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Biochar

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# Continuous biochar amendment to achieve long-term $CH_4$ mitigation in paddy fields under water-saving irrigation: a 5-year experiment

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**Abstract**

Biochar amendment is an effective strategy for mitigating methane ($CH_4$) emissions in paddy fields. However, the long-term efficacy of different biochar amendment strategies for mitigating $CH_4$ emissions remains unclear, particularly under different water management regimes. To address this knowledge gap, a 5-year (2018–2022) field experiment was conducted to determine $CH_4$ production potential, $CH_4$ oxidation potential, and $CH_4$ emissions in paddy fields under six treatments: flooded irrigation (F) without biochar amendment (FB0), F with once biochar amendment (12.5 t $ha^{-1}$, FB1), F with continuous biochar amendment (2.5 t $ha^{-1}$ $year^{-1}$, FB5), controlled irrigation (C) without biochar amendment (CB0), C with once biochar amendment (12.5 t $ha^{-1}$, CB1), and C with continuous biochar amendment (2.5 t $ha^{-1}$ $year^{-1}$, CB5). Additionally, random forest analysis and structural equation modeling (SEM) were used to elucidate interaction pathways among biochar amendment, water management, $CH_4$ production and oxidation potentials, and key soil properties affecting $CH_4$ emissions. In the first year, once biochar amendment demonstrated optimal $CH_4$ mitigation efficacy under different water management regimes, reducing cumulative $CH_4$ emissions by 18.87–36.32% compared to other treatments. However, this mitigation effect diminished progressively over 5 years under different water management regimes, with the most rapid decline occurring under C. Consequently, there was no significant difference in the 5-year cumulative $CH_4$ emissions between FB1 and FB5, while CB5 achieved a significant 29.32% reduction in 5-year cumulative $CH_4$ emissions compared to CB1. Random forest analysis and SEM identified soil redox potential (Eh), dissolved organic carbon (DOC), and ammonium nitrogen ($NH_4^+$-N) as key soil properties driving $CH_4$ emissions. CB5 maintained higher soil Eh and $NH_4^+$-N levels with lower DOC, leading to the lowest $CH_4$ production potential and highest $CH_4$ oxidation potential over 5 years, ultimately achieving the greatest $CH_4$ mitigation. Furthermore, CB5 achieved the lowest $CH_4$-attributed greenhouse gas intensity and net greenhouse gas emissions over 5 years. These findings highlight the necessity of long-term monitoring to accurately assess the effects of biochar amendments on $CH_4$ mitigation and offer technical guidance for implementation of biochar strategies in paddy fields under different water management regimes.

**Highlights**

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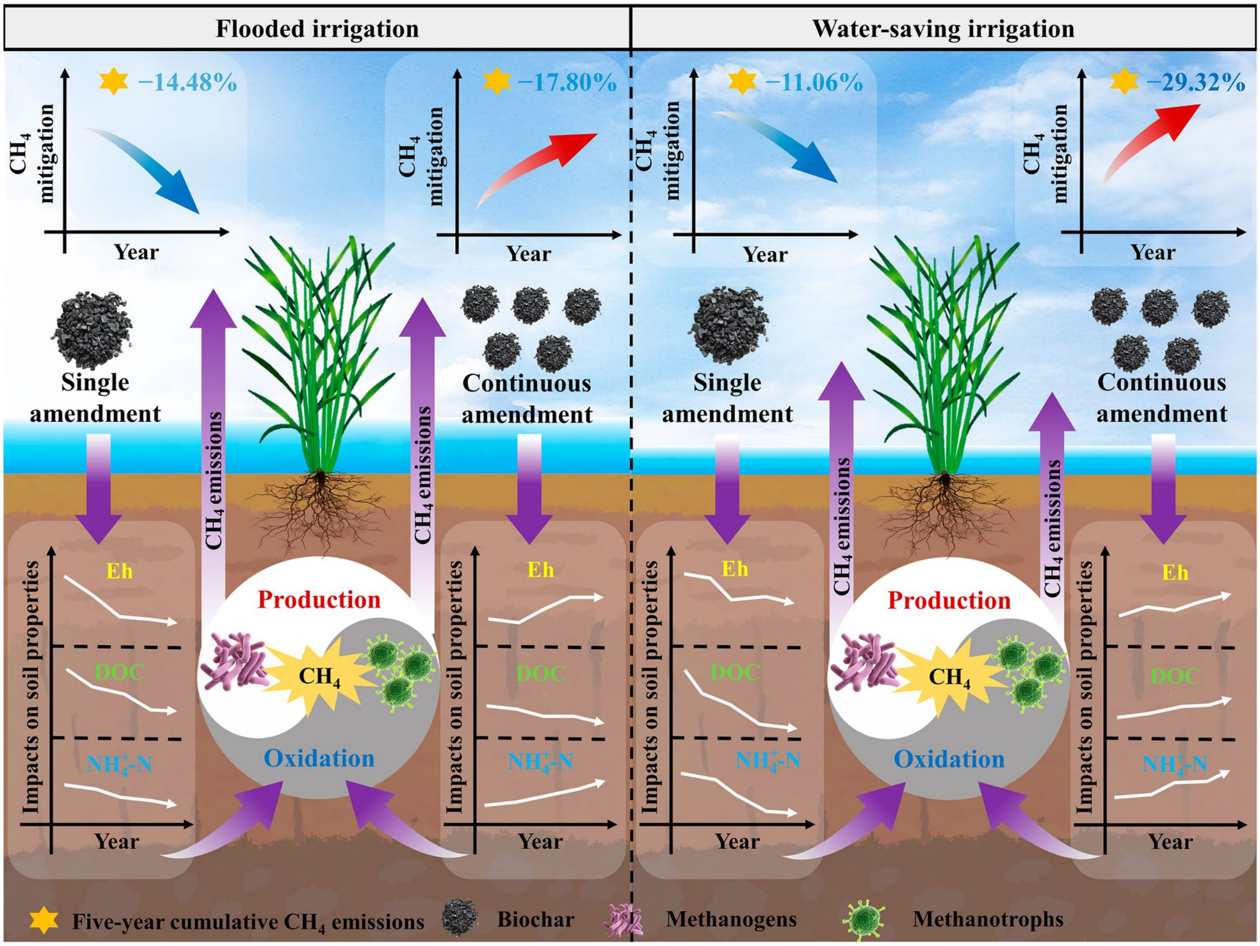
- Water-saving irrigation rapidly diminished the $CH_4$ mitigation effect of the once biochar amendment.
- Continuous biochar amendment combined with water-saving irrigation was the most effective strategy for $CH_4$ mitigation over 5 years.
- Soil Eh, DOC, and $NH_4^+$-N were key drivers of $CH_4$ emissions over 5 years.

**Keywords** Paddy fields, Biochar amendment, Water-saving irrigation, $CH_4$ mitigation

## Graphical Abstract



## 1 Introduction

Methane ($CH_4$) is the second most significant global greenhouse gas (GHG), with a 100-year global warming potential (GWP) 27–30 times higher than that of $CO_2$ (IPCC 2021). Since the preindustrial era (circa 1750), atmospheric $CH_4$ concentrations have increased nearly twofold, with the most pronounced growth occurring throughout the last century (Liu et al. 2025b; Qin et al. 2024). Among agricultural systems, paddy fields are a dominant emitter of biogenic $CH_4$ (Schaefer et al. 2016). From 2010 to 2019, global paddy field $CH_4$ emissions averaged 25.1–37.5 Tg annually, accounting for 6–11% of global anthropogenic emissions (Chen et al. 2025a, b). With the continued expansion of rice cultivation areas (Chen et al. 2024), $CH_4$ emissions from paddy fields are projected to increase further. Therefore, developing efficient and sustainable $CH_4$ mitigation strategies is imperative to support climate-resilient rice production (Qian et al. 2023).

