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Evaluation of agricultural potential of chicken manure biochar: growth and nitrogen use efficiency of kimchi cabbage and N_2O emissions of upland soil

Ikhyeong Lee[1], Han-Na Cho[1], Chang-Gon Lee[1], Ji-Min Song[1] and Se-Won Kang[1,2*]

Abstract
This study investigated the effects of chicken manure biochar (CMBC), produced via co-pyrolysis of chicken manure and woody biomass (80:20 w/w) at 400℃, on the growth, nitrogen use efficiency, and nitrous oxide (N_2O) emissions of kimchi cabbage (*Brassica rapa ssp. pekinensis*) in upland soil. The experiment compared a control group, inorganic fertilizer (IF), and three CMBC application rates (3, 5, and 7 t ha^{-1}, referred to as CMBC3, CMBC5, and CMBC7, respectively). Post-harvest soil analysis revealed that CMBC application increased soil pH, organic matter, available phosphate, and cation exchange capacity (CEC) compared with the control and IF treatments, with these effects showing a dose-dependent pattern. While the IF treatment yielded the highest fresh weight (1,453 g $plant^{-1}$), CMBC7 showed significant growth improvement (1,244 g $plant^{-1}$) and achieved the highest head height (23.2 cm $plant^{-1}$). Notably, CMBC7 demonstrated superior nitrogen dynamics, reaching the highest agronomic efficiency (AE_N: 8.88 kg N ha^{-1}) and apparent recovery fraction (ARF_N: 26.0%), both of which surpassed the IF treatment. Furthermore, CMBC application significantly mitigated N_2O emissions by 59.2% to 72.1% compared to the IF treatment. These results suggest that applying CMBC at 7 t ha^{-1} is an effective strategy for enhancing soil fertility and nitrogen use efficiency while simultaneously reducing greenhouse gas emissions in intensive vegetable production systems.

Keywords Agronomic efficiency of nitrogen, Apparent recovery fraction of nitrogen, Chicken manure biochar

Introduction

Livestock manure is an agricultural by-product that continues to increase with the expansion of the livestock industry [1, 2]. Proper treatment and recycling are required to minimize environmental burden and maximize resource value. Notably, poultry manure tends to have higher concentrations of nitrogen and potassium, as well as a higher total nutrient content compared with other livestock manures. Morvan et al. [3] presented a dataset comparing the chemical composition of cattle, pig, and poultry manures, in which poultry manure generally showed higher total nitrogen (N), phosphorus

*Correspondence:
Se-Won Kang
kangsw@scnu.ac.kr
[1]Department of Agricultural Chemistry, Sunchon National University, Suncheon 57922, Republic of Korea
[2]Department of Agricultural Life Sciences, Sunchon National University, Suncheon 57922, Republic of Korea

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(P), and potassium (K) contents. This implies that poultry manure provides an agronomically superior nutrient source compared with other livestock manures.

To date, livestock manures, including poultry manure, have primarily been treated and recycled through composting or liquid fertilization [4, 5]. Although these methods can improve soil fertility, provide nutrients, and minimize the risk of pathogen and weed spread [6, 7], the composting process can release greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O), which may negatively impact the environment [8]. In addition, long-term application of compost to agricultural soils can lead to nutrient imbalances, including the accumulation of nitrogen and phosphorus [9, 10].

Biochar has recently attracted attention as a promising treatment method for livestock manure. Biochar is a carbonaceous material produced by pyrolyzing organic byproducts under anaerobic or oxygen-limited conditions [11–13]. Biochar, with its porous structure and large specific surface area, helps improve the soil's physicochemical properties, where the pH ameliorates, the electrical conductivity (EC) increases, and the cation exchange capacity (CEC) enhances when biochar is applied to the soil. Moreover, because of its slow decomposition rate, it can sequester carbon in the soil for long periods, rendering it an effective carbon storage means for climate change mitigation [14, 15]. Owing to these characteristics, the broad possibilities for agricultural and environmental applications of biochar, such as soil amendment, organic fertilizers, and pollutant adsorbents, have been suggested [16–18].

