Nitrogen Cycling

Review

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Biochar amendments mitigate trace gas emissions in organic waste composting: a meta-analysis

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Abstract

Composting is valuable for recycling resources and environmental protection, but it emits greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and ammonia (NH_3). Biochar can reduce greenhouse gases and NH_3 emissions, but its effects and mechanisms in composting are debated. We conducted a global meta-analysis of 123 published studies (251 paired comparisons and 1,184 observations) to identify the dominant factors and underlying mechanisms driving CO_2, CH_4, N_2O, and NH_3 emissions during biochar-amended composting. Biochar amendment significantly reduced emissions of CH_4 (53.7%), N_2O (49.8%), and NH_3 (35.9%), but had no significant effect on CO_2 emissions. The application rate of biochar was the key parameter affecting CH_4, N_2O, and NH_3 emissions, demonstrating a dose effect on mitigation efficacy. Biochar decreased CH_4, N_2O, and NH_3 emissions under most parameters, except acidic conditions. Although a high carbon:nitrogen ratio (> 30) and a low moisture content (< 55%) increased CO_2 emissions, high electric conductivity (> 4 mS/cm) impaired the mitigation effects of biochar on all target gases. To achieve optimal composting performance to mitigate trace gases, the following parameters are recommended: a carbon : nitrogen ratio of 20–30, a moisture content of 55%–65%, pH 7.5–8.5, an electric conductivity of < 4 mS/cm, and a biochar dosage of 10%–20% (w/w, dry weight).

Keywords: Greenhouse gases, Ammonia, Meta-analysis, Composting, Biochar, Manure

Highlights

- Biochar altered CH_4 (−53.7%), N_2O (−49.8%), NH_3 (−35.9%), but not CO_2 via meta-analysis.
- The application rate of biochar exhibited a dose effect on CH_4, N_2O, NH_3 mitigation efficacy.
- Four gas mitigation was derived of 123 studies with 1,184 observations for composting.

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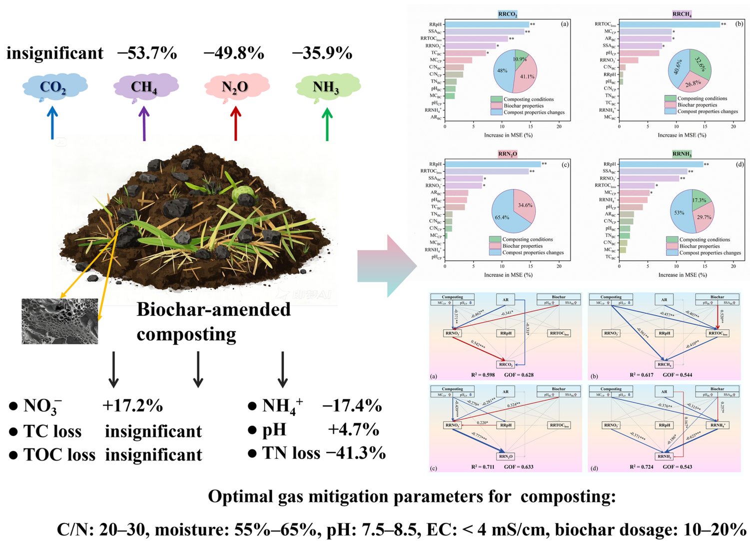
Graphical abstract



Introduction

Composting, an organic solid waste management strategy inherited from agricultural history, has garnered significant attention due to its substantial potential in recycling resources and environmental protection[1,2]. During composting, organic waste is transformed into sanitized, stable, and nutrient-rich humus through microbial metabolism under suitable humidity, temperature, and aeration[3,4]. However, greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and reactive nitrogen (Nr) gases such as ammonia (NH_3) and N_2O will also be emitted during the composting process[5−7]. These gas emissions are inevitable products of carbon and nitrogen's transformation during composting. CO_2 is mainly released by aerobic metabolism, while CH_4 is more easily generated by methanogenic bacteria under anaerobic conditions[8,9]. NH_3 produced by the conversion of ammonium (NH_4^+) will volatilize rapidly and exacerbate nitrogen losses[10,11]. N_2O is primarily produced by autotrophic nitrification, heterotrophic nitrification, and bacterial and fungal denitrification[12−14]. These carbon and nitrogen losses as gas emissions further decrease product quality and amplify the environmental risks[1,15].

Practices for optimizing the composting conditions (e.g., the C/N ratio, moisture content, pH), supplying auxiliary measures (e.g., films and electromagnetic fields), or adding exogenous materials (e.g., biochar, zeolite, and bentonite) have been employed to mitigate GHGs and NH_3 emissions during composting[9,16−19]. Among these technologies, biochar amendment is regarded as a promising avenue due to its exceptional physicochemical properties, such as high surface area, porous structure, and abundant surface functional groups[20−24]. It has been proved that biochar may mitigate gas emissions by regulating the microbial community and adsorbing gas on its surface[25−27]. Specifically, biochar possesses a large surface area anda porous structure that optimizes the distribution of oxygen, enhances aeration, and suppresses the activity of methanogenic and denitrifying bacteria[28−30]. Biochar with abundant surface functional groups can inhibit NH_3 volatilization and reduce GHG emissions via adsorption and redox reactions[30−32]. Notably, other properties of biochar (e.g., application rate, pH, and particle size) also significantly impact the efficiency of mitigation, demonstrating the multifaceted positive effects of biochar on composting processes[11,33−35].

Despite extensive research on the mitigation efficiency of biochar-amended composting, the findings still remain inconsistent or contradictory due to the isolation of many experiments. For example, some studies reported that biochar increased CO_2 emissions by approximately 20%–80% compared with the control[22,36,37]. This phenomenon can be attributed to the more appropriate habitat provided by biochar, which enhanced the degradation of organic matter during composting[38,39]. In contrast, biochar may reduce CO_2 emissions through the adsorption of CO_2 and the sequestration of exogenous organic matter[40]. So what is the overall effect of biochar amendment on CO_2 emissions, and what is the key mechanism? Similarly, a high biochar application rate (> 8%) was reported to minimize CH_4 emissions because biochar can avoid anaerobic pockets and facilitate the diffusion of oxygen[41]. However, a 5.0% application rate of biochar may be the optimal dosage, although a high biochar application rate (20%) increased the formation of compost aggregates and enhanced the anaerobic zone[29]. The mitigating effect of biochar on N_2O emissions is also controversial. Biochar can reduce N_2O emissions by enhancing the expression of the *nosZ* gene but also may increase N_2O emissions by promoting the nitrification process[42,43]. These results indicate that the mitigation efficiency, influencing factors, and key mechanisms of biochar are still not clear. Therefore, a more comprehensive analysis of these issues is necessary to achieve the optimization of gas abatement in composting.

Here, a meta-analysis including 123 studies (Supplementary File 1) was conducted to evaluate the existing data on biochar-amended composting. The objectives of this meta-analysis were: (1) to assess the overall impacts of biochar on compost's properties and gas emissions; (2) to identify the dominant factors mitigating CO_2, CH_4, N_2O, and NH_3 emissions; and (3) to explore the optimal strategies for minimizing gas emissions. The results can offer practical strategies to decrease the gas emissions and environmental risk of composting.

Materials and methods

Literature search

As illustrated in Supplementary Fig. S1, peer-reviewed literature was systematically retrieved from two authoritative databases: Web of

Science (WoS) and the China National Knowledge Infrastructure (CNKI) (2000–2024). The search combined gas terms (CO_2, CH_4, N_2O, NH_3, and GHGs) with composting terms (compost, biochar) to identify studies on composting systems. Following the initial retrieval, we deduplicated and screened articles for relevance to our study objectives. The eligibility criteria required: (1) a biochar vs. control comparison, (2) no co-additives, (3) ≥ 1 target gas emission reported, and (4) valid measurement methods. This identified 123 studies (WOS: 120; CNKI: 3) with 251 paired comparison and 1,184 observations (Supplementary File 1). The global distribution of the selected studies is presented in Fig. 1.

Data extraction and classification

Emission data were extracted from tables and figures in the selected studies. Graphic data were extracted via an online website (https://automeris.io). Cumulative emission data on CO_2, CH_4, N_2O, and NH_3 were extracted and expressed as a percentage (%) of the initial total C or N[10]. When cumulative emissions were not reported, we calculated them by summing the extracted flux measurements. For studies without standard deviations (SDs), these were calculated from the standard error (SE) by using the formula $SD = SE \times \sqrt{n}$, where n is the sample size; 10.0% of the mean was used as a substitute in studies lacking SD or SE values[44].