Recently, biochar has been recognized as an excellent soil amendment for mitigating $CH_4$ emissions, as well as improving nutrient cycling and soil carbon sequestration, thus increasing crop productivity (Sultan et al. 2024; Zhao et al. 2024). Numerous studies have confirmed that biochar amendment generally reduces paddy $CH_4$ emissions, with the mitigation effect closely related to biochar type, application rate, and soil conditions (Nan et al. 2020; Fu et al. 2021). The porous structure of biochar enables direct adsorption of soil $CH_4$, facilitating its subsequent oxidation within soil microhabitats (Bolan et al. 2023). Furthermore, biochar can ameliorate degraded soil properties, including enhanced soil aeration and elevated redox potential (Eh) (Case et al. 2012). These improvements collectively reduce $CH_4$ production. Despite these benefits, biochar contains two primary contaminants: inorganic constituents (mainly heavy metals) and organic compounds (polycyclic aromatic hydrocarbons, dioxins) (Aller 2016). This contamination profile implies that once high-dose of biochar amendments may impart potential phytotoxicity (Dong et al. 2025). Some studies also confirm that once high-dose of biochar amendments ($>20$ t $ha^{-1}$) simultaneously reduce rice yields (Liu et al. 2025a; Qi et al. 2020; Zhang et al. 2010). Consequently, researchers have shifted from once to continuous biochar amendment to avoid the negative impacts associated with high amount of biochar amendments (Nan et al. 2023; Wang et al. 2021). However, the short-term impacts of once biochar amendment on paddy field $CH_4$ emissions have been thoroughly investigated (Dong et al. 2013; Gao et al. 2025; Zhao et al. 2024), while the long-term effects arising from a shift to continuous biochar amendment remain unclear.

Water-saving irrigation is a crucial strategy for enhancing agricultural water-use efficiency globally and is increasingly implemented across major agroecosystems (Benyezza et al. 2021; Zhao et al. 2025; Zou et al. 2025). A meta-analysis has shown that water-saving irrigation can reduce paddy $CH_4$ emissions compared to continuous flooded irrigation while maintaining or even improving rice yields globally (Tan et al. 2025). Water-saving irrigation enhances soil aeration via controlled irrigation and drainage cycles (Yang et al. 2016; Chen et al. 2025a, b). Enhanced soil oxygenation modulates the activity of methanotrophs and methanogens, suppressing $CH_4$ production while enhancing $CH_4$ oxidation, ultimately reducing $CH_4$ emissions (Wu et al. 2022a; Gaihre et al. 2025). Substantial evidence confirms that integrating biochar amendment with water-saving irrigation synergistically increases rice yield while reducing $CH_4$ emissions (Chen et al. 2021b; Sriphirom and Rossopa 2023). However, wet-dry cycles driven by water-saving irrigation can accelerate biochar aging (Long et al. 2024). This process may diminish the capacity of biochar to improve soil Eh and its efficiency in adsorbing $CH_4$, thereby potentially compromising its $CH_4$ mitigation efficacy (Wu et al. 2022b). Consequently, the environmental behavior and $CH_4$ mitigation function of biochar amendment under water-saving irrigation may evolve over time (Chen et al. 2021a). Critically, this evolution diverges significantly across biochar amendment strategies: while once amendment demonstrates progressive efficacy decay, continuous amendment may develop enhanced functionality through soil and biochar interactions (Jiang et al. 2021; López-Piñeiro et al. 2025). However, the persistence of once and continuous biochar amendment modes in mitigating $CH_4$ emissions under water-saving irrigation still lacks sufficient quantification.

Therefore, a 5-year field experiment was conducted to investigate the effects of biochar amendment (once and continuous) on $CH_4$ production potential, $CH_4$ oxidation potentials, and $CH_4$ emissions under different water management regimes (flooded and water-saving irrigation) in paddy fields. In addition, random forest analysis was employed to identify key soil properties and structural equation modeling (SEM) was utilized to elucidate interaction pathways among biochar amendment, water management, and key soil properties affecting $CH_4$ emissions. The objectives of this study were: (1) to determine the long-term effects of biochar amendment strategies on $CH_4$ emissions from paddy fields under different water management regimes, (2) to reveal the mechanistic pathways through which the interactive effects of water management and biochar amendment mode influence $CH_4$ emissions by regulating key soil properties, and (3) to identify the optimal integrated approach combining biochar amendment and water management for long-term $CH_4$ suppression in paddy fields. By deciphering the long-term synergistic effects of biochar amendment and water management, this study provides a scientific basis for targeted regulation of "yield increase and $CH_4$ mitigation" in rice systems, with significant practical implications for advancing synergistic development of agricultural carbon neutrality and food security.

## 2 Materials and methods

### 2.1 Site description

The field experiment was conducted at the State Key Station for Irrigation Experiment in Heilongjiang Province, China (127°40′45″E, 46°57′28″N). The site has a cold temperate continental monsoon climate, with an annual average air temperature of 3 °C and an average precipitation of 550 mm. Typically, the average growth period of rice is 120 days. The soil type is classified as black soil, with a rice cultivation history of over ten years. Prior to the experiment, basic soil properties (0–20 cm depth) were analyzed, with the results shown in Table S1.

### 2.2 Experimental design

A 5-year field experiment (2018–2022) evaluated six treatments (two water management regimes × three biochar amendment strategies) with three replications: flooded irrigation (F) without biochar amendment (FB0), F with once biochar amendment (12.5 t $ha^{-1}$, FB1), F with continuous biochar amendment (2.5 t $ha^{-1}$ $year^{-1}$, FB5), controlled irrigation (C, a water-saving irrigation technique reported in prior studies as optimal for $CH_4$ mitigation (Han et al. 2024; Nie et al. 2023)) without biochar amendment (CB0), C with once biochar amendment (12.5 t $ha^{-1}$, CB1), and C with continuous biochar amendment (2.5 t $ha^{-1}$ $year^{-1}$, CB5). The experimental design consisted of 18 plots (5 m × 5 m each), which were isolated with cement barriers to prevent cross-plot water and fertilizer exchange. After every rice harvest, all above-ground residues (straw and stubble) were thoroughly removed from their respective plots.

Rice straw biochar (Liaoning Jinhefu Agricultural Development Co., Ltd, China) was produced via slow pyrolysis (450 °C, oxygen-limited) and characterized by pH 8.86, carbon content 42.72%, nitrogen content 1.26%, cation exchange capacity 44.7 cmol $kg^{-1}$, ash content 29.7%, specific surface area 85.2 $m^2$ $g^{-1}$, and porosity 0.037 $cm^3$ $g^{-1}$. The biochar application rate was determined based on local resource availability. With an annual rice straw yield of 7 t $ha^{-1}$ yielding approximately 2.5 t $ha^{-1}$ of biochar, the continuous amendment treatment received 2.5 t $ha^{-1}$ $year^{-1}$ to reflect this sustainable supply. Continuous biochar amendment was co-applied with basal fertilizer annually, while the once biochar amendment occurred only in 2018. Fertilization involved urea (110 kg N $ha^{-1}$; 50% basal, 20% tillering, 30% panicle), phosphorus (45 kg P $ha^{-1}$; 100% basal), and potassium (80 kg K $ha^{-1}$; 50% basal, 50% panicle). Field management schedules (including fertilization dates) are provided in Table S2. The irrigation regimes for different water management regimes are presented in Table S3. For the flooded irrigation, a standing water layer was maintained throughout the growing season, except during the mid-season drainage period and the natural drainage at the yellow ripening stage. For the controlled irrigation, soil moisture in the root zone was monitored with water potential sensors (Trime-Pico 64/32, Imko, Germany). Irrigation was triggered when the soil moisture decreased below a preset lower threshold, while drainage was implemented when it exceeded a preset upper limit.