In particular, biochar derived from poultry manure is rich in agronomic components, allowing it to directly improve soil fertility beyond merely acting as a carbon storage medium. Previous studies have reported that poultry manure biochar increases the available phosphate content of the soil and improves the availability of trace elements, promoting early crop growth. Poultry manure biochar also enhances soil microbial and enzyme activities, contributing to soil ecosystem improvement and maintenance of agricultural productivity [19–21]. However, excessive biochar application may increase soil salinity and inhibit crop growth, particularly in the case of chicken manure, which contains relatively high salt levels [22]. Despite its potential, research on chicken manure–derived biochar remains limited, warranting further investigation into its effectiveness for resource recovery.

Hence, this study aimed to evaluate the effects of chicken manure biochar (CMBC), produced by co-pyrolysis with woody biomass, on the growth characteristics of kimchi cabbage and the physicochemical properties of upland soil. We hypothesized that CMBC application would enhance crop growth and improve soil physicochemical properties. Furthermore, this study aimed to assess the potential of CMBC as a sustainable management strategy for recycling livestock manure.

Materials and methods

Raw materials

The chemical properties of the materials used in this study are shown in Table S1. The organic matter content of the chicken manure was 60.1%, and the N, P, and K contents were 1.65, 2.68, and 2.54%, respectively. Meanwhile, peach pruning residues had a higher organic matter content (80.5%) than chicken manure but lower nitrogen (0.73%), phosphorus (0.31%), and potassium (0.24%) contents. Peach pruning residues were selected as the biomass source because they are readily available agricultural by-products generated from orchard management in the study region. In addition, such pruning residues are representative lignocellulosic materials widely produced in orchard systems, making them suitable for biochar production. A mixing ratio of 20% woody biomass was selected based on regulatory limits and preliminary considerations, taking into account the variability in the salinity of raw chicken manure while maximizing its utilization as the primary feedstock [23]. Biochar was produced by completely drying the chicken manure and orchard pruning residues, followed by mixing at a ratio of 80:20 (w/w). The mixture was pyrolyzed at 400℃ for 2 h under anaerobic conditions. The characteristics of the chicken manure biochar are presented in Table S2.

Experimental site and soil properties

This study was conducted in an upland experimental field at the Sunchon National University, Suncheon, Jeollanam-do, Republic of Korea. The soil used was upland soil, and its physicochemical properties including bulk density, porosity, pH, electrical conductivity (EC), organic matter (OM), total nitrogen (TN), available phosphate (Avail. P_2O_5), and exchangeable cations (K^+, Ca^{2+}, and Mg^{2+}), were investigated, as shown in Table 1.

Soil analysis was performed according to the standard methods described by NIAST (2000) [24]. The bulk density and porosity were measured using the core method, and the pH and EC were measured after mixing the soil with distilled water at a ratio of 1:5, followed by shaking for 30 min. The OM, TN, and Avail. P_2O_5 were analyzed using the Tyurin, Kjeldahl, and Lancaster methods, respectively. The exchangeable cations were extracted using 1 N-NH_4OAc solution and then analyzed.

Experimental conditions and sampling

The experiment was conducted from March 27 to June 5, 2024, in an upland experimental field at Sunchon National University. Chicken manure biochar was

Table 1 Properties of the experimental soils used in this study

Property	Value
pH (1:5H_2O)	5.25±0.07
Electrical conductivity (dS m^{-1})	0.14±0.02
OM (g kg^{-1})	20.4±0.14
TN (g kg^{-1})	1.41±0.25
Avail. P_2O_5 (g kg^{-1})	84.4±11.3
Exchangeable cations	
Ca ($cmol_c$ kg^{-1})	2.89±0.19
K ($cmol_c$ kg^{-1})	0.43±0.03
Mg ($cmol_c$ kg^{-1})	0.88±0.04
Cation exchangeable capacity ($cmol_c$ kg^{-1})	7.64±0.56
Bulk density (Mg m^{-3})	1.29±0.13
Soil porosity (%)	51.4±4.78
Soil texture	Silt loam

applied to 4 m^2 plots (length × width: 2 m × 2 m). During the kimchi cabbage cultivation period, the daily minimum and maximum temperatures ranged from – 2.1℃ to 31℃, and the total precipitation was 227.8 mm (Fig. 1).

