Park *et al. Applied Biological Chemistry* (2024) 67:44
https://doi.org/10.1186/s13765-024-00903-9

KSABC
The Korean Society for Applied Biological Chemistry

ARTICLE **Open Access**

Effect of rice hull biochar treatment on net ecosystem carbon budget and greenhouse gas emissions in Chinese cabbage cultivation on infertile soil

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Abstract

Biochar, with its potential to enhance soil fertility, sequester carbon, boost crop yields and reduce greenhouse gas emissions, offers a solution. Addressing the challenges posed by climate change is crucial for food security and agriculture. However, its widespread adoption in agriculture remains in its infancy. This study assessed the effects of rice hull biochar on cabbage production and greenhouse gas emissions, especially nitrous oxide (N_2O). A trial, employing a randomized block design in triplicate was conducted from September 13 to November 23, 2022, where "Cheongomabi" cabbage was cultivated with $N\text{-}P_2O_5\text{-}K_2O$ fertilization at 32—7.8—19.8 kg $10a^{-1}$. Additional fertilizer was applied twice post-sowing. The Biochar application rates were control = 0 ton ha^{-1}, B1 = 1 ton ha^{-1}, B3 = 3 ton ha^{-1}, and B5 = 5 ton ha^{-1}. The aboveground biomass of autumn cabbage harvested 82 days after sowing was 2.40–2.70 kg $plant^{-1}$ in the control and biochar treatments (B1, B3, and B5), with no significant differences ($p > 0.05$). Cumulative CO_2 emissions during cultivation varied across treatment groups, with initial and cumulative emissions of 10.40–17.94 g m^{-2} day^{-1} and 3.63–4.43 ton ha^{-1}, respectively. N_2O emissions decreased with higher biochar application: reductions of 2.9%, 25.4%, and 41.1% in the B1, B3, and B5 treatments, respectively, compared to the control. The biochar application had no significant impact on yield but curbed soil emissions, Net ecosystem carbon balance during cabbage cultivation ranged from 0.42 to 3.41 ton ha^{-1} for the B1, B3, and B5 treatments, respectively, compared to control. Overall, the study underscores biochar's role in mitigating emissions and boosting soil carbon during cabbage cultivation in fall.

Keywords Biochar, Infertile soil, Net ecosystem carbon balance, Infertile soil, Net global warming potential, Greenhouse gas emissions, Chinese cabbage

Introduction

Modern agriculture faces challenges such as soil degradation, nutrient depletion, and climate change [1]. Soil degradation, driven by fertilizer misuse, monoculture, and erosion, is particularly concerning [1]. Excessive use of fertilizers leads to nutrient depletion, affecting crop vitality [2]. Climate change disrupts weather patterns, amplifying extreme events that harm crops [3]. Biochar has emerged as a strategic intervention, to enhance soil properties, nutrient retention, organic matter content,

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and carbon sequestration, thereby mitigating modern agricultural hurdles [4]. Biochar also augments crop yield and curbs greenhouse gas emissions (GGEs) [5]. Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are the main anthropogenic greenhouse gases (GHG) into the atmosphere results from the combustion of fossil and biomass fuels and the decomposition of organic matter, both above and below ground. CO_2 concentrations have gradually increased from over the years, 280 ppmv in 1850 to 410 ppmv in 2019, a remarkable 46.4% increase [6]. CH_4 and N_2O levels also increased over this period, with a steady upward trend. Pacala and Socolow [7] found that fossil fuel combustion contributes about 7 $PgCyr^{-1}$ (1 $Pg = 10^{15}$ g), while deforestation, land-use change and soil cultivation contribute about 1.6 $PgCyr^{-1}$, which together play a key role in driving climate change and subsequent global warming. This highlights the urgent need to stabilize atmospheric GHG concentrations to combat global warming risks. In agriculture, biochar made from agricultural by-products is attracting increasing attention in this regard [8].

Biochar is generated through pyrolysis of agricultural waste [9]. It possesses attributes influenced by the feedstock as well as pyrolysis conditions [10]. Biochar is derived from various raw materials, including agricultural by-products, cellulosic by-products, and livestock manure. Each material has different content of components, and the chemical properties of biochar vary depending on the pyrolysis conditions, such as temperature. For example, biochar produced from livestock manure tends to have a high nitrogen and phosphorus content, whereas that derived from agricultural by-products typically has relatively low nitrogen and phosphorus content [11]. Moreover, even when using the same raw material, the content of components can differ based on the conditions of pyrolysis, leading to significant variations in stability [11]. With a high carbon content and alkalinity, biochar improves soil traits and crop productivity [12]. Various studies have underscored its positive impact on diverse crops, including maize, soybean, chickpea, wheat, bell pepper, and tomato [13–18]. Biochar research extends beyond agriculture to environmental management and carbon–neutral technology [19]. This broader approach enriches biochar's potential applications [19].

