efficiency (including nitrogen, phosphorus, and potassium) ($kg \cdot kg^{-1}$); $FPFP$ is the fertilizer's partial productivity (including nitrogen, phosphorus, and potassium) ($kg \cdot kg^{-1}$); Y_{BC} and Y_{CK} are the yields of biochar application and no biochar treatment ($kg \cdot hm^{-2}$); F is the amount of fertilizers applied (including nitrogen, phosphorus, and potassium) ($kg \cdot hm^{-2}$); B_F is the effective nitrogen, phosphorus, and potassium content in biochar ($kg \cdot hm^{-2}$); SP is the grain output value (yuan); PI, MI, and BI are production, management, and biochar inputs (yuan), MI includes seed cost, fertilizer cost, labor cost, fuel cost, tilling, weeding, and harvesting.; and PR is the unit price of rice (2.7 $yuan \cdot kg^{-1}$).

2.6. Statistical Analysis

To investigate the relationship between multiple soil environmental factors in biochar paddy and their interactions, Amos Graphics (23.0 version) was used to construct a structural equation model (SEM) for carbon sequestration, emission reduction, and efficiency enhancement. Furthermore, the changing characteristics of carbon sequestration, emission reduction, and efficiency enhancement in biochar paddy fields were elucidated, as well as the key influencing factors. Before using Amos Graphics, we calculated multiple soil environmental factors using the trapezoidal area method [39]. Excel (2021 version) and Origin (2022 version) were used for data processing, graphing, and tabulation. One-way analysis of variance (ANOVA) and the least significant difference method (LSD) were used to test the differences among different treatments. The significance level was set at $p = 0.05$. SPSS (19.0 version) was used to perform all statistical analyses. The data analyzed in this study were the average values for 2022 and 2023.

3. Results

3.1. Changes in Soil Physical Properties and Hydrodynamic Parameters

The soil basic properties of biochar-amended paddy were displayed in Table 2. Biochar significantly lowered bulk density (ρ_b) while increasing porosity (P). With the rise of biochar applied, the changes in ρb and P became more dramatic, with BC4.5 achieving the lowest ρ_b (−6.68%) and highest P (+9.97%). This shows that biochar increases the soil aggregation of small particle-sized particles, which in turn creates large pores. They were similar to previous research [40]. Under the action of biochar, the proportion of clay particles gradually decreased by 1.77–8.01%, increasing soil aeration. Biochar rose θ_s and θ_f and dropped θ_r, thereby increasing the effective water content. The highest change rate of θ_s, θ_f, and θ_r was obtained in BC4.5, with +10.69%, +13.64%, and −11.82%, respectively. Therefore, adding adequate biochar to paddy fields enhanced the soil structure, aeration, and water-holding capacity.

The soil water supply capacity was often described using the specific water capacity at a pressure head of 1000 cm. Ks, SWCC, C (log(|h| = 3), h = 1000 cm), Kh, and D were increased by biochar, with BC4.5 exhibiting the largest increase (Figure 2). The highest values of Ks, C (log(∣h∣ = 3), h = 1000 cm), Kh, and D (log(∣h∣ = 1.899) were 0.646 cm·h^{-1}, 0.89 × 10^{-5} cm^{-3}·cm^{-4}, 0.55 cm·h^{-1}, and 42.26 cm^2·h^{-1}, respectively, which were increased by 49.57%, 17.94%, 61.86%, and 172.6% compared with CK. The SWCC of BC was located on the upper side of CK, and it climbed upward with increasing carbon application. The SWCC of the BC4.5 treatment reached the top and then moved downward. In conclusion, biochar-increased Ks might improve water flow performance in saturated soil and encourage soil aeration under the circumstances of long-term flooding. Additionally, a rise in SWCC demonstrated how biochar increased soil water-holding capacity, while an increase in Kh and D encouraged water circulation in paddy fields to lessen the negative effects of rice growth.

Table 2. Basic soil properties of biochar-amended paddy soil.

Parameters	CK	BC1.5	BC3	BC4.5	BC6
Bulk density (ρ_b) (g·cm^{-3})	1.59 ± 0.16 a	1.53 ± 0.15 b	1.52 ± 0.15 b	1.48 ± 0.14 c	1.50 ± 0.15 c
porosity (P) (%)	40.11 ± 2.01 c	42.12 ± 2.11 b	42.66 ± 2.13 b	44.11 ± 2.21 a	43.57 ± 2.18 ab
Sand (%)	21.16 ± 1.06 c	21.93 ± 1.10 c	22.26 ± 1.11 b	22.62 ± 1.13 b	23.00 ±1.15 a
Silt (%)	14.73 ± 0.74 c	15.10 ± 0.75 c	16.20 ± 0.81 b	17.20 ± 0.86 ab	18.03 ± 0.90 a
Clay (%)	64.11 ± 3.21 a	62.97 ± 3.15 b	61.55 ± 3.08 b	60.18 ± 3.01 c	58.97 ± 2.95 d
Saturated water content (θ_s) (%)	35.99 ± 1.80 d	37.02 ± 1.85 c	38.44 ± 1.92 b	39.84 ± 1.99 a	39.19 ± 1.96 a
Field capacity (θ_f) (%)	28.30 ± 1.42 c	29.61 ± 1.48 bc	30.71 ± 1.54 b	32.16 ± 1.61 a	31.49 ± 1.57 ab
Residual water content (θ_r) (%)	6.09 ± 0.61 a	6.03 ± 0.60 ab	5.77 ± 0.58 b	5.57 ± 0.56 c	5.37 ± 0.54 d

Note: The number of samples used to obtain mean values and standard deviation was three. Different lowercase letters in the same column indicate significant differences between different treatments (p < 0.05).