We compiled comprehensive datasets of biochar properties (BC), namely total carbon (TC), total nitrogen (TN), carbon:nitrogen ratio (C/N), moisture content (MC), pH, electric conductivity (EC), specific surface area (SSA), particle size (PS), feedstock type (FT), and application rate (AR), and composting characteristics (CP), such as C/N, MC, initial pH, EC, reactor volume (RV), ventilation instrument (VI), and FT. The ammonium (NH_4^+) and nitrate (NO_3^-) contents of compost were calculated as average values because of their dynamic changes during composting. The pH, total carbon loss (TC_{loss}), total nitrogen loss (TN_{loss}), and total organic carbon loss (TOC_{loss}) were extracted from the final stage of the composting process. All variables are listed in Table 1.

Data analysis

The natural logarithm response ratio (RR) method was used to quantitatively analyze the CO_2, CH_4, N_2O, and NH_3 gas emissions. The RR was calculated as follows:

$$RR = \ln(\bar{X}_t/\bar{X}_c) = \ln\bar{X}_t - \ln\bar{X}_c \tag{1}$$

where, $\bar{X}_t$ and $\bar{X}_c$ represent the means of the variables under biochar treatment and the control, respectively. The variance (v) of the RR and weighted response ratio ($\overline{RR}$) was calculated as follows:

$$v = \frac{S_t^2}{N_t^2\bar{X}_t^2} + \frac{S_c^2}{N_c^2\bar{X}_c^2} \tag{2}$$

$$w_i = \frac{1}{v_i} \tag{3}$$

$$\overline{RR} = \frac{\sum_{i=1}^{n} w_i RR_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

where, S_t, N_t, S_c, and N_c are the standard deviation and sample size for the biochar treatment and control, respectively; w_i and n are the weighting factor and the number of observations, respectively. To facilitate expression, RR was transformed and expressed as a percentage change:

$$\%Change = (e^{\ln RR} - 1) \times 100 \tag{5}$$

Relative to the control, negative values indicate that the biochar treatment reduced the measured parameters, while positive values denote increases. A 95.0% confidence interval (CI) excluding zero implies statistical significance.

Since some studies contributed multiple repeated effect sizes, we fitted a hierarchical random-effects model using the rma.mv() function from the "metafor" R package. To account for within-study dependence, we included the reference number (Rf) of each study as a moderating factor in the model[45]. To assess the heterogeneity across categorical variable groups, we decomposed the total heterogeneity (Q_T) into between-group (Q_M) and within-group (Q_E) components. A significant between-group heterogeneity (Q_M, $p < 0.05$) indicated meaningful differences among subgroups. We computed Q_M and its associated p-value for each subgroup category (Supplementary Table S1). A subgroup was deemed to be meaningful if it exhibited significant heterogeneity in at least one of the four gas metrics: CO_2, CH_4, N_2O, and NH_3[46]. For robustness, we compared the fail-safe N with the threshold of $5n + 10$ (n = number of cases) whenever Kendall's Tau or Spearman's correlations were statistically significant (Supplementary Table S2). To further investigate the combined effect of the application rate (AR) and composting conditions on the mitigation effects of biochar, a sub-meta-analysis was performed. Finally, we conducted linear regression analyses using the "ggplot2" package in R.

Additionally, other compost properties, including NH_4^+, NO_3^-, pH, TC_{loss}, TN_{loss}, and TOC_{loss} were analyzed in this meta-analysis. However, becasue of insufficient reporting of the SD or SE values in many studies, the RR and $\overline{RR}$ were calculated using an equal-weighting

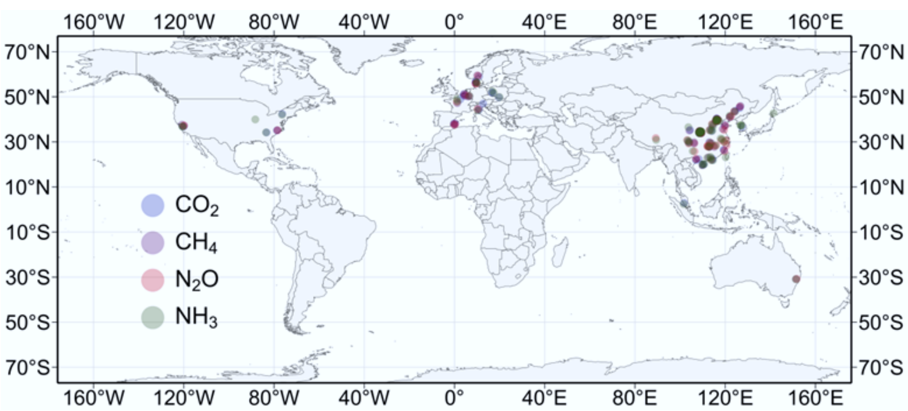


Fig. 1 Global distribution of qualifying studies.

Table 1 The abbreviations and units of all variables in biochar-amended composting systems

Category	Variable	Abbreviation	Unit
Biochar properties	Total carbon	TC_{BC}	g/kg
	Total nitrogen	TN_{BC}	g/kg
	Carbon: nitrogen ratio	C/N_{BC}	–
	Moisture content	MC_{BC}	%, w/w
	pH	pH_{BC}	–
	Electric conductivity	EC_{BC}	mS/cm
	Specific surface area	SSA_{BC}	m^2/g
	Particle size	PS_{BC}	mm
	Feedstock type	FT_{BC}	–
	Application rate	AR	%, w/w (dry weight)
Composting conditions	Carbon:nitrogen ratio	C/N_{CP}	–
	Moisture content	MC_{CP}	%, w/w
	Initial pH	pH_{CP}	–
	Electric conductivity	EC_{CP}	mS/cm
	Reactor volume	RV_{CP}	m^3
	Ventilation instrument	VI_{CP}	–
	Feedstock type	FT_{CP}	–
Compost properties	Average ammonium	NH_4^+	g/kg
	Average nitrate	NO_3^-	g/kg
	Final pH	pH	–
	Total carbon loss	TC_{loss}	%
	Total nitrogen loss	TN_{loss}	%
	Total organic carbon loss	TOC_{loss}	%

approach[10]. These metrics were applied to evaluate changes in compost properties, not for subgroup analysis.

Random Forest models were conducted by using the "randomForest" R package to evaluate the relative importance of explanatory factors in $RRCO_2$, $RRCH_4$, RRN_2O, and $RRNH_3$. The "mice" R package was used to impute missing values, with the resulting dataset restricted to Random Forest analysis and subsequent partial least squares path modeling (PLS-PM)[47,48]. We restricted data imputation to biochar properties and composting conditions, as the variables within each category exhibited strong internal correlations[3, 49].

Using the "plspm" R package, we implemented PLS-PM to determine the primary mechanisms by which biochar mitigates CO_2, CH_4, N_2O, and NH_3 emissions. Only variables demonstrating significant importance in the Random Forest models were included in the PLS-PM analysis. For improved variable interpretation, data standardization was carried out prior to principal component analysis (PCA). PLS-PM performance was assessed through the goodness-of-fit (GOF) index and the R^2 values of target gas emissions.

Results and discussion

The effects of biochar amendment on compost properties

Biochar amendment significantly reduced the NH_4^+ content of compost by 17.4% (95% CI: –22.4% to –12.1%, $p < 0.001$), with the mean NH_4^+ concentration decreasing from 1.94 to 1.59 g/kg (Fig. 2). Biochar amendment significantly increased the NO_3^- content of compost by 17.2% (95% CI: 5.4%–30.3%, $p < 0.01$), with the mean NO_3^- concentration rising from 0.37 to 0.42 g/kg. Adding biochar significantly increased the final pH of compost by 4.7% (95% CI: 1.8%–7.6%, $p < 0.01$), which rose from 7.79 to 8.21. However, adding biochar did not significantly change the total carbon loss during composting (95% CI: –89.2% to 576.1%, $p > 0.05$), as the average total carbon losses between the control and treatment groups were 37.5% and 32.3%, respectively. Similarly, adding biochar did not significantly change the total organic carbon loss during composting (95% CI: –11.6% to 24.7%, $p > 0.05$); the average total organic carbon losses between control and treatment groups were 17.8% and 20.8%, respectively. In contrast, biochar application reduced the total nitrogen loss by 41.3% (95% CI: –53.0% to –26.8%, $p < 0.001$), reducing the mean losses from 27.8% to 20.4%.