### 2.3 $CH_4$ sampling and analysis

$CH_4$ gas sampling was conducted using the static chamber-gas chromatography (GC) (GC-2010 Plus, Shimadzu Corporation, Kyoto, Japan) method (Cheng et al. 2022). Detailed specifications and deployment procedures of the static dark chamber are provided in Methods S1 (Supplementary Materials). Briefly, $CH_4$ emissions were measured every 7 days after rice transplantation. Specifically, the sampling frequency was increased after fertilization, with measurements on the 1st, 4th, and 7th days following application. $CH_4$ collection began at 09:00 am, with samples taken at 0, 10, 20, and 30 min after chamber closure. Following collection, samples were immediately analyzed by GC.

The $CH_4$ emission fluxes were calculated following Xu et al. (2023):

$$f = \rho \times h \times \frac{d_c}{d_t} \times \frac{273}{273 + t} \times \frac{p}{p_0} \tag{1}$$

where $f$ is the $CH_4$ flux (mg $m^{-2}$ $h^{-1}$), the conversion factor from hours to minutes is 60, as the chamber deployment time was measured in minutes and the flux is expressed per hour; $\rho$ is the $CH_4$ density at standard temperature and pressure (0.716 kg $m^{-3}$); $h$ is the chamber height (m); $dc/dt$ is the linear increase in $CH_4$ concentration slope; $t$ is the air temperature recorded inside the chamber (°C); and $p/p_0$ is the chamber-to-standard atmospheric pressure ratio.

The cumulative $CH_4$ emissions were calculated following Nie et al. (2023):

$$F = \sum_{i=1}^{n} \left( \frac{f_i + f_{i+1}}{2} \right) \times (t_{i+1} - t_i) \times 24 \tag{2}$$

where $F$ is the cumulative $CH_4$ emissions (kg $ha^{-1}$); $f_i$ and $f_{i+1}$ are the $CH_4$ fluxes at the $i$-th and $(i+1)$-th sampling events (mg $m^{-2}$ $h^{-1}$), respectively; $t_{i+1}-t_i$ is the time interval between the $i$-th and $(i+1)$-th sampling events (d); and 24 is the factor converting the time interval from days to hours.

The $CH_4$-attributed global warming potential ($CH_4$-GWP) was calculated following Han et al. (2024):

$$CH_4 - GWP = F_{CH_4} \times 27.9 \tag{3}$$

where $CH_4\text{-}GWP$ is the $CH_4$-attributed global warming potential (t $CO_2$-eq $ha^{-1}$); $F_{CH_4}$ is the cumulative $CH_4$

emissions; and 27.9 is the 100-year GWP value of $CH_4$ relative to $CO_2$ (IPCC 2021).

The $CH_4$-attributed GHG intensity (GHGI) was calculated following Han et al. (2024):

$$GHGI = \frac{CH_4 - GWP}{Yield} \tag{4}$$

where *GHGI* is the $CH_4$-attributed GHG intensity (t $CO_2$-eq $t^{-1}$ yield); and *Yield* is the rice yield (t $ha^{-1}$).

### 2.4 Soil sampling and analysis

Topsoil (0–20 cm) was collected following a zigzag pattern across five points in each plot with a stainless-steel soil corer during critical rice growth stages (tillering, jointing, flowering, and maturity). After removing plant residues and stones, subsamples were homogenized into a composite sample per plot. One aliquot was used for soil property analysis, and another for $CH_4$ production and oxidation potentials. For the annual comparison, the mean value of measurements from all critical growth stages within a year was used to represent the annual value for each soil parameter.

#### *2.4.1 Soil properties*

Soil Eh was monitored in situ using an oxidation–reduction potential analyzer (YT-QX6530, Institute of Soil Science, Chinese Academy of Sciences, China) with Pt/Ag–AgCl electrodes. Soil pH was measured in 1:5 (w/v) soil-deionized water extracts using a calibrated pH electrode. Soil ammonium ($NH_4^+$-N) and nitrate ($NO_3^-$-N) nitrogen content were extracted with 2 mol $L^{-1}$ KCl (1:5 w/v, 1 h shaking) and determined by flow injection analysis (Seal AA3, Norderstedt, Germany). Total nitrogen (TN) content was assessed via the micro-Kjeldahl method. Soil bulk density (BD) was determined for the 0–20 cm depth using the cutting ring method (also termed core method). For carbon analysis, both dissolved organic carbon (DOC) content in 1:5 (w/v) soil–water extracts and SOC content from acid-washed samples (1 mol $L^{-1}$ HCl pretreatment until carbonate-free) were quantified by an elemental analyzer (vario TOC cube, Elementar, Hanau, Germany).

The SOC sequestration over the 5-year period was calculated following the method of Yang et al. (2018):

$$SOCS = (SOC_a \times BD_a - SOC_b \times BD_b) \times H \tag{5}$$

where *SOCS* is the SOC sequestration content (kg $ha^{-1}$); $SOC_a$ and $SOC_b$ (g $kg^{-1}$) are SOC content measured in 2022 and 2018, respectively; $BD_a$ *and* $BD_b$ (g $cm^{-3}$) are BD measured concurrently with SOC; and *H* is the thickness of soil (cm).

The $CH_4$-attributed net GHG emission (NGHGE) was calculated per Wang et al. (2022):

$$NGHGE = TotalF_{CH_4} \times 27.9 - SOCS \times \frac{44}{12} \tag{6}$$

where *NGHGE* is the $CH_4$-attributed net GHG emission (kg $CO_2$-eq $ha^{-1}$); $TotalF_{CH_4}$ is the cumulative $CH_4$ emissions over the 5-years; and the factor 44/12 is used to convert carbon mass to equivalent $CO_2$.

#### *2.4.2 $CH_4$ production and oxidation potentials*

The incubation procedure followed established serum bottle protocols (Liu et al. 2022; Yi et al. 2024) with modifications. Briefly, soil samples (10 g dry weight equivalent) were transferred into 200 mL serum bottles sealed with butyl rubber stoppers. Throughout the incubation period, soil moisture was maintained constant by adding distilled water, with all cultures incubated under controlled conditions at 25 °C. All incubations continued for 30 days, and the same operation was performed on the empty bottle without soil samples as a correction.

$CH_4$ production potentials were determined by first purging serum bottle headspaces with high-purity $N_2$ (>99.9%) for 3 min at 200 mL $min^{-1}$ flow rate to establish strict anaerobic conditions. After sealing with butyl rubber stoppers, the culture bottles were incubated in a temperature-controlled chamber. Precisely, headspace gas samples (5 mL) were collected every 24 h using gastight syringes for GC analysis. Immediately following each sampling, an equivalent volume of $N_2$ was injected to maintain isobaric conditions.

$CH_4$ oxidation potentials were determined by first withdrawing 20 mL of headspace gas using gastight syringes and replacing it with an equal volume of high-purity $CH_4$ (>99.9%). The injection ports were immediately sealed with silicone septa and the bottles were incubated at 25 °C. After a 2 h equilibration period, the initial $CH_4$ concentration was quantified by GC. Following 8 h of incubation, 5 mL of headspace gas was sampled for GC analysis. To maintain a normal atmospheric environment, after each gas extraction, an equal volume of high-purity synthetic air was injected into the culture flask to keep the internal and external pressures balanced.