In infertile soils, researchers are faced with unavoidable questions about the sustainability of carbon-based carbon restoration strategies resulting from biochar application. For example, limited knowledge exists regarding how the slow decomposition of these carbon materials in soil affects the net ecosystem carbon budget (NECB) for decades after remediation [20,21]. Soil organic carbon (SOC) mainly measures soil fertility and health [22] and can be elevated by increasing soil CO_2 sequestration and reducing CO_2 emissions. NECB refers to the total rate of organic C accumulation (or loss) in an ecosystem and has been used to estimate SOC changes at crop-seasonal time scales [23]. Increasing SOC or reducing GGEs can lower the net emissions of CO_2 equivalents. Injecting biochar as exogenous C into the soil contributes to the soil C pool while reducing the soil GGEs. Reducing GGEs and increasing soil C storage in cropland is critical for South Korea, as it aligns with the country's goals to reduce its "peak CO_2 emissions" by 2030 and achieve "carbon neutrality" by 2050. Therefore, the abovementioned efforts play a significant role in working toward these environmental targets.

Rice hull biochar, a cellulosic byproduct, and Chinese cabbage, a crop which is currently cultivated annually in Korea, were assessed in infertile soil in this study. Chinese cabbage is the primary ingredient in kimchi and is the most cultivated leafy green vegetable in Korea. Currently, the Chinese cabbage cultivated area in Korea occupies 30,537 ha, accounting for 66% of the total leafy vegetable cultivated area. It is grown in both open fields and facility cultivation sites owing to its year-round sowing and harvesting capabilities [24]. The choice of Chinese cabbage, an important crop in South Korea and Asia, stems from previous studies that have shown positive results by improving growth and yield via biochar treatment [25]. Therefore, this study aimed to assess the greenhouse gas reduction effect of rice hull biochar application in infertile agricultural soils used for Chinese cabbage cultivation. Additionally, the carbon balance in the soil was evaluated using the NECB method, an aspect that is not extensively investigated in previous studies.

Overall, the use of biochar in agriculture presents a promising solution for addressing the challenges faced by modern agriculture. Research on the effects of biochar application on GGEs, global warming, soil C balance, and other related factors in Chinese cabbage crop fields can contribute to developing sustainable agriculture practices and promoting the efficient use of resources.

Materials and methods

Field management and experimental design

This experiment was conducted in a field located within the National Institute of Agricultural Sciences in Wanju-gun, Jeollabuk-do, Republic of Korea (35°49′45.5"N 127°02′39.8"E). The test soil was treated as newly cultivated soil and was arranged in a randomized complete block design using a tillage method. Biochar input levels were Control = 0 ton ha^{-1}, B1 = 1 ton ha^{-1}, B3 = 3 ton ha^{-1}, and B5 = 5 ton ha^{-1}.

During the test period, the atmospheric temperature and precipitation were similar to the average for

September in the past 10 years, with an average temperature of 23.0 °C when the Chinese cabbage was officially planted on September 13, 2022. The mid-September temperature was 25.3 °C, exceeding the average by 3.9 °C, but from the end of September to early November, it was 0.4–1.5 °C lower than the average (Fig. 1).

Chinese cabbage was selected as a crop that requires much N fertilizer, and the variety used was "Cheongomabi." The cultivation period began on September 13, 2022, and harvesting was done on November 23, 2022. The planting distance was 75 cm between rows and 45 cm between plants, and the fertilizer input was based on the crop prescription of N-P_2O_5-K_2O: 32–7.8–19.8 kg $10a^{-1}$. Two applications of additional fertilizer were made after 30 and 45 days of planting.

Gas sampling and measurements

Fluxes of CO_2 and N_2O were measured twice a week during the 60-day growing period using a sealed opaque (white) chamber (24 cm diameter, 37 cm high). Fluxes were measured by placing the chamber on top of the cylinder. The chamber was connected to a portable Fourier transform infrared-based analyzer (GT5000, Gasmet Technologies Oy, Helsinki, Finland). An opaque (white) chamber was semi-permanently installed in the field between the center two rows of each plot, approximately 15 cm from the center of the third crop row, and within 3 m of the center of the treatment plot. The opaque (white) chamber was hammered into the soil so that the collar bottom was at least 3 cm below the soil surface. During flux measurements, the headspace air in the chamber was circulated through 3 mm inlet and outlet tubes. This instrument operates on the principle of measuring the absorption of infrared radiation by GHG and can detect several gases simultaneously. Gas samples were first drawn into a cell where the gas path length was approximately 1 m. The sample cell was then purged with N_2 gas to remove any remaining water vapor, which could interfere with the measurement. The FTIR spectrum of each gas sample was obtained by scanning the instrument's laser over a range of wavelengths and comparing the resulting spectrum to a reference spectrum. The different GHG concentrations were then determined by fitting the measured spectrum to a library of known spectra using a least-square fitting algorithm.