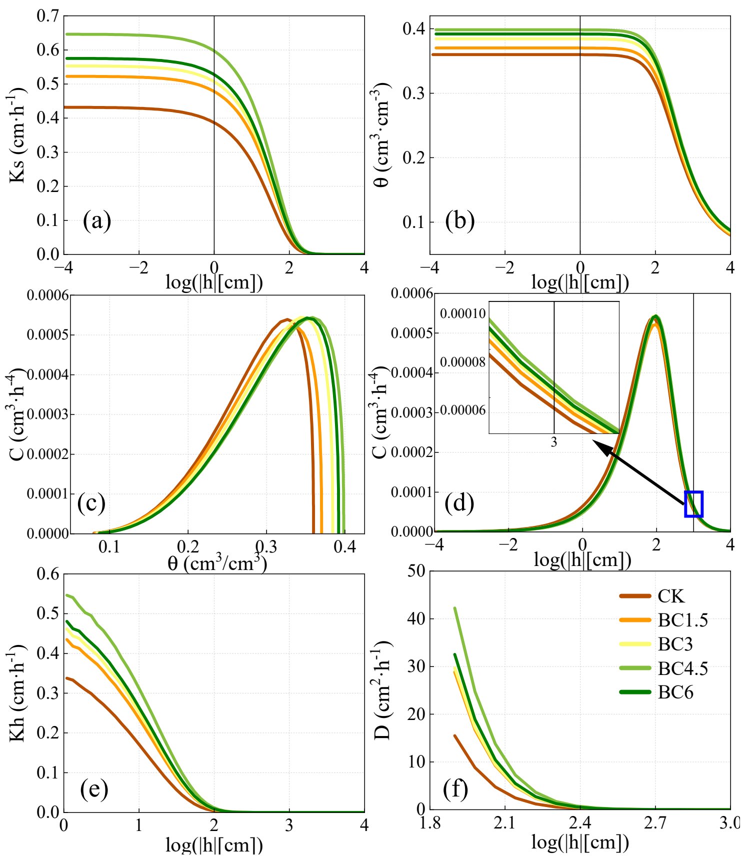

Figure 2. Hydraulic conductivity (Ks) (**a**), soil water characteristic curve (SWCC) (**b**), specific water capacity (C-θ) (**c**), specific water capacity (C-log(∣h∣)) (**d**), unsaturated soil hydraulic conductivity (Kh) (**e**), and unsaturated soil diffusivity (D) (**f**) of biochar-amended paddy soil.

3.2. Changes in Soil Environmental Factors

The suitable soil pH range for rice was 6.8 to 7.5 (red dashed box in Figure 3a), and pH in BC treatments was more suitable for rice growth than CK. Biochar significantly elevated pH ($p < 0.05$). The better treatments were BC4.5 and BC6. (Figure 3a).

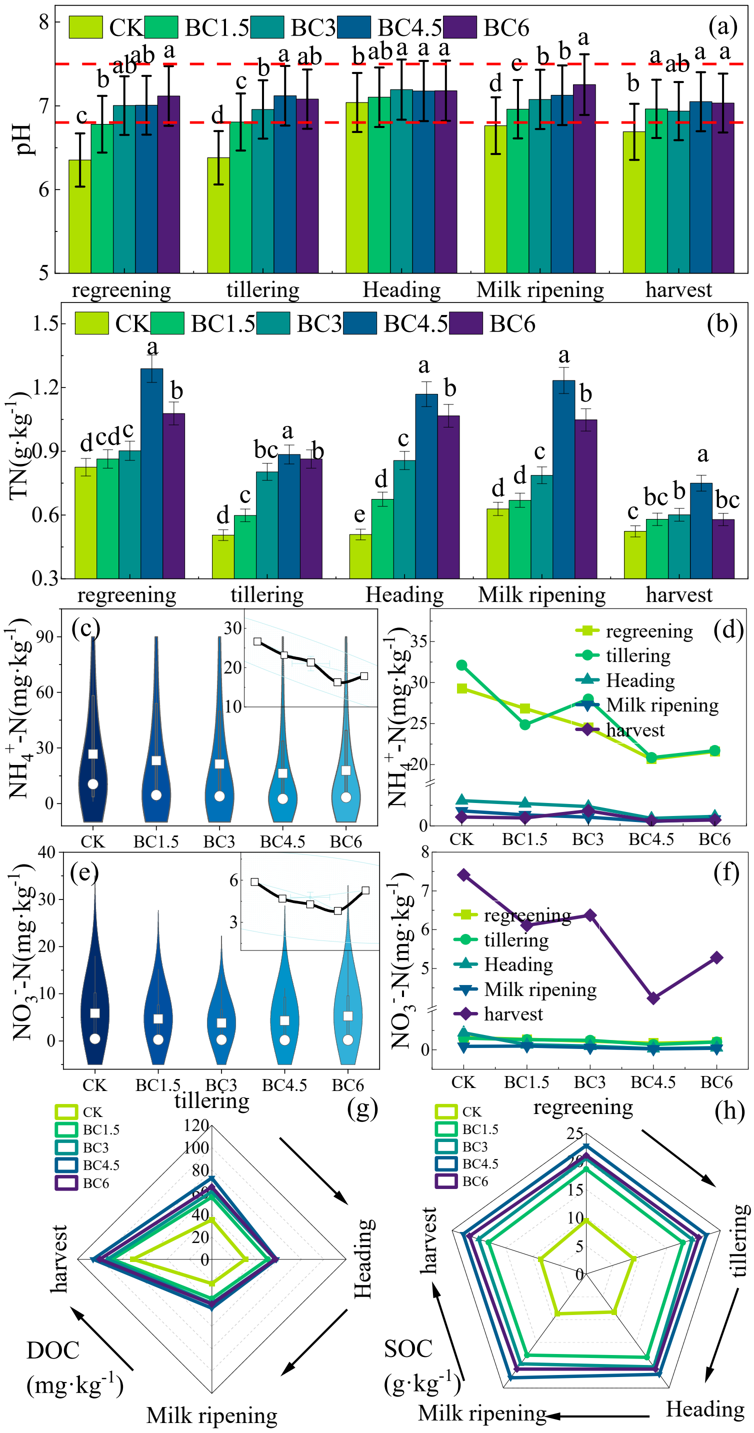

Figure 3. Soil pH (**a**), TN (**b**), NH_4^+ (**c**,**d**), NO_3^- (**e**,**f**), dissolved organic carbon (DOC) (**g**), and SOC (**h**) of biochar-amended paddy soil. Different lowercase letters in the same column indicate significant differences between different treatments ($p < 0.05$). The red dotted lines were the suitable soil pH range for rice.

Due to the growth of rice, the TN content gradually decreased during the growth period (Figure 3b). Biochar significantly improved TN ($p < 0.05$), achieving a maximum of 1.29 $g \cdot kg^{-1}$ under BC4.5, an increase of 46.78% compared to CK. The regreening and tillering stages had higher NH_4^+ levels than other stages as a result of nitrogen fertilizer application. Drying the fields in the harvest period led to higher levels of NO_3^- than at other times. NH_4^+ and NO_3^- dropped with biochar application. Compared with CK, BC1.5, BC3, BC4.5, and BC6 reduced NH_4^+ (NO_3^-) by 13.05% (20.20%), 20.04% (27.12%), 38.83% (35.13%), and 33.07% (10.27%), respectively.