$CH_4$ production and oxidation potentials were calculated as follows:

$$MO = \frac{|(C_0 - C_1)| \times V \times M_{CH_4}}{V_m \times m \times t} \tag{7}$$

where *MO* is the $CH_4$ production or oxidation rate (μg $CH_4$ $g^{-1}$ $h^{-1}$); $C_0 - C_1$ is the $CH_4$ concentration change between two consecutive sampling events (%); *V* is the volume of the culture flask; $M_{CH_4}$ is the molar mass of

$CH_4$ (g $mol^{-1}$); $V_m$ is the molar volume of $CH_4$ (L $mol^{-1}$); $m$ is the dry mass of the soil (g); and $t$ is for time interval (h).

### 2.5 Rice yield

At physiological maturity each year, all rice plants within a randomly selected 1 $m^2$ quadrat per plot were harvested for yield determination, representing plot-level productivity. Plants were threshed, and grains were oven-dried at 105 °C for 30 min followed by drying at 80 °C to constant weight to determine yield at 14% moisture content. The number of filled grains per panicle and effective panicles, the seed setting rate, and the 1000-grain weight were all taken into account for calculating rice yield.

### 2.6 Statistical analyses

SPSS (version 21.0, IBM Corp., USA) was used for all statistical analyses. A three-way analysis of variance (ANOVA) was used to assess the impacts of year, water management, biochar amendment, and their interactions on soil properties, rice yield, and $CH_4$ emissions. Duncan's multiple range test was used to perform post-hoc comparisons among factor levels in cases where significant main effects were found, and $P < 0.05$ was used to determine statistical significance. Origin Pro (version 2021, Origin Lab, USA) was used to visualize each figure. To determine the key soil properties affecting $CH_4$ emissions, random forest analyses were carried out using the "random forest" package in R. The interrelationships between biochar amendments, water management, $CH_4$ production and oxidation potentials, key soil properties, and $CH_4$ emissions in paddy fields were examined using SEM with AMOS (version 21.0, IBM SPSS, Armonk, USA). The model outcomes were assessed using the comparative fit index (CFI), root mean square approximation error (RMSEA), and the ratio of chi-square to the degree of freedom ($\chi^2$/df).

## 3 Results

### 3.1 $CH_4$ emissions

As shown in Fig. 1a, fertilizer application led to a surge in $CH_4$ flux across all treatments, while mid-season drainage caused a rapid decline. Biochar amendment, water management, year, and their interactions significantly affected $CH_4$ emissions ($P < 0.05$; Table S4). In 2018, once biochar amendment demonstrated the lowest $CH_4$ emissions under different water management regimes, reducing average $CH_4$ fluxes by 19.41–34.99% and cumulative $CH_4$ emissions by 18.87–36.32% compared to other treatments ($P < 0.05$; Fig. 1b, g). However, this $CH_4$ mitigation efficacy progressively weakened over 5 years, with mean annual reduction losses of 24.41% under F and 36.68% under C (Fig. 1c, h), indicating accelerated decay under water-saving irrigation. In contrast, continuous biochar amendment achieved superior $CH_4$ mitigation effects over 5 years (Fig. 1). Compared to FB0, FB5 reduced the 5-year cumulative $CH_4$ emissions by 17.80% ($P < 0.05$), which only represented a 3.89% greater reduction than that achieved by FB1. Notably, CB5 resulted in the lowest 5-year cumulative $CH_4$ emissions among all treatments. Specifically, CB5 significantly reduced 5-year cumulative $CH_4$ emissions by 29.32% compared to CB0 and by 18.26% compared to CB1 ($P < 0.05$; Fig. 1g).

### 3.2 Rice yield, $CH_4$-GWP, GHGI and NGHGE

Biochar amendment and water management significantly affected rice yield, $CH_4$-GWP, GHGI, and NGHGE ($P < 0.05$; Table S4). In 2018, once biochar amendment showed the highest rice yield (7.30–12.92% increase), lowest $CH_4$-GWP (18.87–36.32% reduction), and minimal GHGI (27.55–43.60% reduction) compared to other treatments under different water management regimes ($P < 0.05$; Fig. 2a–c). However, these benefits progressively weakened over 5 years for once biochar amendment but strengthened for continuous biochar amendment (Fig. 2a–c). Consequently, FB1 and FB5 showed no significant differences in average rice yield, $CH_4$-GWP, and GHGI. Conversely, CB5 delivered optimal sustainability compared to CB1: highest average rice yield (9.48 t $ha^{-1}$), lowest average $CH_4$-GWP (4.06 t $CO_2$-eq $ha^{-1}$), and minimal average GHGI (0.44 t $CO_2$-eq $t^{-1}$ yield) (Fig. 2a–c). Critically, both once and continuous biochar amendments significantly reduced NGHGE compared to no biochar amendment under different water management regimes ($P < 0.05$). Continuous biochar amendment achieved significantly lower NGHGE than once biochar amendment ($P < 0.05$), with the CB5 treatment even reaching net negative emissions (−4.62 t $CO_2$-eq $ha^{-1}$) (Fig. 2d).

### 3.3 $CH_4$ production and oxidation potentials

Biochar amendment, water management, and their interactions significantly affected $CH_4$ production and oxidation potentials ($P < 0.05$; Table S4). Over 5 years, both once and continuous biochar amendments significantly reduced $CH_4$ production potential and increased $CH_4$ oxidation potential compared to no biochar amendment under different water management regimes ($P < 0.05$; Fig. 3). Continuous biochar amendment achieved significantly lower $CH_4$ production potential and higher $CH_4$ oxidation potential than once biochar amendment ($P < 0.05$), with CB5 demonstrating the lowest $CH_4$ production potential and highest $CH_4$ oxidation potential among all treatments (Fig. 3).