The GHG concentrations generated at varying temperatures during each measurement in a sealed chamber were investigated. Prior to sampling, a vacuum pump was used to inject fresh air into the gas cylinder to remove any pre-existing gas. Gas samples were collected twice a week on Tuesdays and Fridays. The measurement chamber was consistently sealed for a duration of 40 min for each testing session. Before initiating the measurements, all weeds present inside the chamber were thoroughly cleared. Concentrations of CO_2 and N_2O gases were then systematically collected at 20-s intervals for the initial minute. Additionally, for a more comprehensive analysis, these gas concentrations were further recorded at the same interval at three distinct time points: at the beginning, 20 min in, and at the 40-min mark. The gas samples obtained during these periods were meticulously analyzed using a Fourier Transform Infrared (FTIR) spectrometer, namely the Gasmet GT5000 [26, 27, 28, 29, 30]. During the nonsampling periods, the chamber lid was left open to supply sufficient oxygen for normal cultivation. The GHG concentrations in the gas samples were measured using gas chromatography (7890A, Agilent, USA). CO_2 and N_2O emissions were calculated using the following equation (Eq. 1):

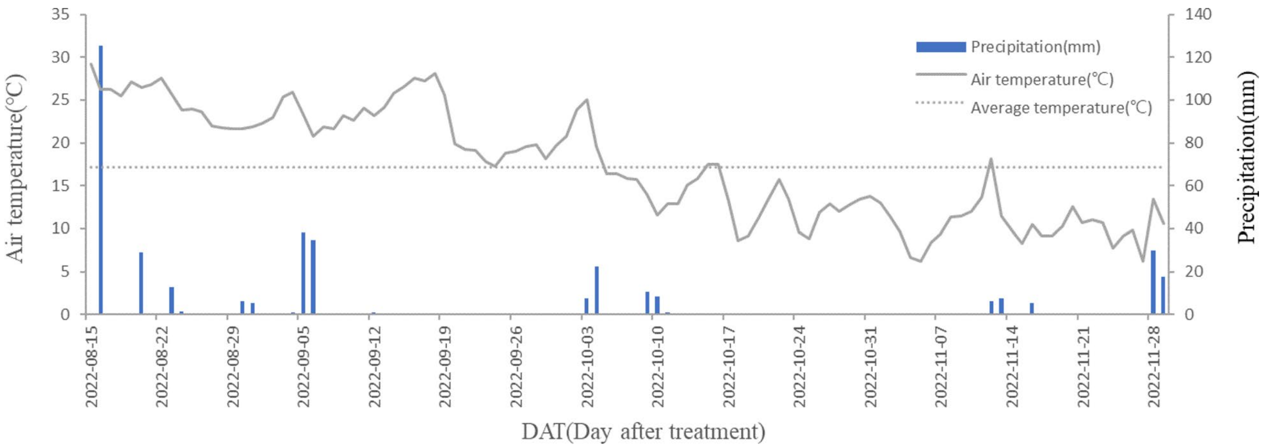

Fig. 1 Temperature and precipitation in the field experiment during the fall cabbage growing season

$$\text{CO}_2\text{ and N}_2\text{O efflux}\left(\text{mg m}^{-2}\text{day}^{-1}\right) = \rho \times \frac{V}{A} \times \frac{\Delta C}{\Delta t} \times \frac{273}{(T + 273)} \tag{1}$$

In this formula, ρ is the gas density 1.967 mg cm $^{-3}$, V represents the volume of the chamber (m^{-3}), and A represents its surface area (m^{-2}). The parameter ΔC/Δt represents the rate of increase in CO_2 concentration in the chamber per unit time (mg m^{-3} day), and T is the constant temperature. Moreover, the total amount of CO_2 and N_2O efflux during constant temperature was calculated using the formula Σ (R × D), where R represents the amount of N_2O generated (mg m^{-3} day) and D represents the sampling interval.