The effects of biochar amendment on gas emissions during composting

Overall, biochar amendment significantly reduced emissions of CH_4 (53.7%), N_2O (49.8%), and NH_3 (35.9%), while CO_2 emissions showed a marginal increase (4.9%) that was statistically nonsignificant (Fig. 3). Biochar ARs significantly and differentially influenced gas emissions. CO_2 emissions increased significantly (20.7%) at moderate ARs (5.0%–10.0%, w/w), while both higher (> 10.0% w/w) and lower (< 5.0% w/w) application rates showed no significant effects. For CH_4 emissions, the greatest reduction (–86.1%) occurred at ARs greater than 10.0% (w/w), demonstrating substantially greater mitigation than lower application rates. N_2O emissions displayed contrasting responses: AR < 5.0% (w/w) significantly increased emissions (51.4%), whereas AR > 10.0% (w/w) strongly suppressed them (–93.7%). Moderate application rates (5.0%–10.0% w/w) had no significant impact on N_2O emissions. NH_3 emissions showed maximum mitigation (–60.2%) at AR > 10.0% (w/w), significantly outperforming both the 5.0%–10.0% and < 5.0% ARs.

Apart from the biochar AR, other biochar properties differentially influenced various gas emissions. For CO_2 emissions, PS, MC, EC, and SSA had significant effects, with the largest increase (41.9%) occurring at MC < 4.5%. Most biochar property groups effectively mitigated CH_4 emissions (reductions of 46.8%–73.8%), except for shell as the FT. The strongest CH_4 mitigation (73.8%) was observed with a PS of >5 mm, while pH 9–10 showed more moderate effects (46.8%). N_2O emissions were most effectively reduced (–64.4%) by a PS of 2–5 mm. Other property groups (pH > 10, PS < 2 mm, PS > 5 mm, and shell as the FT) showed nonsignificant mitigation effects despite positive trends. For NH_3, the maximum reduction (50.3%) occurred with a PS of 2–5 mm, whereas MC, EC, and PS exhibited substantial within-group variability.

Compared with the overall effects, AR > 10.0% (w/w) can simultaneously and significantly enhance the mitigation of CH_4, N_2O, and NH_3 emissions, which indicates that the AR was the key factor in CH_4, N_2O, and NH_3 emissions. The significant convex relationships between AR and the response ratios of CH_4, N_2O, and NH_3 also validated this finding (Supplementary Fig. S2), Moreover, the convex relationships further imply a nonlinear dose-dependent effect, in which the mitigation effects initially increase but subsequently decrease. Despite the existence of influences from other biochar properties on gas emissions, these variables do not serve as critical determinants of emission dynamics.

The effects of composting conditions on gas emissions during composting

The meta-analysis revealed that composting conditions strongly influenced gas emissions (Fig. 4). For CO_2 emissions, all composting conditions groups except VI and RV exhibited significant within-group variability, while C/N > 30, MC < 55.0%, pH > 8.5, EC > 4 mS/cm, and sludge as the FT markedly increased CO_2 emissions by 123.2%, 62.4%, 52.4%, 99.2%, and 93.5%, respectively. For CH_4 emissions, sludge as the FT had the highest mitigation effects (74.2%), whereas no significant effects were observed for EC > 4 and pH < 7.5. For N_2O

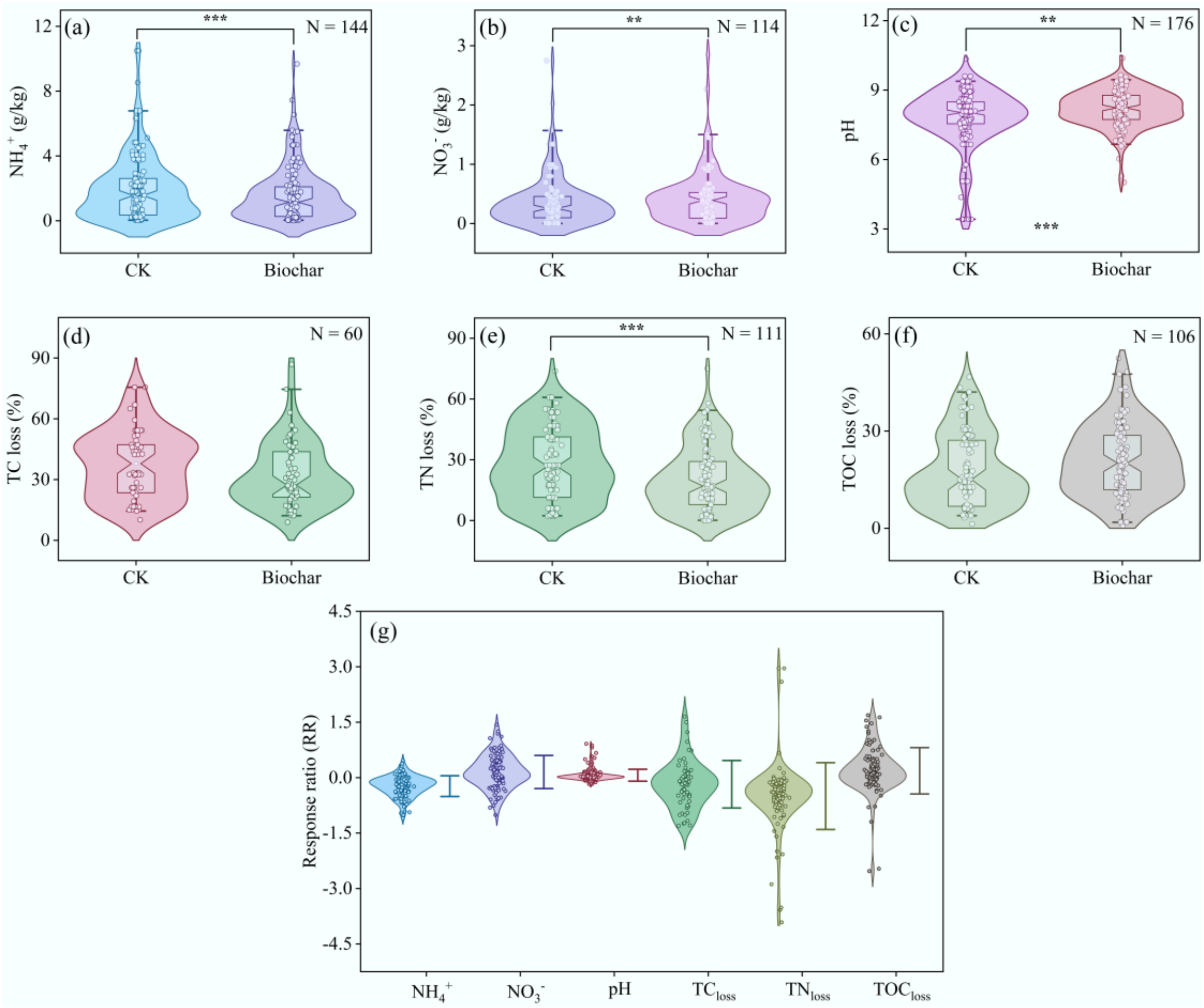


Fig. 2 Violin plots of NH_4^+, NO_3^-, pH, TC loss, TN loss, and TOC loss in the control (CK) and biochar-amended composting systems (**a**)–(**g**). *N* denotes the number of paired samples, with asterisks indicating the statistical significance levels (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$). The response ratios (RR) of NH_4^+, NO_3^-, pH, TC loss, TN loss, and TOC loss are shown in (**f**). The color-coded point markers on the right represent the mean RR values, with the error bars indicating standard deviations.

emissions, most groups of composting conditions demonstrated positive mitigation effects, and the mitigation efficiency ranged from 31.6% in MC 55.0%–65.0% to 78.2% in MC > 65.0%; however, pH < 7.5, EC > 4 mS/cm, RV > 200 m^3, and a turner as the VI showed no significant mitigation effects. For NH_3 emissions, significant emission reduction effects were observed under most composting conditions, although pH < 7.5, EC > 4 mS/cm, and RV > 200 m^3 showed no significant mitigation effects. Compared with the overall effects, the CO_2 emissions can be significantly enhanced by C/N > 30, MC < 55.0%, pH > 8.5, EC > 4 mS/cm, and sludge as the FT, whereas MC > 65.0% markedly decreased N_2O emissions, and C/N > 30 strongly reduced NH_3 emissions. The regression analysis showed that the $RRCO_2$ was negatively correlated with MC (Supplementary Fig. S2). The RRN_2O and $RRNH_3$ exhibited convex and negative relationships with EC, respectively (Supplementary Fig. S2). Additionally, our sub-meta-analysis showed that AR exhibited different effects on $RRCO_2$ under different levels of C/N and MC. Specifically, increasing AR could promote CO_2 emissions under high C/N (>30) and low MC (<55%) (Supplementary Fig. S3). These results indicated that the C/N, MC, pH, EC, and FT of composting conditions are the primary factors affecting gas emissions in biochar-amended compost.