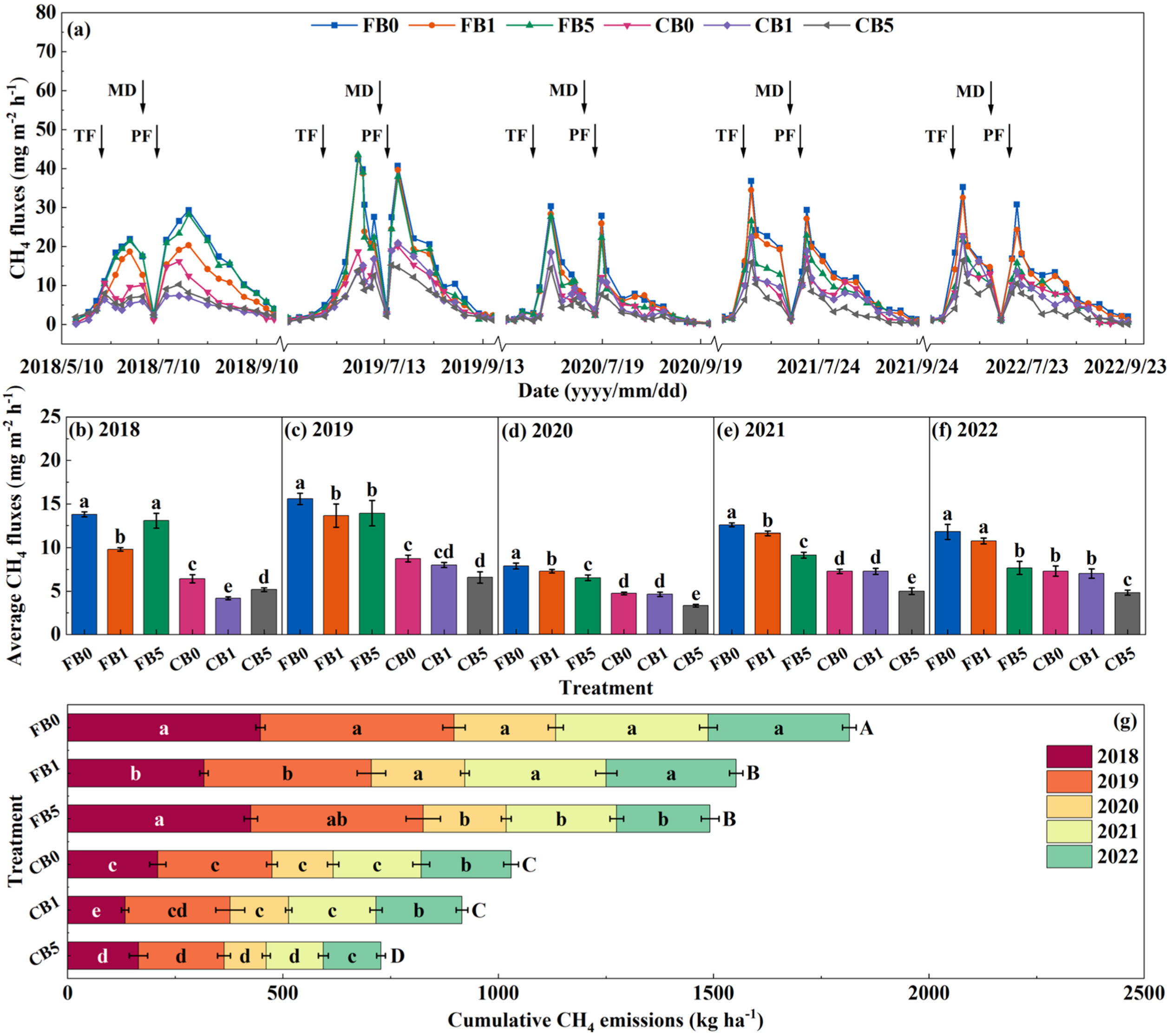


**Fig. 1** $CH_4$ emission fluxes (**a**), average $CH_4$ emission fluxes (**b**–**f**), and cumulative $CH_4$ emissions (**g**) in paddy fields under different treatments during 2018–2022. The lowercase letter indicates that the cumulative $CH_4$ emissions between the treatments in the same year are significantly different ($P < 0.05$), and the uppercase letter indicates that the 5-year cumulative $CH_4$ emissions between the treatments are significantly different ($P < 0.05$). The arrows indicate the dates of key management events: TF, tillering fertilizer; PF, panicle fertilizer; MD, mid-season drainage

### 3.4 Soil properties

Biochar amendment significantly influenced all treatment soil properties except pH and BD ($P < 0.05$; Table S4). Significant interactions between biochar amendment and year were observed for Eh, $NH_4^+$-N, $NO_3^-$-N, and DOC. In 2018, once biochar amendment elevated soil Eh (by 16.11–124.53%), SOC (by 11.64–17.96%), $NH_4^+$-N (by 15.44–29.91%), and $NO_3^-$-N (by 9.23–49.41%), while reducing DOC (by 17.34–27.01%) under different water management regimes compared to other treatments ($P < 0.05$; Fig. 4). However, these effect of once biochar amendment on soil properties progressively declined over 5 years, with a faster rate of decline under C than F (Fig. 4). In contrast, continuous biochar amendment demonstrated progressively enhanced soil properties over 5 years. After 2021, CB5 showed the highest soil Eh and $NH_4^+$-N, and the lowest DOC concentration in all treatments (Fig. 4a, e, i).

### 3.5 Random forest and SEM reveal key drives of $CH_4$ emissions

Random forest analysis identified $CH_4$ production potential as the primary contributor to $CH_4$ emissions (33.31% importance), followed sequentially by oxidation

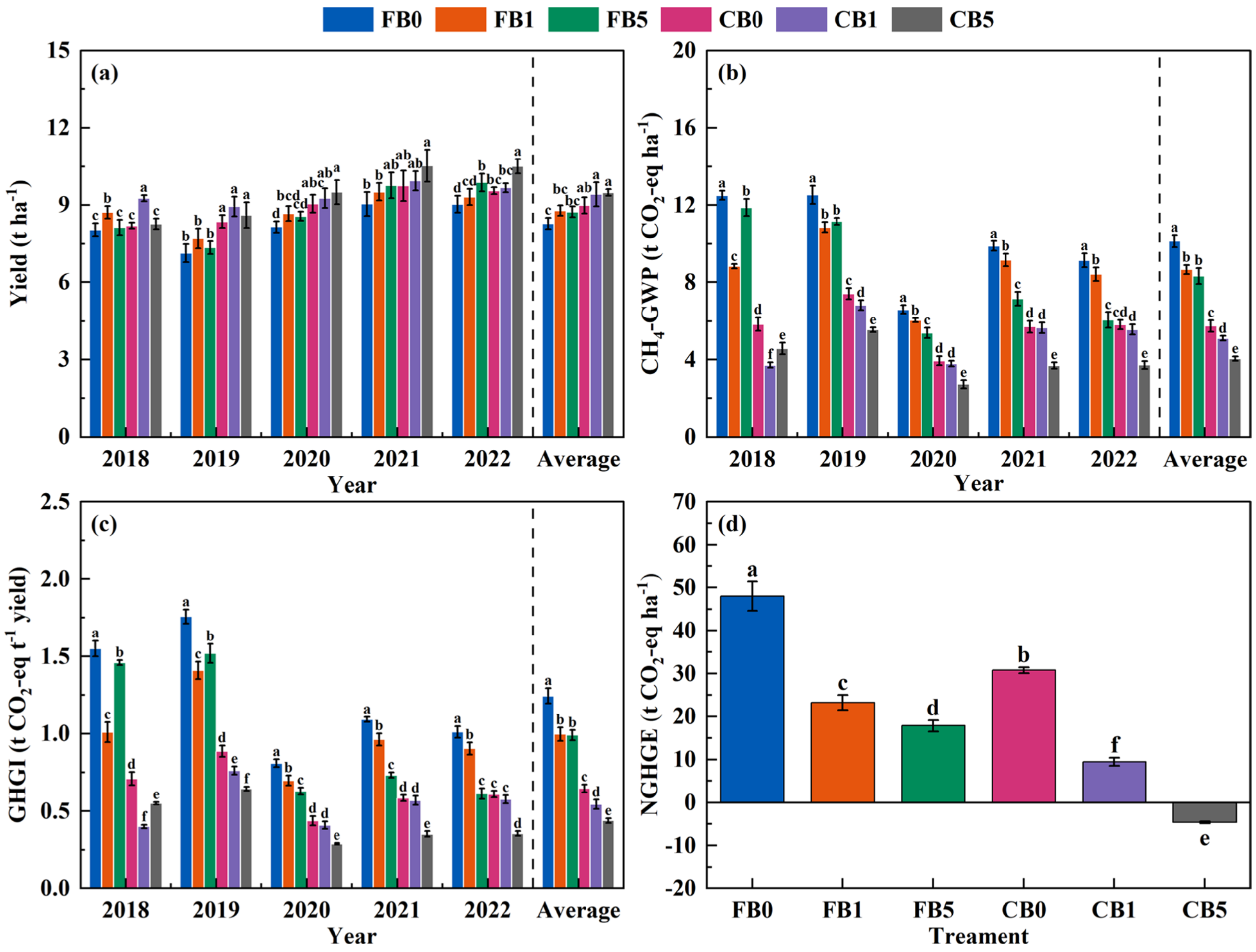


**Fig. 2** Rice yield (**a**), $CH_4$-attributed global warming potential ($CH_4$-GWP) (**b**), GHG intensity (GHGI) (**c**), and net GHG emission (NGHGE) (**d**) in paddy fields under different treatments during 2018–2022. Different letters indicate significant differences ($P < 0.05$) between different treatments