Net ecosystem carbon budget

NECB was performed by calculating the difference between total C inputs and total C outputs by specifically analyzing carbon changes resulting from restoration actions within the system boundary. A detailed method was presented in a previous study [31]. Therefore, NECB was calculated as follows:

$$\begin{aligned}\text{NECB}\left(\text{t C ha}^{-1}\text{yr}^{-1}\right) &= \Delta\text{SOC} \\ &= \sum \text{C input} - \sum \text{C output} \\ &= (\text{NPP} + \text{Fertilizer} + \text{Biochar}) \\ &\quad - (\text{Respired C loss} + \text{Harvest removal})\end{aligned} \tag{2}$$

$$E_{input} = \left(B_{total} \times f_1 + M_{total}\right) \times \frac{44}{12} \tag{3}$$

$$B_{total} = \left(Y_g \times f_2\right) \tag{4}$$

$$E_{output} = M_{output} \times \frac{44}{12} + p_{\text{output}} \tag{5}$$

In this formula, the C input and C output represent the total input and total output (t CO_2-eq ha^{-1}). Y_g is the quantity of Chinese cabbage (ton ha^{-1}), and B_{total} is the Chinese cabbage biomass in Cases 1 and 2 (ton ha^{-1}). f_1 represents the C proportion in Chinese cabbage biomass, and f_2 is the proportion of Chinese cabbage yield converted to Chinese cabbage biomass; according to previous studies, f_1 is 40% and f_2 is 90% [32]. M_{total} is the C content of the restoration material (ton ha^{-1}), and M_{output} is the C emissions resulting from the production and transportation of the restoration material (t CO_2-eq). P_{output} is the C emission (t CO_2-eq ha^{-1}) generated by Chinese cabbage and soil microbial respiration, which reflects the total amount in infertile soil cropland and has been mentioned in the literature [33]. In addition, the C emission changes caused by adding biochar were presented following the literature [34,35].

Global warming potential and greenhouse gas intensity

Global warming potential (GWP) was calculated using Eq. 6 as follows:

$$\text{Total GWP}\left(\text{kg CO}_{2-eq.}\text{ ha}^{-1}\right) = 28 \times \text{CH}_4 + 265 \times \text{N}_2\text{O} \tag{6}$$

The total seasonal emissions of CH_4 and N_2O (kg ha^{-1}) were monitored for Chinese cabbage during the seasons of growth. The GWP of CH_4 and N_2O are 28- and 265-fold greater than that of CO_2 over 100 years, respectively [36,37].

Greenhouse gases emission intensity (GHGI) was calculated using Eq. 7 as follows:

$$\text{GHGI}\left(\text{kg CO}_{2-eq}.\text{ kg}^{-1}\text{ grain}\right) = \text{Total GWP}/\text{grain yield} \tag{7}$$

where GWP is the sum of CH_4 and N_2O (kg $CO_{2\,eq.}$ kg^{-1}) emissions, and Y is the grain yield (kg ha^{-1}) [38,39].

Statistical analysis

Comparisons of GGEs across croplands after rice hull biochar application were statistically processed using SPSS Statistics 25 (IBM, Chicago, IL, USA). All data were presented as the mean ± standard error. A two-way analysis of variance was performed to compare differences between treatments. In addition, Duncan's multiple range test was performed only when the F-test value was significant at $P < 0.05$.

Results

Rice hull biochar and soil

Biochar was produced using rice straw as the feedstock. The rice straw underwent pretreatment involving collection and drying. The actual production of biochar took place at a biochar manufacturing facility located in Yesan-gun, Chungcheongnam-do. This involved utilizing top lit up draft pyrolysis within a carbonization furnace, where the process occurred at a temperature of 500 °C. The pH of rice hull biochar was 10.8, total carbon (TC) content was 566.9 g kg^{-1}, total nitrogen (TN) content was 5.7 g kg^{-1}, and surface area was 71.1 ± 8.8 m^2 g^{-1} (Table 1). The analysis was performed using Vario Max CN (Elementar, Germany) for N and C, whereas Hand Sand Flash 2000 (Thermo Fisher, Italy) was used for O. The H/C and O/C molar ratios of rice hull biochar were 0.21 and 0.05, respectively. These values indicate microbial stability, as ratios below 0.7 and 0.4 (Table 1) are

Table 1 Physicochemical properties of rice hull biochar composition content and H/C, O/C molar ratio (%)

Material	pH	T-C	T-N	T-H	Surface area	Molar ratio	
	1:10	g kg^{-1}	g kg^{-1}	g kg^{-1}	m^2 g^{-1}	H/C	O/C
Rice hull biochar	10.8	566.9	5.7	17.6	71.1 ± 8.8	0.21	0.05