The content of DOC and SOC ranged from 21.72–105.98 $mg \cdot kg^{-1}$ and 8.36–22.94 $g \cdot kg^{-1}$, respectively (Figure 3g,h). During the growth period, DOC gradually rose with no significant change in SOC. However, biochar increased DOC and SOC, with the highest content in the BC4.5 treatment, increasing by 157.29% and 77.87%, respectively (compared to CK).

3.3. *CO_2, CH_4, and N_2O Emissions*

Biochar inhibited CO_2 emissions, and this inhibitory effect was closely related to the amount of biochar applied (Figure 4a). The optimal CO_2 inhibition effect was achieved at 4.5 $kg \cdot m^{-2}$ biochar, with an average inhibition rate of 58.47%. CO_2 gradually increased following fertilization until the drainage period. At this time, the maximum and minimum emission peaks were CK (26.02 $g \cdot m^{-2} \cdot h^{-1}$) and BC4.5 (12.75 $g \cdot m^{-2} \cdot h^{-1}$), respectively. During the drainage and drying period, the CO_2 emissions rapidly decreased and climbed again after being covered with water, maintaining a high level (high emission period). Until matured, the rice fields dried out, and CO_2 emissions dropped again.

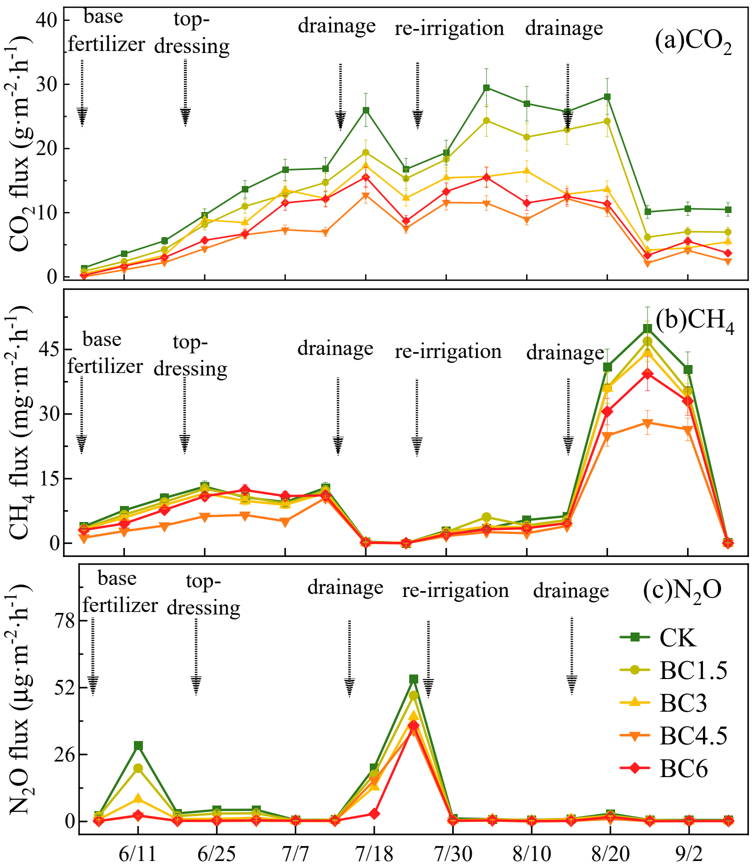

Figure 4. CO_2 (**a**), CH_4 (**b**), and N_2O (**c**) flux of different biochar treatments.

Three stages of CH_4 emissions were present (Figure 4b): the first stage was the rise stage of CH_4 emissions (from regreening to drying), where biochar reduced CH_4 emissions by 5.60% to 46.26%. The second stage was a low-increase stage of the CH_4 emission (in the early stage of covering water), and biochar inhibited CH_4 emissions by −0.38% to 42.09%.

The third stage was the high stage of CH_4 emission (later stage of water cover), with CH_4 emissions in the following order: CK > BC1.5 > BC3 > BC6 > BC4.5. Biochar inhibited up to 39.47% of CH_4 emissions.

Fertilization, drainage drying, and harvest drying were the N_2O emission periods; the remaining times had little N_2O emissions (Figure 4c). The available nitrogen content was increased, and N_2O was released after fertilization. Drainage drying and harvest drying caused the soil to change from an anaerobic to an aerobic condition, emitting N_2O. Biochar had an inhibitory effect on N_2O emissions, with the most prominent inhibitory effect in BC4.5. The three emission periods of BC4.5 were 92.57%, 23.26%, and 52.90% less than CK, respectively.

3.4. Effect of Carbon Sequestration, Emission Reduction, and Efficiency Enhancement

According to Table 3, adding 3–6 $kg \cdot m^{-2}$ of biochar (BC3, BC4.5, BC6) to paddy fields significantly increased soil carbon pool-related indicators ($p < 0.05$), with CPI, AI, and CPMI rising by 12.30–81.70%, 9.53–64.15%, and 23.00–198.26%, respectively. In the SCS range of 0.28–0.53 $kg \cdot m^{-2}$, biochar had a significant carbon sequestration effect, with an increase of 22.88–87.57%. The SNR range was between −0.105 and −0.072 $kg \cdot m^{-2}$, and biochar effectively weakens soil nitrogen loss, with the weakening effect of 17.24–40.08%.

Table 3. Carbon pool management index (CPMI), soil carbon sequestration (SCS), soil nitrogen retention (SNR), carbon pool index (CPI), sample carbon pool activity (A), and carbon pool activity index (AI) of different biochar treatments.

	CPI	A	AI	CPMI	SCS ($kg \cdot m^{-2}$)	SNR ($kg \cdot m^{-2}$)
CK	1.00 ± 0.05 d	0.16 ± 0.02 d	1.00 ± 0.05 d	100.00 ± 5.00 d	0.2833 ± 0.0142 d	−0.1053 ± 0.0053 d
BC1.5	1.12 ± 0.06 d	0.17 ± 0.01 d	1.10 ± 0.05 d	123.00 ± 6.15 d	0.3481 ± 0.0174 c	−0.0872 ± 0.0044 c
BC3	1.53 ± 0.08 c	0.20 ± 0.02 c	1.28 ± 0.06 c	196.03 ± 9.80 c	0.3986 ± 0.0199 c	−0.0797 ± 0.0040 b
BC4.5	1.82 ± 0.09 a	0.26 ± 0.03 a	1.64 ± 0.08 a	298.26 ± 14.91 a	0.4858 ± 0.0243 b	−0.0631 ± 0.0032 a
BC6	1.68 ± 0.08 b	0.22 ± 0.02 b	1.42 ± 0.07 b	237.80 ± 11.89 b	0.5313 ± 0.0266 a	−0.0721 ± 0.0036 b

Note: Different lowercase letters in the same column indicate significant differences between different treatments ($p < 0.05$). The number of soil samples used to obtain mean values and standard deviation was three.