There were six treatment conditions, and each treatment was arranged in a randomized complete block design with three replicates, constituting a total of 18 plots. The treatments consisted of a control group (no treatment), inorganic fertilizer treatment (IF) with basal application of 110 kg N, 78 kg P, and 110 kg K ha^{-1} followed by top dressing of 210 kg N and 88 kg K ha^{-1}, and chicken manure biochar treatments with application rates of 3, 5, and 7 t ha^{-1} (CMBC3, CMBC5, and CMBC7, respectively).

Fertilizer and biochar were applied manually, and tillage was performed two weeks before transplantation. The fertilizer application rates were determined based on the crop-specific fertilizer prescription standards published by the Rural Development Administration.

Kimchi cabbage was transplanted on April 3, 2024, and cultivated for approximately 10 weeks until June 5. The planting distance was set at 50 cm, with a planting density of 4 plants m^{-2}. The soil samples were randomly collected from each plot after harvest, and the growth characteristics of the harvested kimchi cabbages were investigated.

Monitoring of N_2O

The N_2O emissions of soil were monitored using the closed chamber method. The chambers were cylindrical structures made of polyvinyl chloride (PVC) with a diameter of 0.3 m and a height of 0.5 m, installed at the center of each plot. Gas samples were collected for 1 h between 2 p.m. and 3 p.m. with the chamber closed, and emissions were calculated based on the rate of increase in the N_2O concentration over time. Sampling was performed once a week and analysis was conducted using gas chromatography (8890 GC System, Agilent, USA). The N_2O flux was calculated using the following equation:

$$F = p \times (V/A) \times (\Delta c/\Delta t) \times (273/T)$$

where F is the N_2O flux, p is the density of N_2O, V is the chamber volume (m^3), A is the chamber area (m^2), $\triangle c/\triangle t$ is the average rate of increase in gas concentration, and T is the value of the average chamber temperature (℃) plus 273.

The total N_2O flux was calculated as follows:

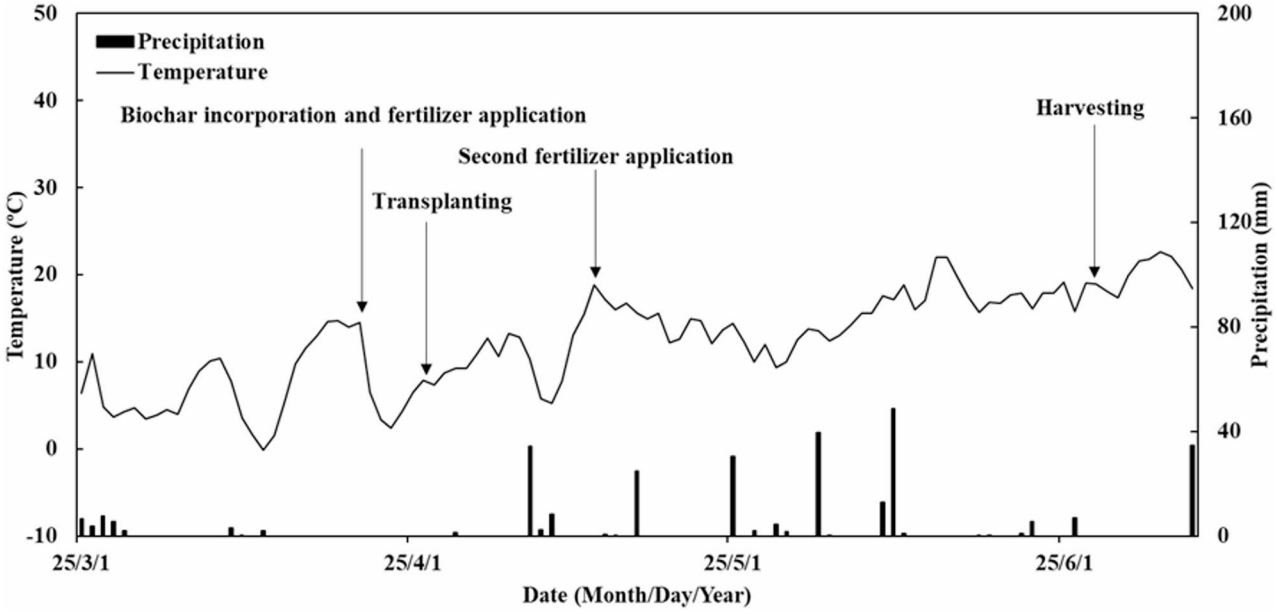


Fig. 1 Daily mean air temperature and precipitation during crop cultivation

Table 2 Changes in the physicochemical properties of the soils applied with chicken manure biochar after harvest

Treatments	pH	EC	OM	T-*N*	Avail. P_2O_5	K	Ca	Mg	CEC	Bulk density	Soil porosity
	1:5 H_2O	dS m^{-1}	g kg^{-1}		mg kg^{-1}	$cmol_c$ kg^{-1}				Mg m^{-3}	%
CN	5.58b*	0.10a	20.0a	1.30a	64.1a	2.53a	0.93b	0.93b	7.54a	1.25a	52.8a
IF	5.45a	0.16b	20.5a	1.55b	85.4b	2.78b	0.88a	0.88a	7.71a	1.26a	52.5a
CMBC3	5.71c	0.18c	27.1b	1.73c	133c	3.58c	1.18c	1.18c	7.97a	1.18a	55.6a
CMBC5	6.05d	0.35e	40.6c	2.03e	159d	4.96e	1.65e	1.54d	8.89b	1.15a	56.7a
CMBC7	6.16e	0.23d	49.7d	1.94d	208e	4.24d	1.54d	1.65e	9.13b	1.06a	60.2a

*Different letters within the same column indicate significant differences, as determined from Duncan's multiple range test, where $p < 0.05$

$$\text{Total } N_2O \text{ flux} = \sum_{i}^{n} (\text{Ri} \times \text{Di})$$

where Ri is the N_2O emission rate in the sampling interval, Di is the number of days in the sampling interval, and n is the total number of sampling intervals.

Analysis of nitrogen use efficiency

The harvested kimchi cabbage samples were dried in an oven at 70℃ for 48 h and then digested using $H_2SO_4 + HClO_4$ for total nitrogen (TN) analysis. The digested samples were filtered and made up to a volume of 100 mL.

The nutrient uptake and nitrogen use efficiency of kimchi cabbage according to the CMBC treatment were calculated as follows:

$$\text{Agronomic efficiency of N (AE_N)} = (Y - Y_0)/\text{Input N}$$

$$\text{Apparent recovery fraction of N (ARF_N)} = (\text{Upt} - \text{Upt}_0)/\text{Input N}$$

where Y is the yield after nitrogen fertilization, and Y_0 is the yield without nitrogen fertilization. Upt is the amount of nitrogen absorbed by the crop after N fertilization, Upt_0 is the nitrogen absorbed without nitrogen fertilization, and Input N is the total amount of nitrogen applied through biochar and fertilizer [25].

Statistical analysis

Statistical analysis was performed using IBM SPSS (version 27) software. The mean values were calculated as the average of three replicates. The significance of the treatments was tested using one-way analysis of variance (ANOVA) and the differences between treatments were compared using Duncan's multiple range test (DMRT).

Results

Evaluation of the soil's properties after CMBC application

The soil's properties were investigated after kimchi cabbage harvesting based on the CMBC application (Table 2). The pH of the soil treated with CMBC ranged from 5.71 to 6.16, and the EC gradually increased from 0.16 dS m^{-1} to 0.35 dS m^{-1} as the application rate increased.

In addition, the available phosphate and organic matter content also increased in proportion to the biochar input. Compared with the IF treatment, which recorded an organic matter content of 20.5 g kg^{-1} and available phosphate of 85.4 mg kg^{-1}, the organic matter increased by up to 142% and the available phosphate increased by up to 144%.

The cation exchange capacity (CEC) of the soil after harvesting also increased with an increase in the CMBC application rate. The CEC value of the soil after IF treatment was 7.71 $cmol_c$ kg^{-1}, whereas it gradually increased with increasing CMBC application rate, recording a value of 7.97, 8.89, and 9.13 $cmol_c$ kg^{-1} for the CMBC3, CMBC5, and CMBC7 treatments, respectively.