T-C Total carbon, *T-N* Total nitrogen, *T-H* Total hydrogen

associated with instability (EBC; European Biochar Certificate, 2016). For the biochar analysis, pH was measured using the same equipment used for soil analysis by mixing biochar and distilled water at a ratio of 1:10 (W V^{-1}) and stirring. TC and total nitrogen (TN) contents were measured by analyzing the total hydrogen using an Elemental Analyzer (Vario MACRO cube, Elementar, Germany), and the specific surface area was determined using a surface area analyzer (BELSORP-max, BEL, Japan). Before the experiment, soil pH ranged from 7.8 in the control to 7.6 in B1. Electrical conductivity (EC) was highest in the control at 0.24 dS m^{-1} and lowest in B3 at 0.21 dS m^{-1}. T-C content peaked in B1 at 4.85 g kg^{-1} and hit the lowest point in B5 at 3.42 g kg^{-1} (Table 2). T-N content was highest in B1 at 0.45 g k^{-1} and lowest in B3 at 0.33 g kg^{-1} (Table 2). Analysis of available P_2O_5 revealed its highest and lowest values in B1 and B3 at 310.1 and 249.6 mg kg^{-1}, respectively (Table 2). In cation exchange analysis, K^+ was highest in B1 at 0.33 cmol$^+$ kg^{-1}, Ca^{2+} was highest in B3 at 9.97 cmol$^+$ kg^{-1}, and Mg^{2+} was highest in control at 4.60 cmol$^+$ kg^{-1} (Table 2). Conversely, K^+ was lowest in B3 at 0.18 cmol$^+$ kg^{-1}, Ca^{2+} was lowest in B1 at 8.21 cmol$^+$ kg^{-1}, and Mg^{2+} was lowest in B3 at 4.08 cmol$^+$ kg^{-1} (Table 2). For the soil analysis, pH, TC, and TN contents were measured based on the soil chemical analysis protocol (NIAS, 2000). To measure the pH, soil and distilled water were mixed at a ratio of 1:5 (W V^{-1}), stirred for 30 min, and measured using a pH meter (S230 Mettler Toledo, Switzerland). TC and TN contents were measured using a CN analyzer (Vario Max CN, Elementar, Germany).

GGEs and cumulative GGE

The analysis of CO_2 emissions by period revealed that, among GHG, CO_2 emissions through soil respiration during the autumn Chinese cabbage cultivation period increased overall until mid-October, with these emissions gradually decreasing from the period when the average atmospheric temperature fell below 20 °C (Fig. 1). The evolution of emissions of CO_2 and N_2O from agricultural soils and biochar capacity throughout the study are shown in Fig. 2. Specifically, changes in CO_2 and N_2O emissions resulting from treatment with biochar in the infertile soil during the period of study are shown in Fig. 2. CO_2 emissions peaked on the first day in B1 treatment at 3.99 g m^{-2} day^{-1}, whereas lowest level was observed in B5 treatment at 2.31 g m^{-2} day^{-1}. On October 5, the highest CO_2 emissions occurred in B5 treatment at 10.64 g m^{-2} day^{-1}, whereas lowest emissions were observed in B3 treatment at 4.44 g m^{-2} day^{-1}. On October 14, the highest CO_2 emissions were recorded at 10.92 g m^{-2} day^{-1} in the control, whereas lowest emissions were at 5.38 g m^{-2} day^{-1} in B1 treatment. N_2O emissions were the highest on the first day in B1 treatment at 5.09 mg m^{-2} day^{-1}, whereas lowest levels were recorded in B3 treatment at 1.69 mg m^{-2} day^{-1}. On October 11, the highest N_2O emissions occurred in B1 treatment at 6.53 mg m^{-2} day^{-1}, whereas lowest emissions were in B5 treatment at 3.68 mg m^{-2} day^{-1}. N_2O emissions were high (1.69–5.09 mg m^{-2} day^{-1}) in the early stages of cultivation, increased even during the growing period (Fig. 2). Furthermore, the cumulative CO_2 emissions during the cultivation period were 3.28, 3.23, 3.29,

Table 2 Chemical properties by soil characteristics in cropland

Treatment	pH	EC	T-C	T-N	Av. P_2O_5	Ex. cation		
						K^+	Ca^{2+}	Mg^{2+}
	1:5	dS m^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	$\mathrm{coml_c}^+$ kg^{-1}		
Control	7.8	0.24	4.70	0.35	295.2	0.26	9.09	4.60
B1	7.6	0.23	4.85	0.45	310.1	0.33	8.21	4.11
B3	7.7	0.21	4.26	0.33	249.6	0.18	9.97	4.08
B5	7.7	0.23	3.42	0.36	279.7	0.23	9.36	4.23