Affected by biochar, the cumulative emissions of CH_4, N_2O, and CO_2 decreased by 17.12–58.63%, 7.72–42.20%, and 18.53–58.44%, respectively (Figure 5). The degree of reduction of greenhouse gases by biochar went in the following order: CH_4 > CO_2 > N_2O. Biochar considerably reduced GWP and GHGI ($p < 0.05$), with the lowest value appearing in BC4.5. Biochar exceeding 4.5 $kg \cdot m^{-2}$ would cause negative consequences. A lower GWP demonstrated a smaller greenhouse gas effect per unit of mass per unit of time, whereas a lower GHGI indicated a weaker intensity of greenhouse gas emissions.

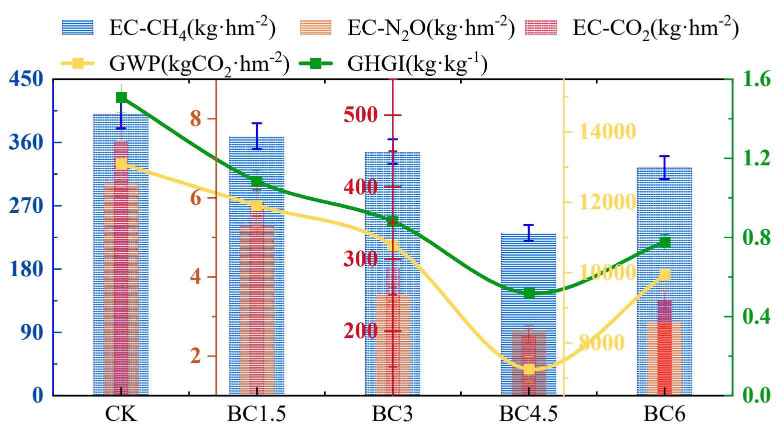

Figure 5. Cumulative emissions (EC-CH_4, EC-N_2O, EC-CO_2), global warming potential (GWP), and greenhouse gas emission intensity (GHGI) of different biochar treatments.

ET, Y, and WUE in rice fields were 837.20–976.85 mm, 8684.7–1402.1 kg·hm^{-2}, and 0.89–1.63 kg·m^{-3}, respectively (Figure 6). BC reduced ET by 4.27–12.15%, boosted Y by 26.39–61.43%, and strengthened WUE by 32.02–83.76% when compared to CK. Biochar improved fertilizer use efficiency greatly ($p < 0.05$). BC4.5 achieved the highest value, with nitrogen, phosphorus, and potassium agricultural utilization efficiency and nitrogen, phosphorus, and potassium partial productivity of 28.58, 46.39, 74.10, 75.11, 121.91, and 194.72 kg·kg^{-1}, respectively. The fluctuation pattern of EP rose and then reduced as the amount of biochar increased. BC4.5 had the greatest EP (16,539.27 yuan), which climbed by 48.55% when compared to CK. The ROI varied from 1.4 to 2.0, with only BC1.5 outperforming CK by 3.44%, and the rest falling short. Only from an economic standpoint, BC1.5 was preferable.