Table 3 Growth characteristics of kimchi cabbage affected by chicken manure biochar at different application rates

Treatment	Fresh weight	Head circumference	Head height	Head width
	(g $plant^{-1}$)	(cm $plant^{-1}$)		
CN	530a*	21.9a	17.2a	8.30a
IF	1,453e	38.0d	20.8b	12.5c
CMBC3	904b	31.2b	21.7bc	11.1b
CMBC5	1,016c	32.2bc	22.3 cd	10.9b
CMBC7	1,244d	33.8c	23.2d	11.2b

*Different letters indicate significant differences at $p < 0.05$, according to Duncan's multiple range test. The same letter indicates that there are no significant differences between treatments

Crop growth characteristics after CMBC application

The kimchi cabbage growth characteristics were significantly affected by the application of CMBC and inorganic fertilizer (Table 3). The fresh weights of the kimchi cabbage were 530, 1,453, 904, 1,016, and 1,244 g $plant^{-1}$ for the control (CN), IF, CMBC3, CMBC5, and CMBC7 groups, respectively, where the highest values were obtained for the IF treatment. In addition, the fresh weight increased as the application rate of CMBC increased. In particular, the CMBC7 group showed a 134.7% increase compared with the control group, confirming that the CMBC had a positive effect on kimchi cabbage growth. The head circumference and head width also showed the highest values after IF treatment, with a

value of 20.8 cm and 12.5 cm, respectively. Similar to the fresh weight, head circumference and head width of the kimchi cabbage improved as the CMBC application rate increased. On the other hand, the highest head height (23.2 cm) was recorded after CMBC7 treatment. Overall, kimchi cabbage growth, particularly fresh weight, followed the order: IF > CMBC7 > CMBC5 > CMBC3 > CN.

Nitrogen uptake and nitrogen use efficiency after CMNC application

Significant differences were observed in the dry weight and nitrogen uptake of kimchi cabbage based on the CMBC application rate (Table 4). The shoot dry weight was lowest in the control group (CN), with a value of 60.3 g plant^{-1}, and gradually increased with an increase in the CMBC application rate, peaking at 89.0 g plant^{-1} after the CMBC7 treatment. The root dry weight also increased from 7.68 g plant^{-1} to 10.9 g plant^{-1} with an increase in the CMBC application rate.

The total nitrogen content ranged from 1.84% to 2.52% in the shoots and from 1.44% to 2.04% in the roots, where the highest values were obtained after the IF treatment. Nitrogen uptake was the lowest in the control group (CN), with a value of 5.04 g m^{-2}, and significantly increased to 8.82 g m^{-2} after the IF treatment. For the CMBC groups, the nitrogen uptake increased in the following order: CMBC7 (8.77 g m^{-2}) > CMBC5 (7.03 g m^{-2}) > CMBC3 (6.09 g m^{-2}). In particular, the CMBC7 treatment resulted in a nitrogen uptake level similar to that of the IF treatment.

Nitrogen use efficiency indices also differed among the treatments (Table 5). The AE_N value was lowest in the IF treatment (3.38 kg N ha^{-1}), whereas the CMBC treatments showed higher AE_N values with increasing application rate, reaching the highest value in the CMBC7 treatment (8.88 kg N ha^{-1}). Similarly, the ARF_N value was highest in the CMBC7 treatment (26.0%), which was markedly higher than that of the IF treatment (11.8%). Overall, both AE_N and ARF_N increased as the CMBC application rate increased, indicating improved nitrogen use efficiency following CMBC application.

N_2O emission characteristic during cultivation

The N_2O emission rates and total emissions from the treatments during kimchi cabbage cultivation were also investigated in this study (Fig. 2). The N_2O emissions peaked on the 35th day after the application of inorganic fertilizer and CMBC. The N_2O emission rate after the IF treatment ranged from 12.0 μg m^{-2} h^{-1} to 514 μg m^{-2} h^{-1}, with an average of 139 μg m^{-2} h^{-1}.