Dominant factors driving CO_2, CH_4, N_2O, and NH_3 emissions during composting

Random Forest analysis was used to predict the relative importance of composting parameters to the response ratios of CO_2, CH_4, N_2O, and NH_3 emissions. The key factors associated with $RRCO_2$ were RRpH, SSA_{BC}, MC_{CP}, $RRTOC_{loss}$, $RRNO_3^-$, and TC_{BC} (Fig. 5). Among the three categorized drivers, changes in compost properties exhibited the strongest response to $RRCO_2$ (48%). $RRTOC_{loss}$, MC_{CP}, AR_{BC}, and SSA_{BC} played a more important role in $RRCH_4$, wheeras changes in compost properties accounted for the largest proportion at 40.6%. RRpH, $RRTOC_{loss}$, SSA_{BC}, and $RRNO_3^-$ were the dominant factors influencing RRN_2O, whereas changes in compost properties contributed the largest proportion at 65.4%. RRpH, SSA_{BC}, $RRNO_3^-$, $RRTOC_{loss}$, and MC_{CP} governed $RRNH_3$, with the largest proportion (53%) provided by changes in compost properties.

Our PLS-PM results explained 59.8%, 61.7%, 71.1%, and 72.4% of the variance in the RR of CO_2 (Fig. 6a), CH_4 (Fig. 6b), N_2O (Fig. 6c), and NH_3 (Fig. 6d) emissions, respectively. According to PLS-PM, AR had a negative effect on $RRCO_2$, whereas composting conditions, AR, and biochar properties all indirectly influenced emissions through $RRNO_3^-$ (Fig. 6a). Composting conditions and $RRTOC_{loss}$ directly

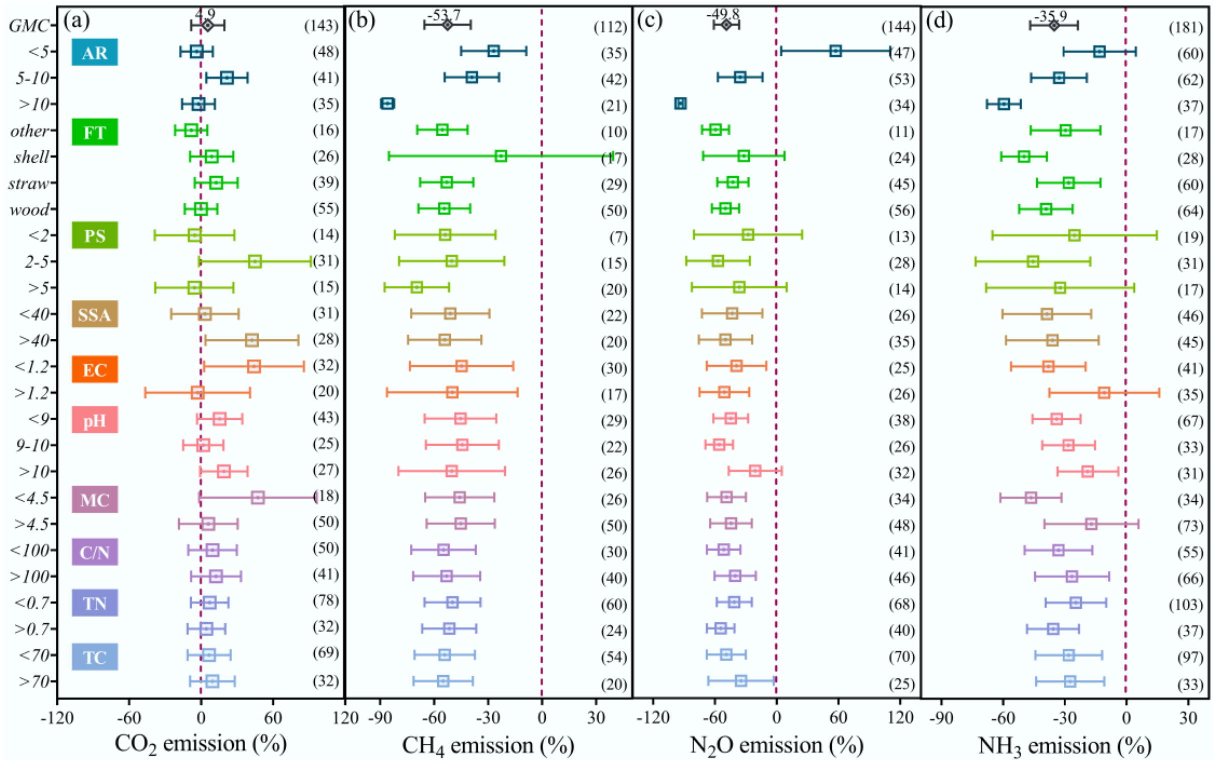


Fig. 3 Effects of biochar properties on CO_2, CH_4, N_2O, and NH_3 emissions during composting (**a**)–(**d**). The center of the small square represents the average value, and the error line represents the ± 95% CIs. The numbers in brackets represent sample sizes. TC, total carbon; TN, total nitrogen; C/N, carbon : nitrogen ratio; MC, moisture content; EC, electric conductivity; SSA, specific surface area; PS, particle size; FT, feedstock type; AR, application rate.

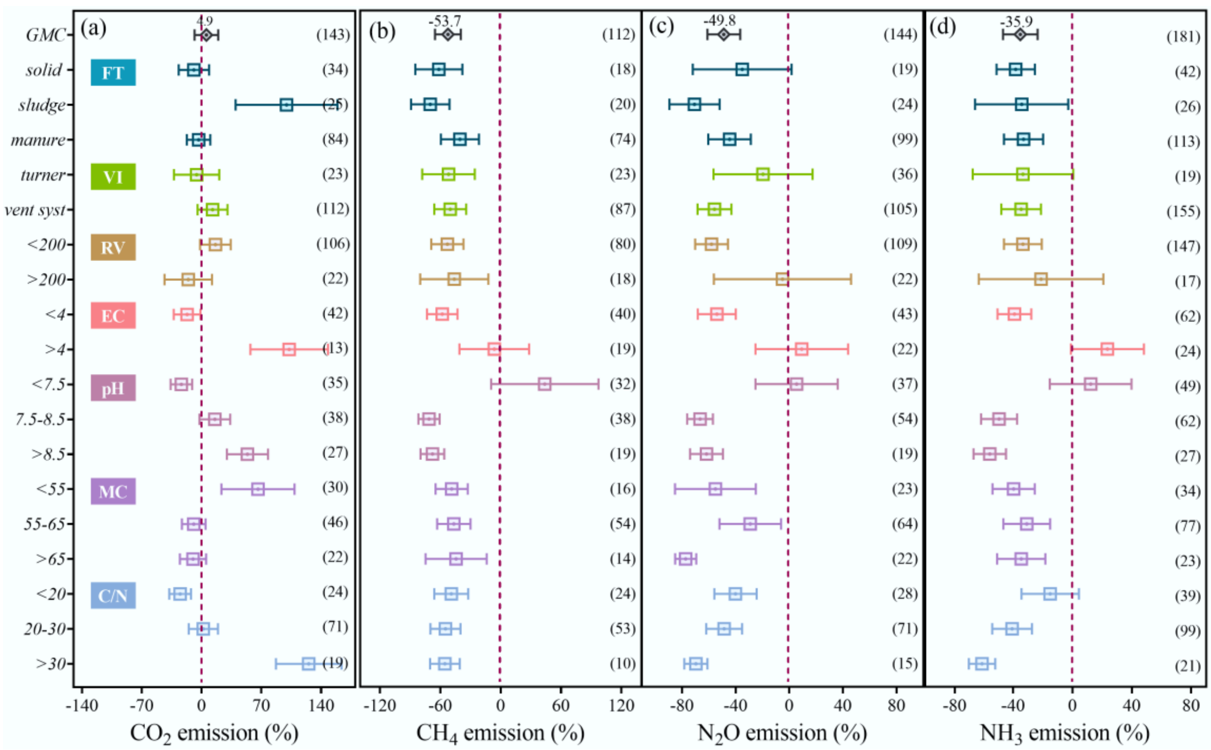


Fig. 4 Effects of composting conditions on CO_2, CH_4, N_2O, and NH_3 emissions during composting (**a**)–(**d**). The center of the small square represents the average value, and the error line represents the ± 95% CIs. The numbers in brackets represent the sample sizes. C/N, carbon : nitrogen ratio; MC, moisture content; pH, initial pH; EC, electric conductivity; RV, reactor volume; VI, ventilation instrument; FT, feedstock type.