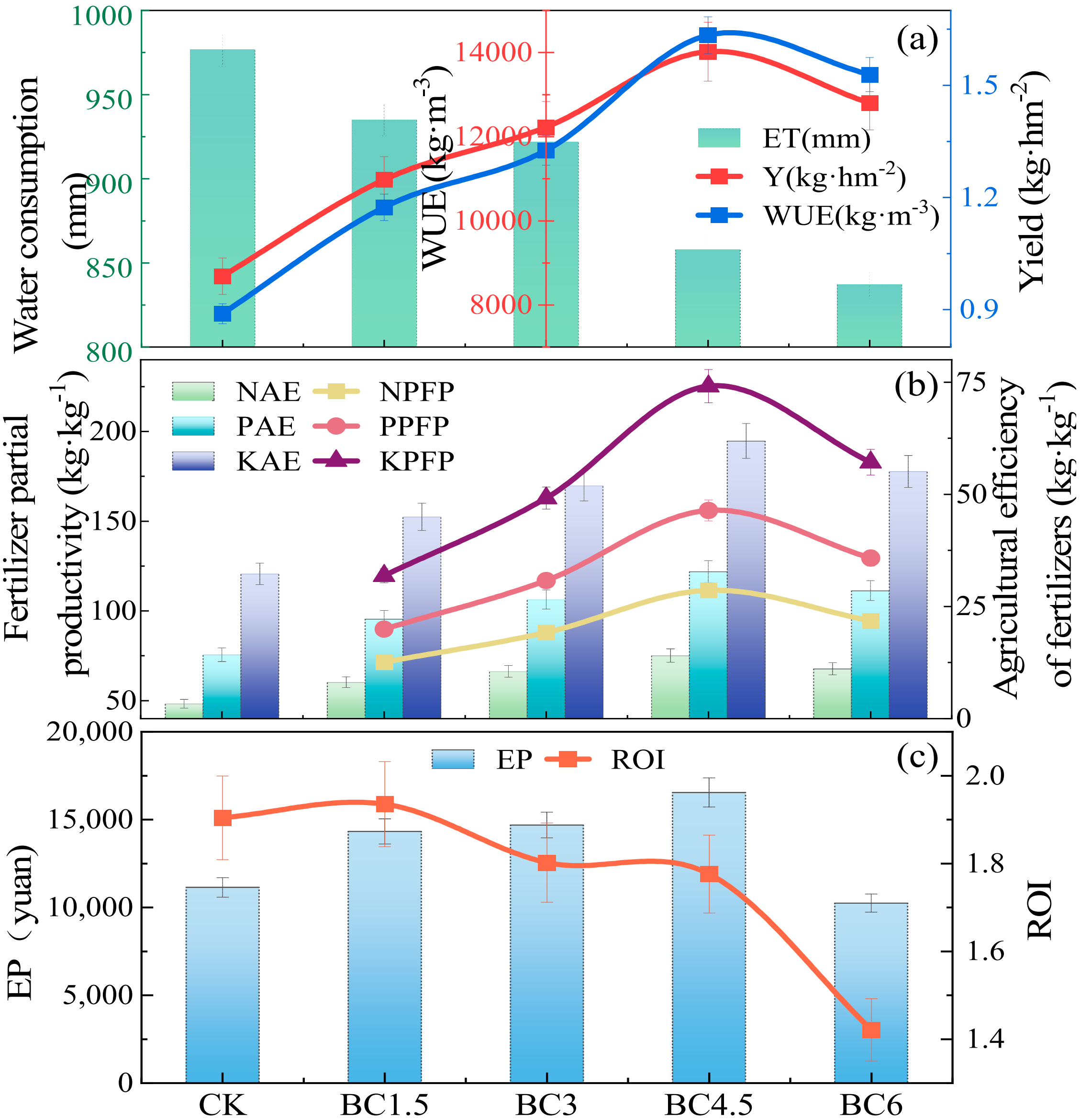

Figure 6. Water consumption (ET), yield (Y), water use efficiency (WUE), nitrogen fertilizers agricultural utilization efficiency (NAE), phosphorus fertilizers agricultural utilization efficiency (PAE), potassium fertilizers agricultural utilization efficiency (KAE), nitrogen fertilizers the partial productivity (NPFP), phosphorus fertilizers the partial productivity (PPFP), potassium fertilizers the partial productivity (KPFP), economic profit (EP), and the ratio of output to input (ROI) of biochar rice fields. (**a**) Water use efficiency of different treatments. (**b**) Fertilizer utilization efficiency of different treatments. (**c**) Economic efficiency of different treatments.

3.5. Relationship Between Carbon Sequestration, Emission Reduction, Efficiency Enhancement, and Soil Factors

The structural equation model (SEM) of the effects of soil factors and biochar on CPMI and SCS was illustrated in Figure 7. Biochar, *ρb*, and SOC positively influenced CPMI, whereas SOC, pH, and DOC positively affected SCS. Based on the total impact, the primary impact factors for CPMI were biochar (0.958), CH_4 (−0.871), and SOC (0.75), and those for SCS were SOC (1.057) and biochar (0.882). Biochar did not directly affect SCS, but indirectly affected it by modifying soil properties.

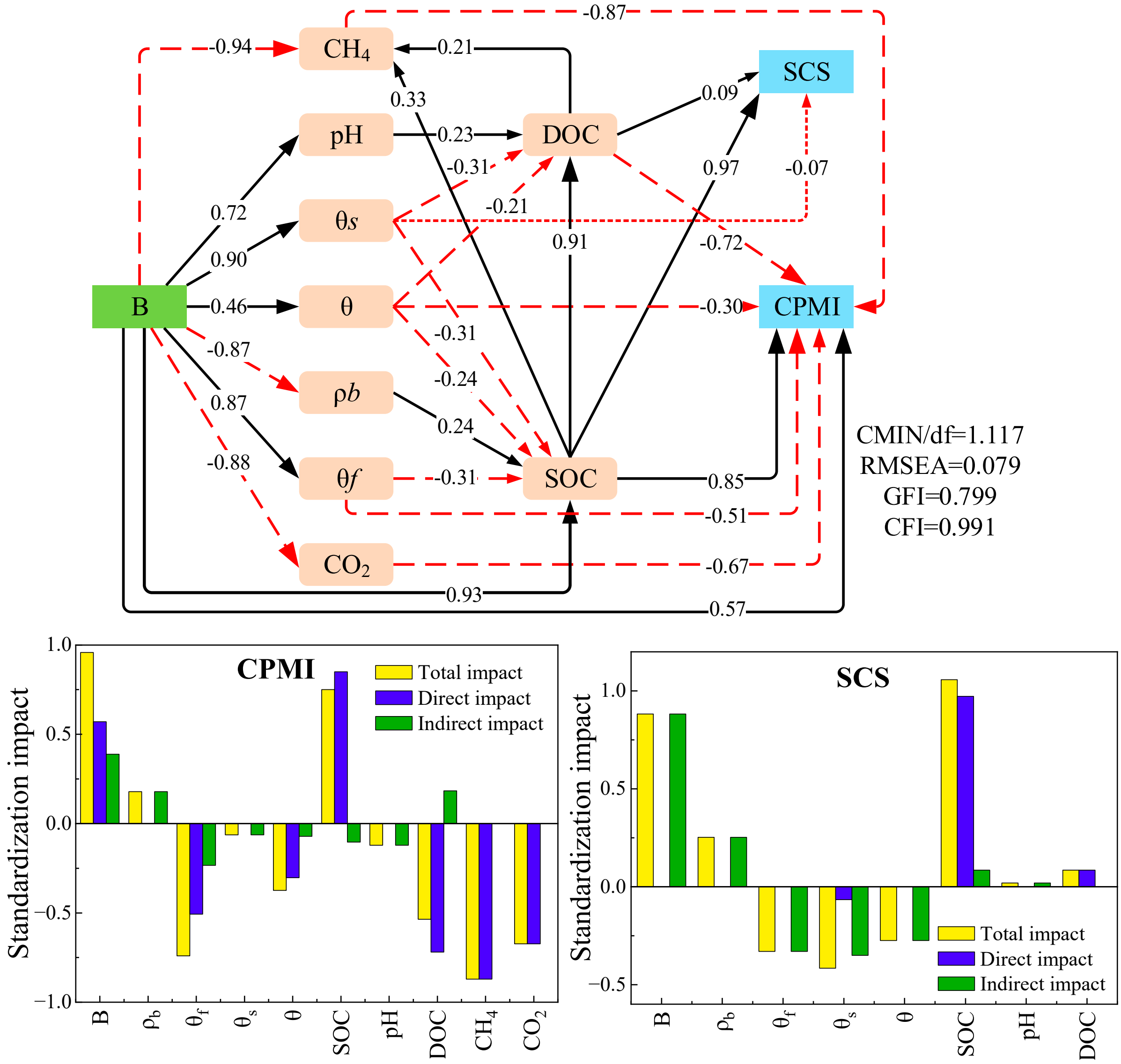

Figure 7. The structural equation model (SEM) for the effects of soil environmental factors and biochar (B) on carbon pool management index (CPMI) and soil carbon sequestration (SCS). The soil environmental factors include ρb, θs, θf, θr, θ, SOC, pH, DOC, CH_4, and CO_2. The black solid lines and the red dotted lines represent positive and negative relationships, respectively. The width of the arrow is proportional to the strength of the path coefficient.

GWP had positive effect variables such as silt, N_2O, and CH_4, while GHGI had positive impact elements such as silt, CO_2, and CH_4 (Figure 8). Biochar had a good emission reduction effect owing to its negative impact on GWP and GHGI. Ignoring the relevant terms in the calculation formula, the important influencing factors for GWP were biochar and silt, which explain 83% and 32% of GWP. The key influencing factors of GHGI were biochar, TN, and SOC, which explain 91%, 25%, and 24% of GHGI, respectively.