Emission rates in the IF treatment were 1.44 ~ 2.56 times higher than those in the CMBC treatments. Cumulative N_2O emissions increased progressively across treatments (CN < CMBC3 < CMBC5 < CMBC7 < IF), ranging from 46.9 to 257 mg m^{-2}.

Table 4 Dry weight and nitrogen content of kimchi cabbage subjected to different treatments

Treatment	Dry weight		T-*N* content		*N* uptake
	Above	Below	Above	Below	
	g plant^{-1}		%		g m^{-2}
CN	60.3a*	7.68a	1.84a	1.44a	5.04a
IF	84.9bc	10.2b	2.52c	2.04c	8.82c
CMBC3	66.1a	8.12a	2.02a	1.71ab	6.09a
CMBC5	78.6b	10.0b	2.00a	1.83bc	7.03b
CMBC7	89.0c	10.9b	2.25b	1.71ab	8.77c

*Different letters indicate significant differences at $p < 0.05$, according to Duncan's multiple range test. The same letters indicate that there are no significant differences between treatments

Table 5 Nitrogen use efficiency in production of kimchi cabbage, which is affected by chicken manure biochar

Treatment	Input *N*	AE_N*	ARF *N***
	kg *N* ha^{-1}		%
IF	320	3.38a	11.8a
CMBC3	61.5	4.04a	16.8ab
CMBC5	102.5	8.02b	19.4ab
CMBC7	143.5	8.88b	26.0b

*AE_N: Agronomic efficiency of nitrogen (kg yield increase per kg input of nitrogen). **ARF_N: Apparent recovery fraction of nitrogen (kg nitrogen uptake increase per kg input of nitrogen)

Discussion

Soil properties after harvest

In this study, the soil treated with CMBC showed an overall improvement in the major chemical properties, including pH, EC, CEC, Avail. P_2O_5, and OM, compared with the control and IF groups. The biochar exhibited a high pH due to the decomposition and loss of organic matter during pyrolysis, which concentrated the inorganic components [26, 27]. The EC also increased as the concentration of soluble inorganic salts, such as K^+, Na^+, Ca^{2+}, and Mg^{2+}, increased [14]. However, all EC values remained below 0.4 dS m^{-1}, which is substantially lower than the salinity threshold (1 ~ 2.5 dS m^{-1}) reported for most vegetable crops [28]. Therefore, the increase in EC did not induce salinity stress and was unlikely to negatively affect kimchi cabbage growth under the conditions of this study. In addition, the porous structure and surface negative charge of biochar increased the soil CEC and improved nutrient retention [29, 30].

Because chicken manure used as a raw material is rich in agronomic components, such as nitrogen, phosphorus, and potassium [3], CMBC acts as a source of essential nutrients in the soil and contributes to the overall improvement of fertility. Obayomi et al. [31] reported that dairy manure biochar enhances soil nitrogen and phosphorus contents and improves soil fertility, microbial diversity, and function. Zhang et al. [32] also stated