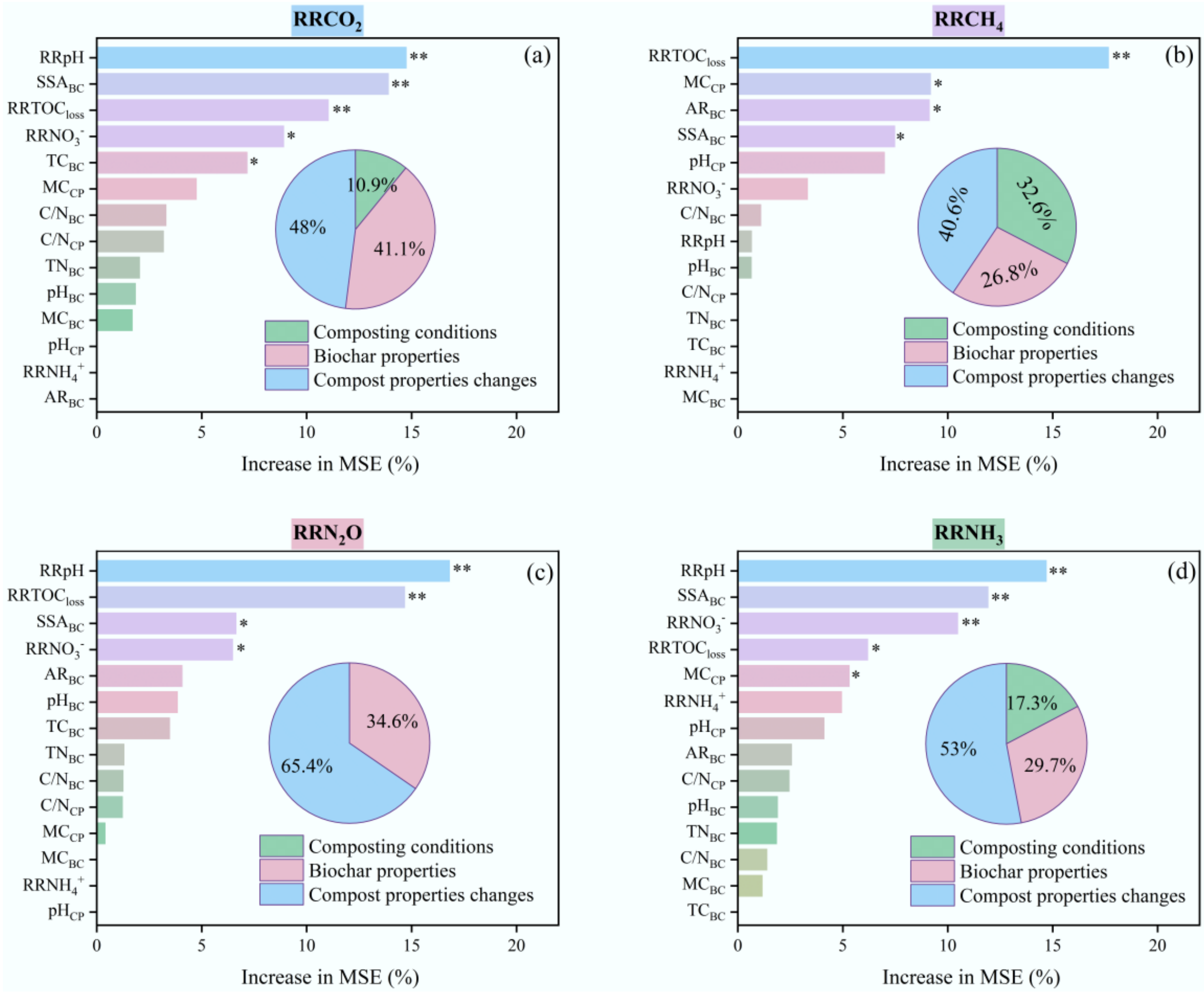


Fig. 5 Random Forest models used to rank the predictive variables of response ratios (RR) of CO_2, CH_4, N_2O, and NH_3 emissions (**a**)–(**d**). The percentage increase in the mean squared error (%IncMSE) represents the importance of the main predictors; negative values of %IncMSE are not shown. Statistical significance levels are denoted by asterisks (* $p < 0.05$ and ** $p < 0.01$). The predictive variables are categorized into three classes, namely composting conditions, biochar properties, and changes in compost properties. Composting conditions include the carbon : nitrogen ratio (C/N), moisture content (MC), and initial pH. Biochar properties include total carbon (TC), total nitrogen (TN), C/N, MC, pH, specific surface area (SSA), and application rate (AR). Changes in compost properties include the RRs of NH_4^+, NO_3^- final pH, and TOC loss.

regulated CH_4 emissions, whereas $RRTOC_{loss}$ is governed by composting conditions, AR, and biochar properties (Fig. 6b). Similarly, composting conditions, AR, and biochar properties indirectly influenced N_2O emissions by controlling RRpH and $RRNO_3^-$ (Fig. 6c). The key factors influencing NH_3 emissions included AR, $RRNO_3^-$, and $RRNH_4^+$, whereas $RRNH_4^+$ predominantly governed NH_3 emissions (Fig. 6d). Above all, $RRNO_3^-$ was the dominant factor driving $RRCO_2$ and RRN_2O, whereas $RRTOC_{loss}$ and $RRNH_4^+$ were the dominant factors driving $RRCH_4$ and $RRNH_3$, respectively, as illustrated in the PLS-PM model (Fig. 6a–d).

Discussion

Biochar facilitates nitrogen conservation, carbon stability, and synergistic mitigation of CH_4, N_2O, and NH_3 during composting

Biochar amendment demonstrated multiple benefits in composting systems by mitigating gas emissions (CH_4, N_2O, and NH_3), conserving nitrogen nutrients, and contributing to carbon stability. Our analysis confirmed that biochar significantly reduced NH_4^+, increased NO_3^-, and elevated pH during composting (Fig. 2), implying that biochar stimulates nitrification[21]. Simultaneously, biochar markedly reduced TN losses, supporting the role of biochar in optimizing nitrogen conservation[50]. The stable TC and TOC levels suggest that biochar did not increase carbon mineralization losses. Additionally, although biochar did not significantly alter TC or TOC loss, its recalcitrant structure could contribute to carbon stocks and stabilization in the composting system. Importantly, our results demonstrated that biochar could significantly reduce CH_4, N_2O, and NH_3 emissions, with no significant influence on CO_2 mitigation (Fig. 3). Compared with other mitigation methods (e.g., adding zeolite, adding clay, and adjusting C/N), biochar demonstrates superiority in reducing multiple gases[9,10, 16]. This multi-gas efficacy, validated by our expanded sample sizes, underscores the broad applicability of biochar for the mitigation of targeted gases in composting systems.