potential, $NH_4^+$-N, DOC, and Eh ($P < 0.01$; Fig. 5). SEM explained 74% of the variance in $CH_4$ emissions (Fig. 6a), demonstrating that water management indirectly regulated emissions through modifications in soil $NH_4^+$-N, DOC, and Eh, which subsequently governed $CH_4$ production and oxidation potentials. Additionally, biochar amendment not only shared these indirect pathways but also directly enhanced $CH_4$ oxidation potential (Fig. 6a). Notably, water management exerted a stronger negative total effect on $CH_4$ emissions (−0.617) than biochar amendment (−0.322), while $CH_4$ production rate demonstrated the highest positive total effect (0.936) on $CH_4$ emissions (Fig. 6b).

## 4 Discussion

### 4.1 Effects of once biochar amendment on $CH_4$ mitigation under different water management regimes over 5 years

Our study demonstrates that once biochar amendment significantly mitigates $CH_4$ emissions from paddy fields under different water management regimes in the short term, which is consistent with previous studies (Gao et al. 2025; Nan et al. 2025; Wang et al. 2023). Notably, CB1 achieved significantly greater $CH_4$ mitigation than FB1. This enhanced efficacy may stem from synergistic interactions between once biochar amendment and water-saving irrigation: (1) Both practices enhance soil aeration and elevate Eh (Hussain et al. 2021; Xiao et al. 2025). Their combination synergistically elevates soil Eh (Table S4; Fig. 4a), amplifying methanogen suppression while stimulating methanotroph activity (Xiao et al. 2022). This drives concurrent reduction in $CH_4$ production and enhancements in $CH_4$ oxidation, thereby

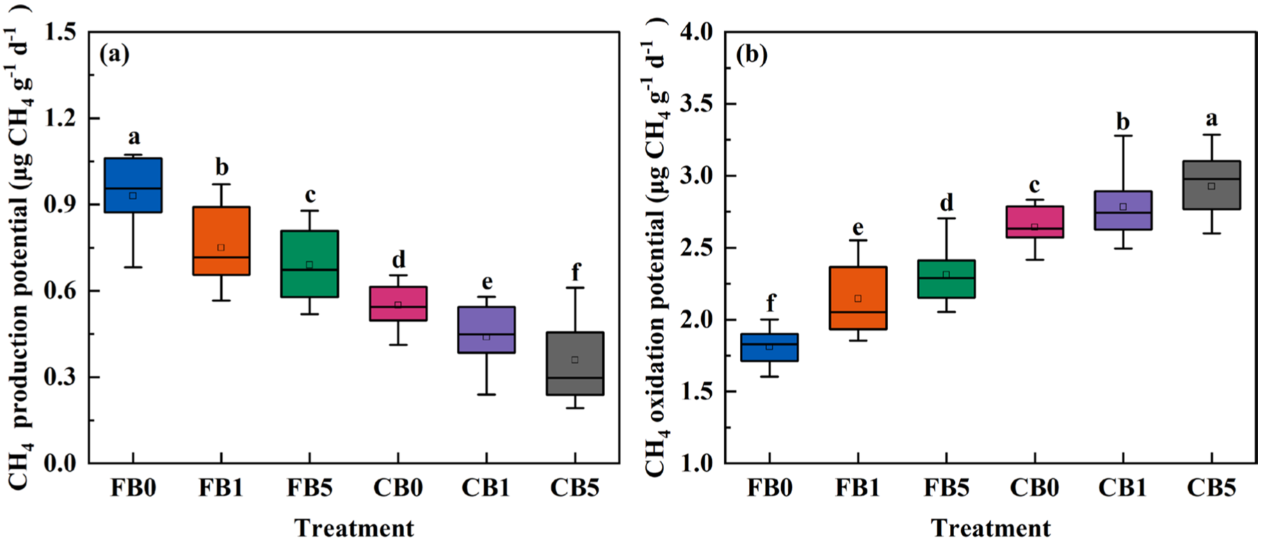


**Fig. 3** $CH_4$ production (**a**) and oxidation (**b**) potentials in paddy fields under different treatments during 2018–2022. Different letters indicate significant differences ($P < 0.05$) between different treatments. In the boxplots, the central line represents the median, the box boundaries show the upper and lower quartiles (25th and 75th percentiles), and the whiskers extend to 1.5 × interquartile range. Data points beyond the whiskers are plotted as outliers

reducing short-term $CH_4$ emissions. (2) Water-saving irrigation inherently reduces soil DOC while increasing $NH_4^+$-N (Fig. 4e). Biochar adsorption further retains $NH_4^+$-N and limited DOC availability for methanogenic decomposition (Dong et al. 2019; Speratti et al. 2018; Zheng et al. 2016). These combined effects intensified substrate limitation and simultaneously enhanced methanotrophic activity, resulting in the lowest observed $CH_4$ emissions in the short term.

However, the suppressive effect of once biochar amendment on $CH_4$ emissions attenuated annually under different water management regimes. This attenuation is attributed to biochar aging in paddy fields, characterized by reduced pore diameter and diminished liming effect (Nan et al. 2020; Yi et al. 2020). Reductions in biochar pore diameter not only compromise soil aeration but also diminish its adsorption capacity for DOC and $NH_4^+$-N (Jiang et al. 2019). The aging process progressively diminished the control of the once biochar amendment over $CH_4$ emissions. Initially, its influence on key soil properties (Eh and DOC) weakened annually, ultimately converging with the effects of FB5 and showing no significant difference by 2022 (Fig. 4). Furthermore, the fading of its liming effect led to increased soil acidity, thereby creating an unfavorable environment for methanotrophs (Vieira Fontoura et al. 2019). Consequently, the ability of the once biochar amendment to suppress both $CH_4$ production and oxidation was attenuated each year, resulting in a progressive decline in its overall effectiveness in controlling $CH_4$ emissions. Notably, the $CH_4$ suppressive efficacy of CB1 attenuated more rapidly under water-saving irrigation than FB1 over 5 years. This may be due to the frequent dry–wet cycles induced by water-saving irrigation, which accelerated the aging of biochar in paddy fields (Luo et al. 2025). Consequently, biochar loses its capacity to modify soil properties (Fig. 4), while concurrently diminishing its ability to suppress methanogenic activity and enhance $CH_4$ oxidation (Xiao et al. 2022). Thus, by hastening biochar aging, water-saving irrigation rapidly diminishes the $CH_4$ mitigation efficacy of once biochar amendment.