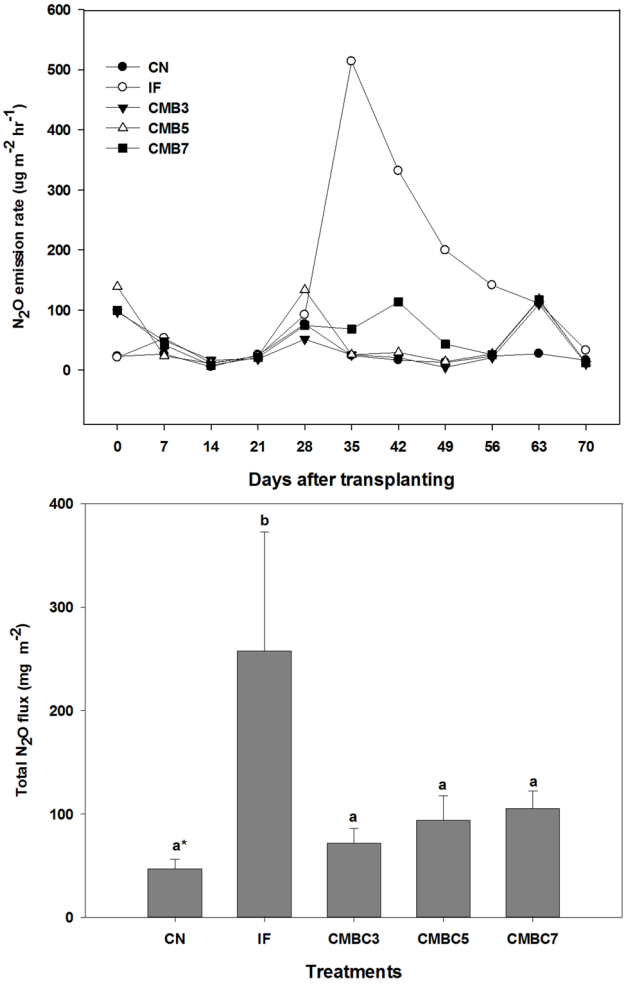


Fig. 2 Changes in N_2O emission rate and total N_2O flux during kimchi cabbage cultivation. Different letters indicate significant differences between treatments at a significance level of 5%. The error bars represent the standard deviations ($n = 3$)

that the combined use of organic fertilizer and biochar significantly increases soil organic matter, total nitrogen, total phosphorus, and total potassium contents. Recent studies have confirmed that biochar significantly increases soil organic matter and is effective in maintaining its stability over a long period [33, 34]. Therefore, CMBC application appeared to contribute to soil organic matter accumulation by incorporating stable carbon structures and residual organic matter.

Kimchi cabbage growth characteristics

The kimchi cabbage growth characteristics after CMBC application were distinctly improved compared with those of the control group. In particular, the CMBC7 treatment increased the fresh weight, plant height, head circumference, and head width of the kimchi cabbage. However, the overall growth of the kimchi cabbage was most superior after the IF treatment, which was attributed to the immediate supply of available nitrogen, phosphorus, and potassium, leading to rapid early growth and fresh weight formation [35]. Nevertheless, the CMBC treatment also significantly improved the kimchi cabbage growth characteristics as the application rate increased, which is likely because the CMBC improves the physicochemical properties of the soil and enhances nutrient availability. Indeed, biochar application has been reported to positively affect crop growth by increasing the soil's CEC, improving water retention, and enhancing microbial activity [36, 37]. Meanwhile, Joardar et al. [38] reported that when poultry litter biochar was applied at a level of 1 ~ 3% by soil weight, the plant height and fresh weight of water spinach (*Ipomoea aquatica*) increased by up to 32.4 and 200%, respectively, compared with the control group, with the best growth observed after the 3% treatment. Furthermore, the poultry litter biochar treatment improved the plant height and fresh weight by 18.2 and 33.7%, respectively, compared with the equivalent poultry litter treatment, emphasizing that poultry litter biochar was a more effective organic amendment than simple poultry litter application. The results of our study are consistent with these findings, which support the interpretation that the growth enhancement effect of the CMBC is due to soil amelioration and improved nutrient availability.

Nitrogen use efficiency

The increase in nitrogen uptake of kimchi cabbage after CMBC application is attributed to the improved retention capacity and increased CEC of the soil [39, 40]. Furthermore, it has been reported that the porous structure and high specific surface area of biochar promote the adsorption of ammonium (NH_4^+) and nitrate (NO_3^-), reduce nitrogen leaching and volatilization losses, and increase the amount of nitrogen available for plant uptake [41–43].

In this study, the nitrogen uptake of kimchi cabbage after the CMBC5 and CMBC7 treatments increased by approximately 1.21 ~ 1.75 times compared with that of the control group. In particular, the CMBC7 treatment resulted in a nitrogen uptake level similar to that of the IF treatment. This implies that applying CMBC at a level 5 ~ 7 t ha^{-1} provides sufficient nitrogen supply for kimchi cabbage growth.