Control; *B1* Rice hull biochar 1 ton ha^{-1}, *B3* Rice hull biochar 3 ton ha^{-1}, *B5* Rice hull biochar 5 ton ha^{-1}

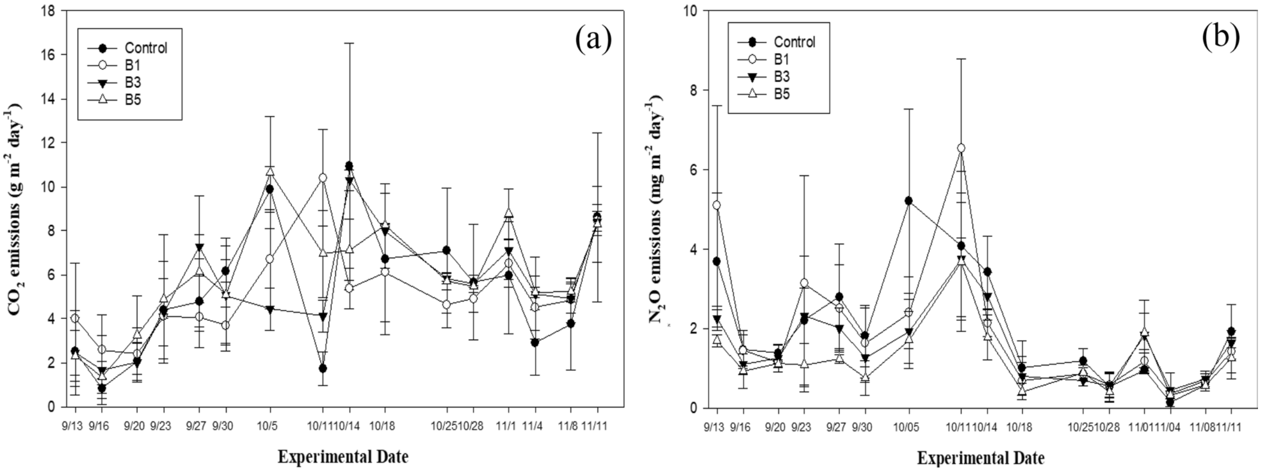

Fig. 2 Greenhouse gas emissions from Infertile soil cropland to the application of rice hull biochar under closed chamber conditions for 60 days: **a** CO_2 emissions and **b** N_2O emissions. Values are the means of triplicate, and vertical bars are the standard errors of the means (n = 3). Error bars are often too small to be depicted

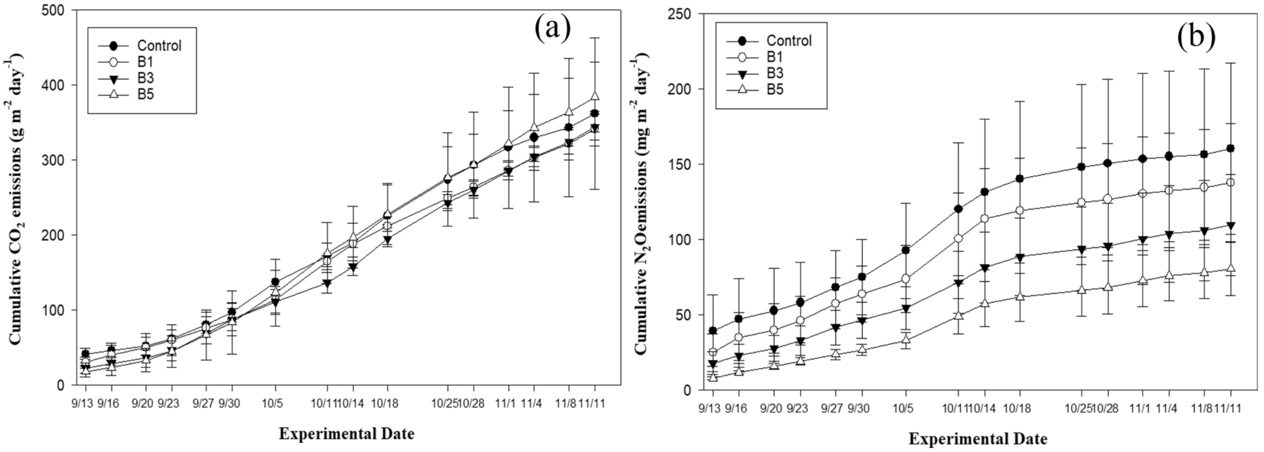

Fig. 3 Cumulative greenhouse gas emissions from Infertile soil cropland to the application of rice hull biochar under closed chamber conditions for 60 days: **a** Cumulative CO_2 emissions and **b** Cumulative N_2O emissions. Values are the means of triplicate, and vertical bars are the standard errors of the means (n = 3). Error bars are often too small to be depicted