### 4.2 Effects of continuous biochar amendment on long-term $CH_4$ mitigation under different water management regimes

In this study, continuous biochar amendment achieved significant long-term suppression of $CH_4$ emissions. This is because continuous annual biochar amendment under different water management regimes counters aging through annual replenishment of reactive surfaces and alkaline minerals (Nan et al. 2020), sustaining soil property enhancement with significantly elevated soil Eh, reduced DOC, and increased $NH_4^+$-N compared to no biochar amendment (Fig. 4). This regenerative process maintains methanotroph activity while persistently suppressing methanogens (Dong et al. 2013), driving durable $CH_4$ mitigation through sustained electron transfer and optimized $CH_4$ oxidation potential (Figs. 1g, 3). However, no significant

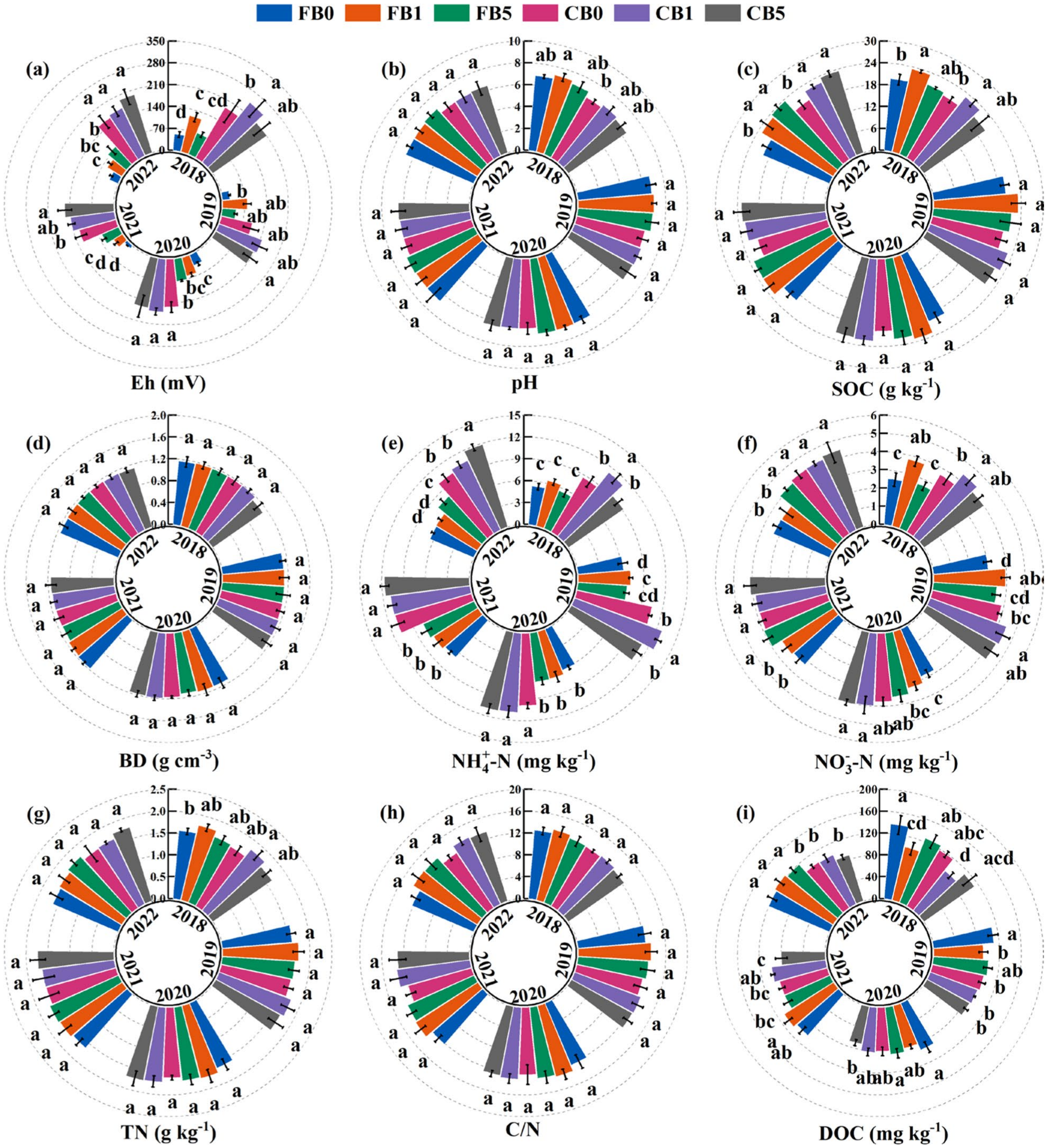


**Fig. 4** Soil redox potential (Eh) (**a**), pH (**b**), organic carbon (SOC) content (**c**), bulk density (BD) (**d**), ammonium $NH_4^+$-N content (**e**), nitrate ($NO_3^-$-N) content (**f**), total nitrogen (TN) content (**g**), C/N ratio (**h**), and dissolved organic carbon (DOC) content (**i**) in paddy fields under different treatments during 2018–2022. Different letters indicate significant differences ($P < 0.05$) between different treatments

difference was observed in 5-year cumulative $CH_4$ emissions between FB1 and FB5, while CB5 showed significantly lower 5-year cumulative $CH_4$ emissions compared to CB1. The reason may be twofold: (1) Frequent redox oscillations under water-saving irrigation enhance organo-mineral bonding between fresh biochar and $Fe^{3+}/Al^{3+}$ oxides (Xu et al. 2021). This mineral association reduced the availability of DOC to methanogens (Han et al. 2024; Kubaczyński et al.

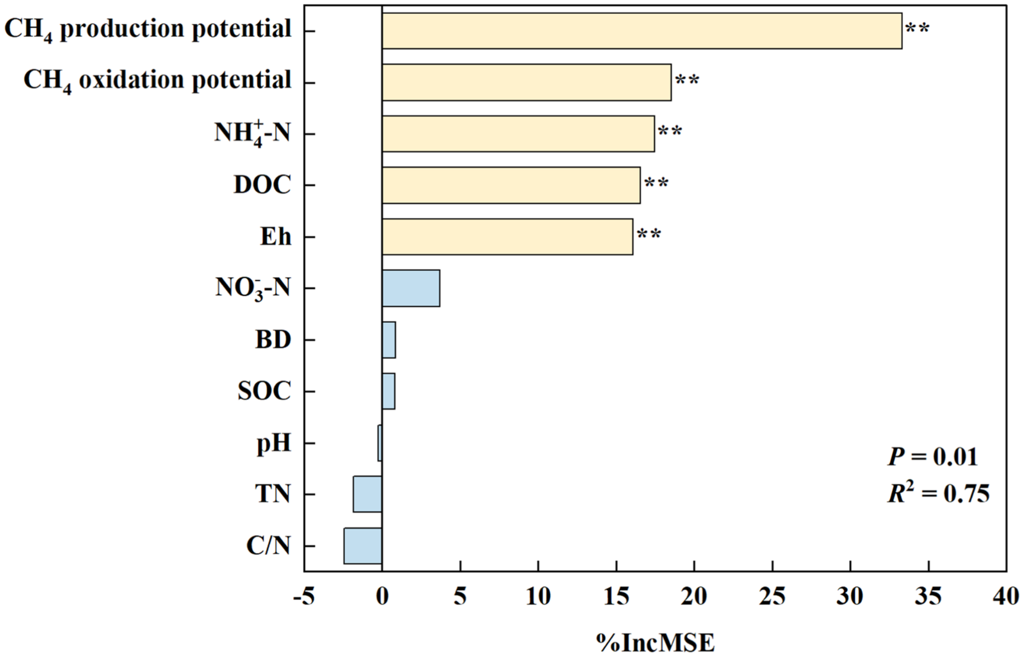


**Fig. 5** Random forest analysis quantified the relative importance of soil factors influencing CH$_4$ emissions, with model performance evaluated by mean squared error (MSE). Significance thresholds are denoted as follows: **$P < 0.01$