Meanwhile, the nitrogen use efficiency showed distinct differences between the treatments (Table 5). The AE_N for the IF treatment was the lowest (3.38 kg N ha^{-1}) whereas for the CMBC treatments, the AE_N gradually increased with the application rate, reaching 8.88 kg N ha^{-1} for the CMBC7 treatment, which was approximately 2.6 times higher than that of the IF treatment. Moreover, the ARF_N was 26.0% for the CMBC7 treatment, which was a significant increase compared with that for the IF

treatment (11.8%). Similar results have been reported in previous studies. Ghorbani et al. [44] reported that the combined use of biochar and nitrogen fertilizer in wheat cultivation significantly reduced nitrate leaching and improved nitrogen use efficiency (NUE) by more than two-fold compared with the nitrogen fertilizer application alone. Through meta-analysis, Liu et al. [45] stated that biochar applications improve rice NUE by an average of 12%, and cultivating rice using livestock manure biochar can improve NUE by up to 38%. These findings align with the effects of CMBC investigated in this study, suggesting that livestock manure biochar is highly effective in suppressing nitrogen loss and improving nitrogen use efficiency.

N_2O emissions

N_2O generated in agricultural soils is a major greenhouse gas associated with nitrogen fertilizer application, with a global warming potential approximately 298 times higher than that of CO_2 [46]. Nitrogen fertilization can enhance N_2O production through nitrification and denitrification processes in soil, and this effect varies depending on fertilizer type, soil conditions, and microbial activity [47–49]. Biochar has been reported to influence N_2O emissions by affecting nitrogen transformation processes in soil [50, 51]. Several studies have shown that biochar application can reduce N_2O emissions from agricultural systems [52, 53].

In particular, chicken manure–derived biochar has also been shown to reduce N_2O emissions. For example, Alami et al. [54] reported that the application of chicken manure biochar in subtropical vegetable fields significantly reduced cumulative N_2O emissions by 35.9 ~ 65.7% compared to chemical fertilizer and raw manure treatments.

In this study, CMBC application was associated with significantly lower N_2O emissions compared with the IF treatment. The emission rates in the IF treatment were 1.44 ~ 2.56 times higher than those in the CMBC treatments, and total emissions showed an increasing trend in the order of CN < CMBC3 < CMBC5 < CMBC7 < IF. These results suggest that CMBC application may reduce N_2O emissions relative to conventional inorganic fertilization.

The observed reduction in N_2O emissions in the CMBC treatments may be related to changes in soil properties and nitrogen availability following biochar application [55–57]. Previous studies have suggested that biochar can influence nitrogen transformation processes [53–55]. However, these mechanisms were not directly evaluated in the present study. Therefore, they should be considered as possible explanations rather than confirmed processes.

Overall, the results of this study are consistent with previous findings and suggest that CMBC application has potential to mitigate N_2O emissions in agricultural systems.

In this study, chicken manure biochar (CMBC) was produced by co-pyrolysis with woody biomass and applied to upland soil to evaluate its effects on soil physicochemical properties, kimchi cabbage growth, nitrogen use efficiency, and N_2O emissions. Overall, CMBC application improved soil properties, including pH, EC, CEC, available phosphate, and organic matter content, compared with the control and IF treatments. The CMBC7 treatment (7 t ha^{-1}) showed crop growth and nitrogen uptake comparable to those of the IF treatment, suggesting that this application rate can provide a fertilization effect. In addition, CMBC treatments were associated with lower N_2O emissions than the nitrogen fertilizer treatment. These effects may be related to changes in soil properties and nitrogen dynamics following CMBC application; however, the underlying mechanisms were not directly evaluated in this study. Overall, CMBC application improved soil properties and reduced N_2O emissions, while supporting crop growth under the conditions of this study.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13765-026-01103-3.

Supplementary Material 1.

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Author contributions

Lee, I. designed and conducted the experiment and participated in sample analysis and data interpretation. Kang, S.W. conceived and supervised the overall study, designed and conducted the experiment, wrote the original draft, and revised and finalized the manuscript. Cho, H.N., Lee, C,G., and Song J.M. performed sample analysis, conducted N_2O measurements, and contributed to data interpretation. All authors participated in the preparation of the manuscript, read, and approved the final version.

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Data availability

All data is available in the main text.

Declarations

Competing interests

The authors declare that they have no competing interests.

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