and 3.73 ton ha^{-1} in the control, B1, B3, and B5, respectively (Fig. 3). The cumulative N_2O emissions during the cultivation period were 1.32, 1.28, 0.99, and 0.78 kg ha^{-1} in the control, B1, B3, and B5, respectively. Cumulative N_2O emissions decreased with increasing biochar application, with reductions of 2.9%, 25.4%, and 41.1% in the B1, B3, and B5 treatments, respectively, compared to the control (Fig. 3).

NECB, GWP, net GWP, and GHGI

During the cabbage cultivation period, the NECB for each treatment was 1.96, 2.58, 3.65, and 4.58 ton ha^{-1} in the control, B1, B3, and B5, respectively. The soil C balance increased in proportion to the biochar input, increasing by 0.62, 1.69, and 2.70 ton ha^{-1} for B1, B3, and B5 treatments, respectively, compared to the control (Table 3). A comprehensive evaluation was undertaken to assess the impact of biochar on soil improvement and crop productivity. This encompassed analyzing soil chemistry and crop production based on varying levels of biochar input, along with calculations for GWP and greenhouse gas intensity (GHGI), ultimately leading to the determination of net global warming potential potential (net GWP).

The total GWP, including CO_2 emissions, for each treatment during the autumn Chinese cabbage cultivation period was 3.69, 3.63, 3.59, and 3.97 ton ha^{-1} in the control, B1, B3, and B5, respectively (Tabel 4). GHGI

Table 3 Mean annual greenhouse gas emissions, Harvest, NPP, NECB, C balance, total GWP, GHGI, and net GWP over the 2022 growing season

Treatment	N_2O	CO_2	Harvest	NPP	C input	C output	NECB	C balance	Total GWP	GHGI	Net GWP
t N_2O ha^{-1} yr^{-1}	t CO_2 ha^{-1} yr^{-1}	t ha^{-1} yr^{-1}	t C ha^{-1} yr^{-1}	t C ha^{-1} yr^{-1}	t CO_2*eq* ha^{-1} yr^{-1}	t CO_2*eq* ha^{-1} yr^{-1}	t CO_2*eq* ha^{-1} yr^{-1}	t CO_2*eq* ha^{-1} yr^{-1}	t CO_2*eq* ha^{-1} yr^{-1}	t N_2O t^{-1} yr^{-1}	t CO_2*eq* ha^{-1} yr^{-1}
Control	0.00132^a	3.28^b	3.47^a	3.55^a	6.33^b	4.37^b	1.96^b	–	3.63^b	1.04^a	-6.84^b
B1	0.00128^a	3.23^b	3.20^a	3.32^a	6.67^b	4.09^b	2.58^{ab}	0.62^b	3.57^b	1.12^a	-9.12^b
B3	0.00099^b	3.29^b	3.77^a	3.84^a	8.31^a	4.66^a	3.65^a	1.69^a	3.55^{ab}	0.94^{ab}	-13.12^{ab}
B5	0.00078^b	3.73^a	4.45^a	4.53^a	10.13^a	5.47^a	4.58^a	2.70^a	3.93^a	0.88^b	-16.59^a

Control; *B1* Rice hull biochar 1 ton ha^{-1}, *B3* Rice hull biochar 3 ton ha^{-1}, *B5* Rice hull biochar 5 ton ha^{-1}

Total GWP (t CO_2-*eq*. ha^{-1}) = $28 \times CH_4 + 265 \times N_2O$,

GHGI (t CO_2-*eq*. kg^{-1} grain) = Total GWP / grain yield,

Net GWP (t CO_2-*eq*. ha^{-1}) = GWP – 12 / 44 × NECB,

[a–b] Different letters in the same column indicate significant statistical differences ($P < 0.05$)

were 0.51, 0.54, 0.55, and 0.62 ton ton^{-1}, with GHG increasing proportionally with biochar input amount (Tabel 4). Evaluation of the net GWP showed that carbon absorption increased with increasing biochar input amount, with -6.84, -9.12, -13.12, and -16.59 ton ha^{-1} in the control, B1, B3, and B5, respectively (Tabel 4). Overall, this study provides valuable insights into the effects of biochar treatment on soil C balance and GGEs during cabbage cultivation in the fall.