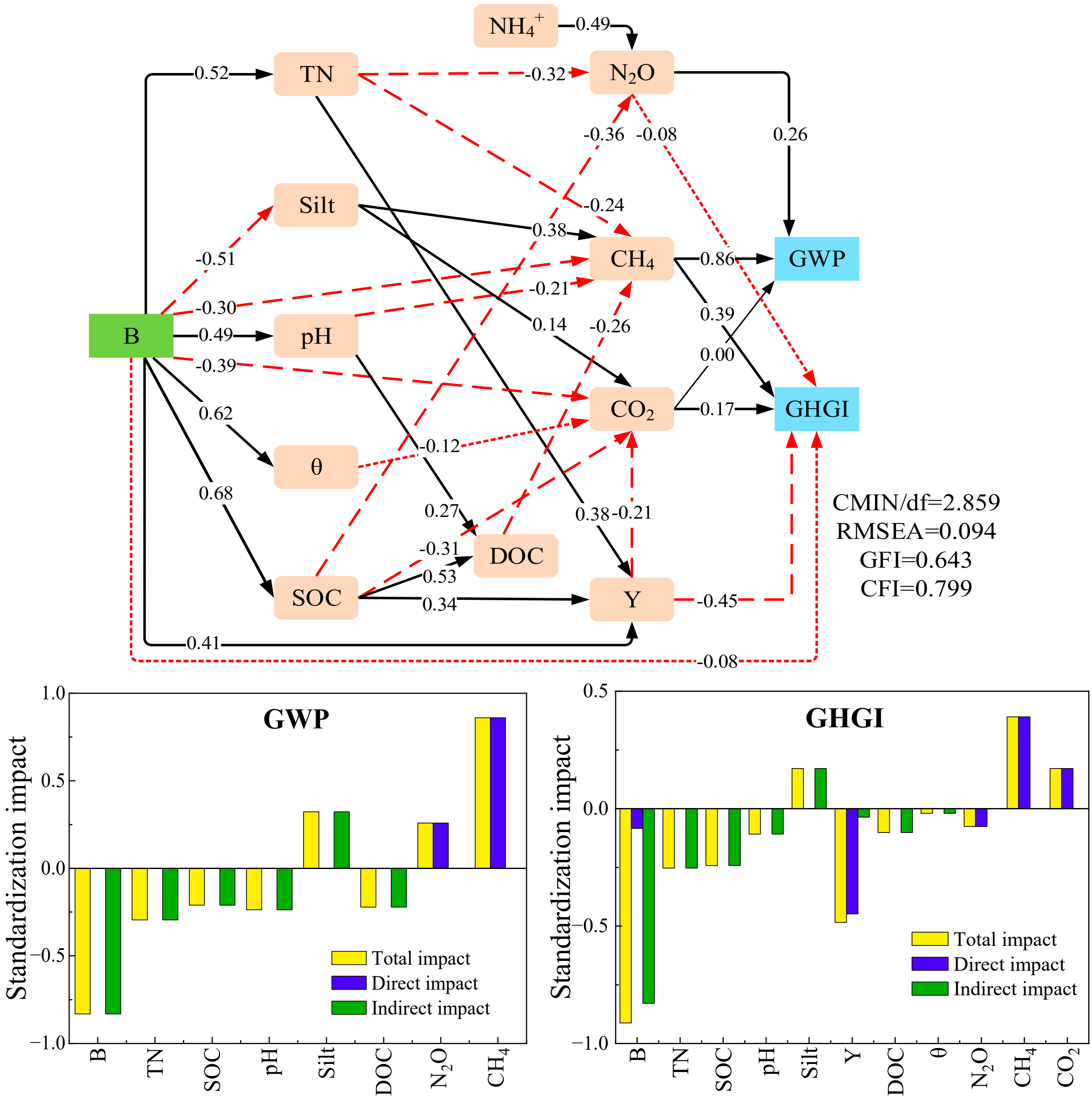

Figure 8. The structural equation model (SEM) for the effects of soil environmental factors and biochar (B) on global warming potential (GWP) and greenhouse gas emission intensity (GHGI). The soil environmental factors include TN, SOC, pH, DOC, silt, θ, N_2O, CH_4, and CO_2. The black solid lines and the red dotted lines represent positive and negative relationships, respectively. The width of the arrow is proportional to the strength of the path coefficient.

Soil factors had no direct impact on WUE (Figure 9), but they act as intermediate links and are influenced by biochar on yield and water consumption, ultimately affecting WUE. The main influencing factors of WUE are Ks (1.021) and biochar (0.833). EP is majorly affected by biochar (0.935) and SOC (0.179).