Biochar dose controls CH_4, N_2O, and NH_3 emissions during composting

Our results indicated that biochar amendment significantly reduced CH_4, N_2O, and NH_3 emissions, with the efficiency of mitigation strongly

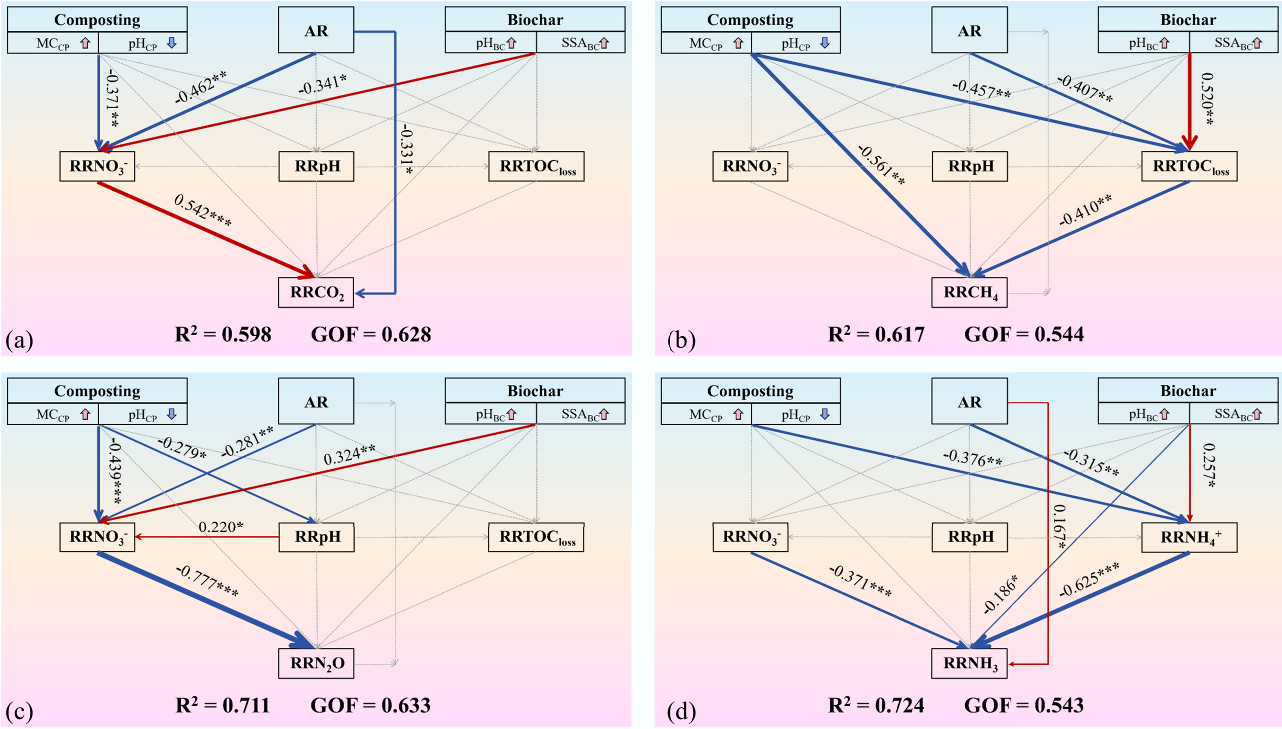


Fig. 6 Partial least squares path models (PLS-PMs) demonstrating how composting conditions (MC_{CP}, moisture content of compost; pH_{CP}, initial pH of compost), the application rate of biochar (AR), biochar properties (pH_{BC}, pH of biochar; SSA_{BC}, specific surface area of biochar), and changes in compost properties ($RRNO_3^-$, response ratio of average NO_3^- contents; RRpH, response ratio of final pH; $RRTOC_{loss}$, response ratio of total organic carbon loss; $RRNH_4^+$, response ratio of average NH_4^+ contents) influence the response ratios of (**a**) CO_2, (**b**) CH_4, (**c**) N_2O, and (**d**) NH_3 emissions. Pink and blue arrows refer to positive and negative relationships (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$). Dotted arrows denote insignificant correlations ($p > 0.05$). The numbers next to the arrows indicate the standardized path coefficient.

depending on the AR (Fig. 3). Biochar exhibited differential impacts on the gas emissions and even increased N_2O emissions at low ARs (> 10%, w/w), indicating that biochar promotes the nitrification process and thus N_2O emissions at a low AR. This was supported by our observation of elevated NO_3^- levels during composting (Fig. 2). With increased ARs, biochar progressively enhanced its mitigation efficacy for CH_4, N_2O, and NH_3, indicating that biochar enhances aeration performance at a high AR and improves the gas mitigation effect[41]. However, our further regression analysis between AR and $RRCH_4$, RRN_2O, and $RRNH_3$ revealed a dose effect, indicating a saturation point beyond which the mitigation efficacy of biochar declines (Supplementary Fig. S2). A possible explanation is that excessive biochar promotes aggregate formation and expands anaerobic sites in compost piles[29]. Collectively, our regression analysis indicates that the peak mitigation efficacy for the three target gases occurs within the AR range of 10%–20% w/w. We proposed that AR at 10%–20% w/w may be the optimal range to achieve co-mitigation effects on CH_4, N_2O, and NH_3.

Rebalancing of carbon and nitrogen possibly influenced CO_2 emissions in composting

Biochar addition did not significantly alter CO_2 emissions (Fig. 3), whereas the TC loss and TOC loss results indirectly support this conclusion (Fig. 2). However, the overall nonsignificant effect does not imply that biochar has no impact on compost CO_2 emissions. Critically, our PLS-PM results distinctly identified $RRNO_3^-$ as the most critical direct driver of $RRCO_2$ (Fig. 6a), which was not mentioned in previous research[31,38]. This finding suggests a pivotal role of nitrogen processes (specifically nitrification–denitrification dynamics influencing NO_3^- levels) in governing CO_2 dynamics in composting, challenging the conventional focus on carbon cycle mechanisms[51–53]. The meta- and sub-meta-analyses also showed that the impacts of AR on CO_2 emissions vary significantly under different C/N ratios (Fig. 4 and Supplementary Fig. S3). Specifically, at C/N ratios > 20, increasing AR tended to promote CO_2 emissions, but CO_2 emissions are suppressed at C/N ratios < 20. This opposite response implies that the nitrogen concentration in compost is a key regulator determining whether biochar stimulates or inhibits CO_2 production. Since biochar is known to enhance nitrogen mineralization, promote nitrification, and modulate denitrification processes[13,18,43,54], we reasonably hypothesized that biochar may regulate the composting environment, rebalance carbon and nitrogen's interdependence, and redistribute microbial activity, ultimately influencing CO_2 emissions. This rebalancing of carbon and nitrogen caused by biochar results in a nonsignificant overall effect on CO_2 emissions, as the process is inherently complex and highly dependent on the composting conditions. According to the predictive model of PLS-PM, the rebalancing of carbon and nitrogen is the possible underlying mechanism regulating CO_2 emissions in composting.

The optimal parameters for mitigating gas emissions in composting

Biochar decreased CH_4, N_2O, and NH_3 emissions under most composting parameters except acidic conditions (Fig. 4). Notably, the C/N ratio and MC are important factors determining the responses of CO_2 emissions to biochar, with high C/N ratios (> 30) and low MC (< 55%) increasing CO_2 emissions. The EC impairs the mitigation effects of biochar on all target gases. Hence, to achieve stable and effective mitigation efficiency for CO_2, CH_4, N_2O, and NH_3 emissions, appropriate parameters should be established for composting. It is a challenge to achieve synergistic optimization because of the different gas mitigation mechanisms. According to our meta-analysis and discussion, we propose the following optimal parameters: a C/N ratio of 20–30, a moisture content of 55%–65%, a pH of 7.5–8.5, EC < 4 mS/cm, and 10%–20% (w/w, dry weight) biochar dosage to mitigate gas emissions in composting. Compared with previous studies[31], this new proposal further bounded the pH and EC conditions which decrease the mitigation efficiency of biochar for CH_4, N_2O, and NH_3 emissions at pH < 7.5 and EC > 4 mS/cm (Fig. 4). The AR of biochar dosage at 10%–20% (w/w, dry weight) was chosen due to its convex relationships with the response ratios of CH_4, N_2O, and NH_3 (Fig. 3 and Supplementary Fig. S2).

The C/N ratio is a pivotal parameter in the composting process[55]. Our meta-analysis showed that biochar promotes CO_2 emissions under high C/N ratios (> 30), but reduces CO_2 emissions under a low C/N (< 20) (Fig. 4 and Supplementary Fig. S3). However, there is a lack of in-depth research into and explanations of the mechanisms related to this phenomenon. A possible explanation is that biochar may modulate nitrogen's availability[31, 55]. Under nitrogen-poor conditions, biochar may mitigate nitrogen limitations and stimulate microorganisms to decompose organic carbon, thereby promoting CO_2 emissions[56,57]. In contrast, under nitrogen-rich conditions, biochar may adsorb excess readily available nitrogen and alleviate nitrogen-induced suppression of microbial carbon metabolism efficiency, thereby reducing futile carbon loss[58].