Discussion

Contrary to previous assumptions, our study revealed that application of biochar, an organic fertilizer, did not significantly increase Chinese cabbage production yields, contrasting with previous findings [40]. This discrepancy may arise from varying effectiveness of biochar, influenced by specific regional and crop conditions, as well as different research settings. Although biochar is recognized for enhancing soil fertility, particularly in less fertile soils [41], its efficacy relies on several factors, including origin, properties [42,43], and interactions among soil characteristics, plant responses to environment, biochar–soil dynamics, and nutrient absorption [44,45].

The influence of biochar on crop development varies depending on several key factors that include biochar's specific nutritional content, its water and nutrient retention capacities, and its effectiveness in mitigating moisture stress in different soil types [46,47]. However, these benefits may vary based on the biochar's feedstock, pyrolysis temperature [48,49], and particle size, with each factor having a substantial impact on soil properties.

The role of biochar in enhancing soil's biological environment is well-recognized, especially for its alkaline pH and soil-aggregating capacity [44]. Although previous research has largely focused on its impact on physicochemical properties of soil, including fertility and quality improvement, biochar's impact on soil biology and its interactions with microorganisms and soil fauna, is increasingly garnering attention. The potential application of biochar in sustainable agriculture and climate management is emphasized by its ability to improve soil quality and fertility, serving as a soil amendment, as well as its carbon sequestration potential [50,51]. Representing a persistent carbon source in soil, biochar can effectively mitigate climate change by capturing atmospheric CO_2, thereby potentially enhancing soil fertility [52]. For example, the conversion of crop residue into biochar in China can sequester over 920 kg of CO_2 equivalent per ton, highlighting its importance in long-term storage of carbon [53,54].

Our analysis of GGEs aligns with the findings of Chun et al. [40], who revealed a reduction in N_2O emissions following biochar treatment compared with control group. Additionally, a consistent relationship between seasonal temperature and N_2O emissions was observed. These findings suggest that biochar can play an integral role in reducing soil GGEs despite not significantly affecting the yield of Chinese cabbage. Further previous research has confirmed that biochar used as a soil amendment effectively lowers soil-to-atmosphere GGEs [52,55].

Our study also revealed an increase in soil carbon storage during the autumn Chinese cabbage growing season with biochar application. The rise in soil carbon was directly proportional to the amount of biochar applied, indicating a positive effect on soil carbon balance [56]. This is consistent with the findings of Shi et al. [57], highlighting the importance of soil carbon balance and GGE assessments following biochar treatment. We observed a marked increase in soil carbon stocks with higher biochar inputs, indicating the potential for carbon capture. These findings improve our understanding of the role of biochar role in soil carbon storage promotion and GGE reduction in agricultural systems. Biochar–soil amendments have exhibited the ability to enhance SOC, TN, and C:N ratio. Furthermore, a 3-year study performed by Major et al. [58] showed significant increases in maize grain yield and soil nutrient improvements with biochar application at 20 Mg ha^{-1}.

In summary, the present study offers valuable insights into the impact of biochar application on soil carbon balance and GGEs during Chinese cabbage's autumn cultivation period. Our findings underscore the potential of biochar as an amendment in infertile soils, emphasizing its ability to enhance soil quality and reduce GGEs while contributing to sustainable agricultural practices. Particularly, this study highlights biochar's effectiveness in enriching SOC through the NECB method as well as its contribution to the soil carbon pool. Moreover, this research underscores the essential requirement for deeper understanding of biochar's physicochemical properties and its interactions with various soil types and crop systems. Such knowledge will facilitate maximization of biochar's benefits in agriculture and climate change mitigation.

Abbreviations

GGEs	Greenhouse gas emissions
GWP	Global warming potential
GHGI	Greenhouse gas intensity
SOC	Soil organic carbon
TC	Total carbon
TN	Total nitrogen
TLUD	Top lit up draft
NECB	Net ecosystem carbon budget
N_2O	Nitrous oxide
CO_2	Carbon dioxide

Acknowledgements
This work was supported by the "Cooperative Research Program for Agriculture Science and Technology Development (RS-2021-RD009776)" Rural Development Administration, Republic of Korea.

Author contributions
DGP wrote the manuscript and performed the analysis. DGP and EBJ carried out the experiments and performed analysis. JML, HCJ, and HSL contributed to the interpretation of results. HRP verified the analytical methods. SIL and TKO conceived the idea, revised the manuscript, and supervised the findings of this work. All authors have read and agreed to the published version of this manuscript.

Funding
This work was supported by the "Cooperative Research Program for Agriculture Science and Technology Development (RS-2021-RD009776)" Rural Development Administration, Republic of Korea.

Availability of data and materials
All data generated or analyzed during this study is included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 9 November 2023 Accepted: 1 May 2024

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