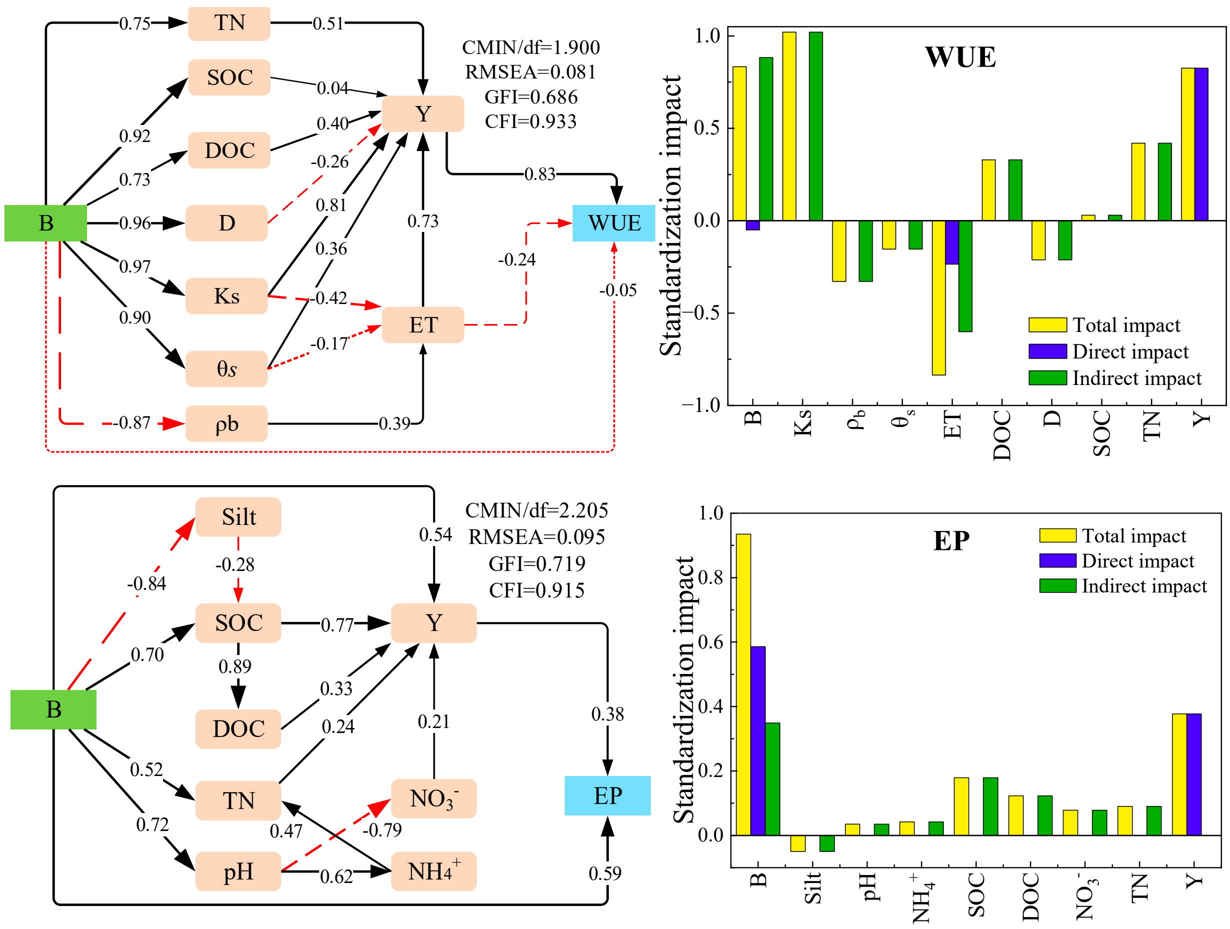

Figure 9. The structural equation model (SEM) for the effects of soil environmental factors and biochar (B) on economic profit (EP) and the ratio of output to input (ROI). The soil environmental factors include Ks, ρb, θs, D, ET, SOC, DOC, Y, TN, silt, NH_4^+, and NO_3^-. The black solid lines and the red dotted lines represent positive and negative relationships, respectively. The width of the arrow is proportional to the strength of the path coefficient.

4. Discussion

4.1. Soil Carbon Sequestration

Farmland with more soil organic carbon (SOC), a crucial component of soil fertility, has a stronger physical structure and lower erosion [41]. The anaerobic conditions caused by flooding in paddy fields inhibit the decomposition of organic matter, which is conducive to SOC sequestration [41]. This is the reason why rice has attracted widespread attention in the field of agricultural carbon sequestration.

Our study found that the changes in SOC were not significant at different growth stages of rice, but the application of biochar had a significant impact ($p < 0.05$) (Figure 3g). The SOC of no biochar treatment was significantly lower than that of the biochar treatment due to the slow decomposition and oxidation rate of soil carbon as the strong stubbornness of biochar [22]. Additionally, owing to biochar's strong adsorption ability, soil particles and SOC can progressively form big aggregates and hold together in the soil [2]. Several studies demonstrated the promoting effect of biochar on SOC sequestration [21–23,25]. In our study, it was found that BC4.5 treatment was the most effective, and this application dosage has generalization in the middle Yangtze River. Dissolved organic carbon (DOC) is a directly available nutrient for rice growth and development, and it is related to rice growth and methane emissions. We found that biochar increased DOC by 45.73–77.87% (Figure 3h), which was consistent with previous studies that biochar increased DOC by 4–70% [14,26].

The soil carbon pool management index (CPMI) includes soil carbon pool and carbon pool activity under human interference, so CPMI can fully reflect the impact of external changes on the quantity of SOC and active organic carbon. Table 3 shows that biochar increased CPMI, indicating that land management measures or treatments improved soil quality and fertility. Biochar increased soil carbon sequestration (SCS) with a growth rate of 71.48% (Table 3), which is convenient for reducing greenhouse gas emissions and increasing grain yield in paddy fields [23]. This study demonstrated that biochar and SOC were the key influencing factors for carbon sequestration indicators (CPMI and SCS) (Figure 7).

4.2. GHG Emissions

Many factors, including SOC, crop respiration, microbial activity, climate, and management, have an impact on soil CO_2 emissions. According to this study, compared to rice fields without biochar application, CO_2 emissions from biochar-amended rice fields significantly decreased by 58.47% ($p < 0.05$) (Figure 4a). With the addition of biochar, the stable, large aggregates in the soil increased, resulting in a decrease in the contact surface of the reaction substrate surrounded by the aggregates. These changes reduce the reaction intensity and the formation of more organic molecules that are difficult to decompose, thus inhibiting CO_2 emissions [2,22]. Because biochar itself is inert and alkaline, which prevents microbial activity in the soil [42]. Related studies have shown that adding biochar to soil can weaken microbial degradation abilities [43]. The CO_2 emissions in all treatments increased with the gradual growth of rice and decreased during the drainage and drying period (Figure 4a). However, after covering the water once more, the CO_2 emissions remained stable at a relatively high level (Figure 4a). Given that root development influences leaf reproduction, changes the intensity of plant autotrophic and heterotrophic respiration, and encourages soil microbial decomposition of organic matter, changes in CO_2 during rice growth are strongly tied to the roots [22].

CH_4 is generated by methanogens in a completely anaerobic environment. The CH_4 generated in the methanogenesis process is oxidized by methane-oxidizing bacteria, and the unoxidized CH_4 is released directly or through crop roots into the atmosphere [30]. The CH_4 emission process in the paddy field has obvious growth period changes (Figure 4b). The gradual increase of CH_4 in the early stage was due to the soil saturation (submerged state) and the gradual reduction of redox potential, creating favorable conditions for CH_4 generation [44]. The rice root system and aerenchyma both developed adequately at the tillering and heading stages, with an increase in CH_4-responsive substrates and vents and increased CH_4 emissions [27]. During the rice drainage and drying period, the anaerobic environment of the soil turned into an aerobic environment, and the circumstances required for CH_4 production were eliminated, which caused a quick drop in emissions. After flooding again, the soil formed strong reduction conditions, and CH_4 emissions peaked once more just before harvest and then gradually decreased [1]. We discovered that biochar improved soil quality and inhibited CH_4 emissions, reducing emissions by −0.38–46.26% (Figure 4b). Additionally, CH_4 emissions were highly sensitive to soil pH and oxygen. Due to its porous nature, biochar reduced soil bulk density and rose porosity (Table 2), allowing more oxygen to enter the soil. Further, biochar has negatively charged phenols, carboxyls, and hydroxyl groups on its surface, and a large number of alkaline substances (K, Ca, Na, Mg, oxides, hydroxides, carbonates, etc.), which react with H^+ to increase soil pH (Figure 3a) [27,29]. Therefore, biochar increases soil pH and oxygen content and disrupts the anaerobic and acidic environments where methanogens exist [29,32], limiting methanogenic activity and reducing CH_4 emissions [22,33]. And biochar absorbs CH_4 with its adsorption capacity to reduce CH_4 emissions [45]. According to Nan reports [46], biochar accelerated CH_4 oxidation (enhanced the activity of methane-oxidizing bacteria and their associated enzymes) and reduced CH_4 emissions. Studies have shown a significant positive correlation between soil CH_4 emissions and SOC and DOC [13,27]. However, in our work, the rise in SOC and DOC caused by biochar did not increase CH_4 emissions

(Figure 3g,h and Figure 8), possibly due to the stronger adsorption capacity of biochar for SOC and DOC.