The MC is the key factor in starting composting, with MC directly determining the oxygen environment of the compost[59]. Our meta-analysis and regression results showed that as the MC increases, the impact of biochar on CO_2 emissions shifts from promoting to inhibiting (Fig. 4 and Supplementary Fig. S2). This transition suggests that biochar stabilizes CO_2 emissions within an optimal range by regulating moisture to appropriate aerobic conditions during composting[51]. This conclusion can also be used to explain our observations of CH_4 and N_2O emissions (Fig. 4). Because biochar regulates an appropriate aerobic environment, there were significant mitigation effects on CH_4 and N_2O emissions under all the different MC conditions.

The pH mainly influences the microbial activity during composting[59]. Our meta-analysis showed that biochar’s mitigation effects on CH_4, N_2O, and NH_3 significantly decrease at a low pH (< 7.5) (Fig. 4), indicating that an acidic environment (< 7.5) compromises the alkaline buffering capacity of biochar. Notably, there was no significant increase in NH_3 emissions at high pH values, indicating that appropriately managed higher pH levels may not necessarily promote the volatilization of ammonia in biochar-amended composting. Additionally, we detected that biochar promoted CO_2 emissions when pH increased, which may be explained by the partial decomposition of biochar in an alkaline environment[27, 60]. Although pH significantly influences gas emissions levels across biochar treatments, these variations remain unaltered by changes in the biochar dosage (Supplementary Fig. S3), suggesting that the inherent chemical properties of biochar may primarily drive differences in emissions in acidic versus alkaline environments[49].

The EC is an important indicator for evaluating the quality of compost products[61]. Our results firstly indicated that the initial EC of compost influenced the effectiveness of biochar's mitigation effects (Fig. 4). As the initial EC increased, the mitigation effects of biochar on all targeted gases were weakened. This phenomenon may be explained by the competitive adsorption between nutrients and salinity[62,63]. Unfortunately, the mechanisms between biochar's mitigation effects and the initial salt content have not been fully proved and remain to be further studied.

The optimal parameters we proposed for gas mitigations fall into the ranges for optimal compost quality, although this was not the current focus[31]. Future research should be further carried out to validate compost quality as well as gas mitigation for sustainable organic waste management and climate-smart agricultural practices.

Conclusions

Biochar amendment demonstrated a tripartite benefit: mitigating gas emissions (CH_4, N_2O, and NH_3), conserving nitrogen nutrients, and contributing to carbon stocks' stability in composting. Biochar could significantly reduce CH_4 (53.7%), N_2O (49.8%), and NH_3 (35.9%) emissions during composting. Biochar amendment could reduce NH_4^+ (17.4%), increase NO_3^- (17.2%), elevate pH (4.7%), and decrease TN losses (41.3%) in composting. There were no significant changes in CO_2 emissions, TC loss, and TOC loss with added recalcitrant carbon stocks. Subgroup analysis and regression analysis showed that biochar's AR was the key parameter affecting CH_4, N_2O and NH_3 emissions, demonstrating dose-dependent effects on the efficacy of mitigation. Biochar decreased CH_4, N_2O, and NH_3 emissions under most parameters except acidic conditions. High C/N ratios (> 30) and low MC (< 55%) increased CO_2 emissions, whereas high EC (> 4 mS/cm) impaired the mitigation effects of biochar on all target gases. The optimal parameters were identified as a C/N ratio of 20–30), moisture content of 55%–65%), pH 7.5–8.5, an EC of < 4 mS/cm, and biochar dosage at 10%–20% (w/w dry weight) for mitigating gas emissions in composting.

Supplementary information

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Author contributions

The authors confirm their contributions to the paper as follows: study conception and design: Xu J, Xiong Z; material preparation, data collection, and data analysis: Xu J; writing – draft manuscript preparation: Xu J; conceptualization, funding acquisition, supervision, writing – review and editing: Xiong Z. Both authors read and approved the final manuscript.

Data availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

All authors declare that they have no competing interests.

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References

[1] McNicol G, Jeliazovski J, François JJ, Kramer S, Ryals R. 2020. Climate change mitigation potential in sanitation via off-site composting of human waste. *Nature Climate Change* 10:545

[2] Wang Y, Ying H, Stefanovski D, Shurson GC, Chen T, et al. 2025. Food waste used as a resource can reduce climate and resource burdens in agrifood systems. *Nature Food* 6:478−490

[3] Ji Z, Zhang L, Liu Y, Li X, Li Z. 2023. Evaluation of composting parameters, technologies and maturity indexes for aerobic manure composting: a meta-analysis. *Science of The Total Environment* 886:14

[4] Aguilar-Paredes A, Valdés G, Araneda N, Valdebenito E, Hansen F, et al. 2023. Microbial community in the composting process and its positive impact on the soil biota in sustainable agriculture. *Agronomy* 13:24

[5] Nordahl SL, Preble CV, Kirchstetter TW, Scown CD. 2023. Greenhouse gas and air pollutant emissions from composting. *Environmental Science & Technology* 57:2235−2247

[6] Rosik J, Karczewski M, Stegenta-Dąbrowska S. 2024. Optimizing the early-stage of composting process emissions – artificial intelligence primary tests. *Scientific Reports* 14:27299

[7] Ba S, Qu Q, Zhang K, Groot JCJ. 2020. Meta-analysis of greenhouse gas and ammonia emissions from dairy manure composting. *Biosystems Engineering* 193:126−137

[8] Ye P, Fang L, Song D, Zhang M, Li R, et al. 2023. Insights into carbon loss reduction during aerobic composting of organic solid waste: a meta-analysis and comprehensive literature review. *Science of The Total Environment* 862:160787

[9] Zhang Z, Liu D, Qiao Y, Li S, Chen Y, et al. 2021. Mitigation of carbon and nitrogen losses during pig manure composting: a meta-analysis. *Science of The Total Environment* 783:147103

[10] Liu Y, Tang R, Li L, Zheng G, Wang J, et al. 2023. A global meta-analysis of greenhouse gas emissions and carbon and nitrogen losses during livestock manure composting: Influencing factors and mitigation strategies. *Science of The Total Environment* 885:163900

[11] Hoang HG, Thuy BTP, Lin C, Vo DVN, Tran HT, et al. 2022. The nitrogen cycle and mitigation strategies for nitrogen loss during organic waste composting: A review. *Chemosphere* 300:134514

[12] Guo S, Bol R, Li Z, Wu J, Lin H, et al. 2025. Patterns and drivers of soil autotrophic nitrification and associated N_2O emissions. *Soil Biology & Biochemistry* 203:109730

[13] Roothans N, Gabriëls M, Abeel T, Pabst M, van Loosdrecht MCM, et al. 2024. Aerobic denitrification as an N_2O source from microbial communities. *The ISME Journal* 18:wrae116

[14] Maeda K, Toyoda S, Philippot L, Hattori S, Nakajima K, et al. 2017. Relative contribution of nirK and nirS bacterial denitrifiers as well as fungal denitrifiers to nitrous oxide production from dairy manure compost. *Environmental Science & Technology* 51:14083−14091

[15] Lin L, Xu F, Ge X, Li Y. 2018. Improving the sustainability of organic waste management practices in the food-energy-water nexus: a comparative review of anaerobic digestion and composting. *Renewable & Sustainable Energy Reviews* 89:151−167

[16] Cao Y, Wang X, Bai Z, Chadwick D, Misselbrook T, et al. 2019. Mitigation of ammonia, nitrous oxide and methane emissions during solid waste composting with different additives: a meta-analysis. *Journal of Cleaner Production* 235:626−635

[17] Li X, Zhao Y, Xu A, Chang H, Lin G, et al. 2022. Conductive biochar promotes oxygen utilization to inhibit greenhouse gas emissions during electric field-assisted aerobic composting. *Science of The Total Environment* 842:156929

[18] Wu JX, Shangguan HY, Fu T, Chen JJ, Tang JH, et al. 2021. Alternating magnetic field mitigates N_2O emission during the aerobic composting of chicken manure. *Journal of Hazardous Materials* 406:124329