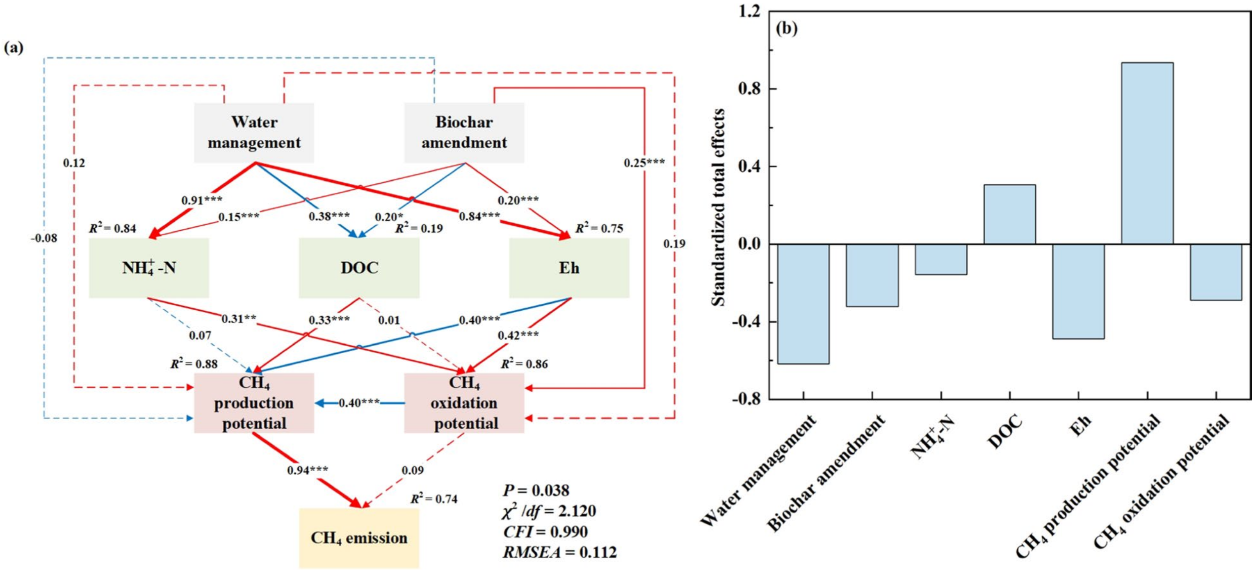


**Fig. 6** Standardized total effects of soil factors on the CH$_4$ emissions in paddy fields under different treatments based on structural equation modeling (SEM) (**a**, **b**). The width of each arrow corresponds to the magnitude of the standardized path coefficient. Color-coding indicates the direction and significance of relationships: red arrows signify significant positive coefficients, blue arrows represent significant negative coefficients, and gray arrows denote non-significant pathways. Statistical significance levels are indicated as follows: *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$

2022), thereby decreasing CH$_4$ production. (2) CB5 maintained the highest Eh after 2020 (Fig. 4a). This elevated Eh maximizes instantaneous activation of fresh biochar, consequently increasing methanotroph activity while suppressing methanogen activity (Zheng et al. 2024). Thus, continuous biochar amendment under water-saving irrigation synergistically minimizes $CH_4$ production while maximizing oxidation capacity, resulting in the lowest 5-year cumulative $CH_4$ emissions. Furthermore, it steadily increased rice yield and SOC compared to flooded irrigation without biochar amendment, resulting in lowest 5-year $CH_4$-GWP, GHGI, and NGHGE among all treatments.

### 4.3 Implications for biochar amendment and water management strategies

Our 5-year field experiment demonstrates that once biochar amendment under water-saving irrigation offers only short-term $CH_4$ mitigation due to accelerated biochar aging from frequent wet-dry cycles (Zhang et al. 2022). This aging rapidly degrades biochar pore structure and adsorption capacity, critically increasing DOC leaching risks in water-saving irrigation systems as carbon retention capacity diminishes (Jiang et al. 2019). Elevated DOC availability in water-saving irrigation soils may fuel mineralization, undermining SOC sequestration (Yan et al. 2022). Therefore, in the context of expanding water-saving irrigation (Echeverría-Progulakis et al. 2025), once high-dose biochar amendment is not recommended. Critically, our yield analysis reveals that continuous biochar amendment combined with water-saving irrigation (CB5) not only achieved the highest cumulative $CH_4$ reduction but also maintained stable grain yield throughout the 5-year study period, demonstrating a synergistic “win-win” scenario for both environmental and agronomic objectives. Continuous biochar amendment is therefore essential not only to counteract aging effects and mitigate inherent carbon loss risks, but also to ensure yield sustainability. In this study, continuous biochar amendment maintained high soil Eh and low DOC levels, sustaining conditions that minimize $CH_4$ production while maximizing oxidation. The integration of continuous biochar amendment with water-saving irrigation demonstrated superior efficacy, achieving the greatest 5-year cumulative $CH_4$ reduction and lowest GHGI and NGHGE through sustained optimization of soil conditions. This synergistic combination represents the optimal strategy for climate-resilient rice cultivation, simultaneously delivering high rice yields and maximized long-term $CH_4$ mitigation, thereby addressing both food security and climate change mitigation goals.

Crucially, these findings rely on extended-duration experimental verification. Short-term studies may inadequately assess biochar efficacy, as demonstrated by Zhao et al. (2024), who reported effective three-year $CH_4$ mitigation with once biochar amendment and higher oxidation potential than continuous biochar amendment in the third year. The divergence from our 5-year results likely stems from temporal scope differences. In our 5-year experiment, continuous biochar amendment proved more effective for sustained $CH_4$ mitigation, particularly under water-saving irrigation. Notably, continuous amendment with water-saving irrigation maintained significantly higher average $CH_4$ oxidation potential than once biochar amendment. Therefore, multi-year field experiments spanning multiple cropping cycles are crucial for accurately quantifying the inhibitory effect of biochar amendment strategies on $CH_4$ mitigations from rice systems.

## 5 Conclusions

Through 5-year field experiments, both once and continuous biochar amendments significantly reduced $CH_4$ emissions in paddy fields under different water management regimes. However, no significant difference in $CH_4$ mitigation was observed between once and continuous amendments under flooding irrigation, while continuous amendment demonstrated significantly stronger $CH_4$ mitigation than once biochar amendment under water-saving irrigation. Under flooding irrigation, biochar regulation of soil Eh, DOC, and $NH_4^+$-N diminished within 5 years, equalizing $CH_4$ mitigation between once and continuous biochar amendment strategies. Conversely, water-saving irrigation accelerated biochar amendment efficacy attenuation, whereas continuous biochar amendment enhanced this effect through sustained improvement of soil Eh, DOC, and $NH_4^+$-N, achieving minimal 5-year cumulative $CH_4$ emissions. Furthermore, continuous biochar amendment coupled with water-saving irrigation consistently increased rice yield and SOC, resulting in minimal GHGI and NGHGE. These findings demonstrate that continuous biochar amendment under water-saving irrigation represents the optimal management practice for achieving significant and sustained reductions in $CH_4$ emissions while concurrently improving overall environmental footprint in rice cultivation.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-026-00578-z.

Additional file 1.

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### Author contributions

Yu Han: writing-review & editing, writing-original draft, software, resources methodology, investigation, data curation. Peng Chen: writing-review & editing, formal analysis. Zhongxue Zhang: funding acquisition, project administration. Xiaoyuan Yan: funding acquisition. Guangbin Zhang: project administration. Zuohe Zhang: visualization, validation, conceptualization. Tiecheng Li: formal analysis. Tangzhe Nie: software. Sicheng Du: data curation.

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### Data availability

Data and material will be made available on request.

## Declarations

### Competing interests

Xiaoyuan Yan is an Editor of the journal Biochar, and he was not involved in the peer-review or handling of the manuscript. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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