N_2O emissions are mainly determined by nitrification and denitrification processes [27], and denitrification dominates in rice fields. The influencing factors of N_2O emissions include soil moisture content, nitrogen fertilizer, soil properties, and farmland management. During the growth process of rice, N_2O emissions occur after fertilization and during the drying period (Figure 4c). Many substrates are available from nitrogen fertilizers for nitrification and denitrification processes, which encourage soil to produce N_2O [28]. The soil with increased oxygen is in an incomplete anaerobic environment when the soil is dry (drainage period and one week before harvest, Figure 4c), which promotes N_2O emissions. Our study demonstrated that adding biochar into paddy fields inhibited N_2O emissions, and the cumulative N_2O emissions of BC were 7.72–42.20% lower than those of CK (Figure 5). The findings are consistent with earlier studies [47,48]. Biochar lowers N_2O emissions for four reasons. (1) Biochar increases pH, leading to an increase in N_2O reductase abundance, further lowering N_2O to N_2 [22,29]. (2) Biochar adsorbs NH_4^+, NO_3^-, and N_2O in soil, leading to a reduction in N_2O substrate concentration (low NH_4^+ and NO_3^-, Figure 3c–f) and a decrease in N_2O emissions [47]. (3) The relative excess of carbon and the decrease of C/N in biochar-amended soil, combined with the role of the biochar 'electron shuttle', facilitate the denitrification process to a more thorough N_2 [22,47,48]. (4) Biochar enhanced soil moisture content (Figure S1) and inhibited the nitrification process and N_2O emissions [32]. Biochar reduced greenhouse gas emissions and would contribute to slowing down climate warming. This study was more necessary as it is aligned with global climate change mitigation goals (Paris Agreement targets).

The GWP of BC treatment was much smaller than that of CK treatment, and the rice yield was significantly increased by biochar ($p < 0.05$) (Figure 6a), with the highest yield and lowest GWP in BC4.5. The BC4.5 treatment obtained the smallest GHGI, indicating that the most suitable biochar application rate in rice fields in the Jianghan Plain was 4.5 $kg \cdot m^{-2}$. This is consistent with previous studies that biochar is not the more, the better; suitable is the best [49]. Since the high biochar concentration, soil pore blockage prevents ventilation [50] and instead increases CH_4 and N_2O emissions. The high biochar application rates will lead to high GHG emissions and the high risks of climate warming.

4.3. Paddy Field Efficiency

Agricultural ecosystems contain multiple efficiency issues. The effects of different biochar application rates on water use efficiency (WUE), fertilizer use efficiency (N, P, K), economic benefits (EP), and input–output ratio (ROI) were investigated in this study (Figure 6). Biochar improved soil aeration, hydraulic conductivity, and water-holding capacity by altering soil hydrodynamic parameters and basic indicators [2], thereby reducing water consumption (ET). Biochar promotes root growth by improving soil cultivability and reducing root growth resistance, giving rice access to water and nutrients [51]. Moreover, biochar provides more effective nutrients for plants [52], increasing rice yield (Y). The average WUE increased by 59.22% due to the more yield and less water consumption of biochar treatment (Figure 6a), which is consistent with our previous results on soil columns [36]. This study also found that high biochar dosage led to nutrient imbalance, which was not conducive to agricultural efficiency.

The nutrient absorption of rice, which is impacted by both the direct impacts of nutrients from biochar and the indirect effects of nutrients from soil generated by biochar [53], determines the yield of rice. Biochar improved the utilization efficiency of N, P, and K fertilizers in farmland, which is consistent with previous results [2,16]. However, the order of magnitude of fertilizer use efficiency in this study was N, P, K, whereas the previous study's order was P, N, K [16], which may be a reason for differences in soil properties and fertilizer application ratios. The main mechanisms of biochar improving fertilizer utilization efficiency were (1) adsorbing more fertilizers in the soil to reduce their loss [47]; (2) improving the number and activity of microorganisms by increasing pH; and (3) a slow release effect in which the fertilizer in the soil is slowly released and fully utilized. The economic efficiency of rice was closely related to yield (Figure 9). The ROI was slightly lower due to the slightly higher cost of the biochar, but the EP of rice was still noticeably raised (Figure 6c). From an economic perspective, BC1.5 was preferable. In summary, biochar offers a new idea for capturing carbon and reducing greenhouse gas emissions in rice fields while also taking into account their synergistic effects.

5. Conclusions

In our study, the change in soil properties, soil carbon sequestration, greenhouse gas emissions, and agricultural efficiency were investigated by adding biochar into the paddy field. Rice farmland's soil structure, aeration, water-holding capacity, and fluidity were improved by biochar. Soil properties climbed initially and subsequently fell as the amount of biochar applied increased, with BC4.5 having the best effect. The carbon sequestration capacity of biochar-amended rice increased significantly ($p < 0.05$). The SCS and CPMI were increased by biochar, and the major influencing factors were biochar and SOC in the SEM model. The cumulative emissions of CO_2, CH_4, and N_2O were significantly dropped by biochar, resulting in lower GWP and GHGI. Additionally, biochar enhances fertilizer use efficiency by boosting soil nutrient availability and absorption and promotes rice yield and EP. With biochar, soil moisture was more fully converted into grain, improving WUE. The somewhat greater cost of biochar, offsetting some of rice's high-yield benefits, resulted in the highest ROI in BC1.5. The SEM explained that WUE was mainly influenced by Ks and biochar while EP was mainly affected by biochar and SOC. In conclusion, the addition of biochar to soil proved advantageous for carbon sequestration, emission reduction, and agricultural efficiency enhancement in paddy soil. This study recommends that the optimum amount of biochar to be added to paddy in the middle Yangtze River is 4.5 $kg \cdot m^{-2}$.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14123067/s1, Figure S1: Soil moisture content of different biochar treatments.

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