[19] Robledo-Mahón T, Martín MA, Gutiérrez MC, Toledo M, González I, et al. 2019. Sewage sludge composting under semi-permeable film at full-scale: Evaluation of odour emissions and relationships between microbiological activities and physico-chemical variables. *Environmental Research* 177:108624

[20] Harrison BP, Moo Z, Perez-Agredano E, Gao S, Zhang X, et al. 2024. Biochar-composting substantially reduces methane and air pollutant emissions from dairy manure. *Environmental Research Letters* 19:014081

[21] Abban-Baidoo E, Manka'abusi D, Apuri L, Marschner B, Frimpong KA. 2024. Biochar addition influences C and N dynamics during biochar co-composting and the nutrient content of the biochar co-compost. *Scientific Reports* 14:23781

[22] Liu Y, Pan J, Wang J, Yang X, Zhang W, et al. 2024. Insight into the humification and carbon balance of biogas residual biochar amended co-composting of hog slurry and wheat straw. *Environmental Science and Pollution Research*

[23] Nguyen MK, Lin C, Hoang HG, Bui XT, Ngo HH, et al. 2023. Investigation of biochar amendments on odor reduction and their characteristics during food waste co-composting. *Science of The Total Environment* 865:161128

[24] Wang J, Xiong Z, Kuzyakov Y. 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. *Global Change Biology Bioenergy* 8:512−523

[25] Godlewska P, Schmidt HP, Ok YS, Oleszczuk P. 2017. Biochar for composting improvement and contaminants reduction: A review. *Bioresource Technology* 246:193−202

[26] Wang Z, Zhang M, Li J, Wang J, Sun G, et al. 2024. Effect of biochar with various pore characteristics on heavy metal passivation and microbiota development during pig manure composting. *Journal of Environmental Management* 352:120048

[27] Sanchez-Monedero MA, Cayuela ML, Roig A, Jindo K, Mondini C, et al. 2018. Role of biochar as an additive in organic waste composting. *Bioresource Technology* 247:1155−1164

[28] Chen H, Awasthi SK, Liu T, Duan Y, Ren X, et al. 2020. Effects of microbial culture and chicken manure biochar on compost maturity and greenhouse gas emissions during chicken manure composting. *Journal of Hazardous Materials* 389:121908

[29] Harrison BP, Gao S, Thao T, Gonzales ML, Williams KL, et al. 2024. Methane and nitrous oxide emissions during biochar-composting are driven by biochar application rate and aggregate formation. *Global Change Biology Bioenergy* 16:e13121

[30] Dang R, Cai Y, Li J, Kong Y, Jiang T, et al. 2024. Biochar reduces gaseous emissions during poultry manure composting: Evidence from the evolution of associated functional genes. *Journal of Cleaner Production* 452:142060

[31] Nguyen MK, Lin C, Hoang HG, Sanderson P, Dang BT, et al. 2022. Evaluate the role of biochar during the organic waste composting process: A critical review. *Chemosphere* 299:134488

[32] He X, Yin H, Han L, Cui R, Fang C, et al. 2019. Effects of biochar size and type on gaseous emissions during pig manure/wheat straw aerobic composting: Insights into multivariate-microscale characterization and microbial mechanism. *Bioresource Technology* 271:375−382

[33] Awasthi MK, Wang Q, Huang H, Li RH, Shen F, et al. 2016. Effect of biochar amendment on greenhouse gas emission and bio-availability of heavy metals during sewage sludge co-composting. *Journal of Cleaner Production* 135:829−835

[34] Ottani F, Parenti M, Santunione G, Moscatelli G, Kahn R, et al. 2023. Effects of different gasification biochar grain size on greenhouse gases and ammonia emissions in municipal aerated composting processes. *Journal of Environmental Management* 331:117257

[35] Liu H, Awasthi MK, Zhang Z, Syed A, Bahkali AH. 2024. Evaluation of gases emission and enzyme dynamics in sheep manure compost occupying with peach shell biochar. *Environmental Pollution* 351:124065
[36] Steiner C, Nathan M, Keith H, Das KC. 2011. Biochar as bulking agent for poultry litter composting. *Carbon Management* 2:227−30
[37] Zhang F, Wei Z, Wang J. 2021. Integrated application effects of biochar and plant residue on ammonia loss, heavy metal immobilization, and estrogen dissipation during the composting of poultry manure. *Waste Management* 131:117−125
[38] Yin Y, Yang C, Li M, Zheng Y, Ge C, et al. 2021. Research progress and prospects for using biochar to mitigate greenhouse gas emissions during composting: A review. *Science of The Total Environment* 798:149294
[39] Guo XX, Liu HT, Zhang J. 2020. The role of biochar in organic waste composting and soil improvement: a review. *Waste Management* 102:884−899
[40] Vandecasteele B, Sinicco T, D'Hose T, Vanden Nest T, Mondini C. 2016. Biochar amendment before or after composting affects compost quality and N losses, but not P plant uptake. *Journal of Environmental Management* 168:200−209
[41] Awasthi MK, Wang M, Chen H, Wang Q, Zhao J, et al. 2017. Heterogeneity of biochar amendment to improve the carbon and nitrogen sequestration through reduce the greenhouse gases emissions during sewage sludge composting. *Bioresource Technology* 224:428−438
[42] Sánchez-García M, Alburquerque JA, Sánchez-Monedero MA, Roig A, Cayuela ML. 2015. Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions. *Bioresource Technology* 192:272−279
[43] Li S, Song L, Jin Y, Liu S, Shen Q, et al. 2016. Linking N_2O emission from biochar-amended composting process to the abundance of denitrify (nirK and nosZ) bacteria community. *AMB Express* 6:37
[44] Bezabih Beyene B, Li J, Yuan J, Dong Y, Liu D, et al. 2022. Non-native plant invasion can accelerate global climate change by increasing wetland methane and terrestrial nitrous oxide emissions. *Global Change Biology* 28:5453−5468
[45] Tang B, Man J, Lehmann A, Rillig MC. 2023. Arbuscular mycorrhizal fungi benefit plants in response to major global change factors. *Ecology Letters* 26:2087−2097
[46] Ainsworth EA. 2008. Rice production in a changing climate: A meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. *Global Change Biology* 14:1642−1650
[47] van Buuren S, Groothuis-Oudshoorn K. 2011. mice: multivariate imputation by chained equations in R. *Journal of Statistical Software* 45:1−67
[48] Aurangzeib M, Zhang S, Yan S, Zhou J, Niu X, et al. 2024. Biochar application can improve most of the chemical properties of acidic soils: a global meta-analysis. *ACS Agricultural Science & Technology* 4:292−306
[49] Jeyasubramanian K, Thangagiri B, Sakthivel A, Dhaveethu Raja J, Seenivasan S, et al. 2021. A complete review on biochar: Production, property, multifaceted applications, interaction mechanism and computational approach. *Fuel* 292:120243
[50] Zhou S, Kong F, Lu L, Wang P, Jiang Z. 2022. Biochar—An effective additive for improving quality and reducing ecological risk of compost: a global meta-analysis. *Science of The Total Environment* 806:151439
[51] Chowdhury MA, de Neergaard A, Jensen LS. 2014. Potential of aeration flow rate and bio-char addition to reduce greenhouse gas and ammonia emissions during manure composting. *Chemosphere* 97:16−25
[52] Mao H, Lv Z, Sun H, Li R, Zhai B, et al. 2018. Improvement of biochar and bacterial powder addition on gaseous emission and bacterial community in pig manure compost. *Bioresource Technology* 258:195−202
[53] Liu N, Zhou J, Han L, Ma S, Sun X, et al. 2017. Role and multi-scale characterization of bamboo biochar during poultry manure aerobic composting. *Bioresource Technology* 241:190−199
[54] López-Cano I, Roig A, Cayuela ML, Alburquerque JA, Sánchez-Monedero MA. 2016. Biochar improves N cycling during composting of olive mill wastes and sheep manure. *Waste Management* 49:553−559
[55] Zhan Y, Wei Y, Zhang Z, Zhang A, Li Y, et al. 2021. Effects of different C/N ratios on the maturity and microbial quantity of composting with sesame meal and rice straw biochar. *Biochar* 3:557−564
[56] Yan H, Niu Q, Zhu Q, Wang S, Meng Q, et al. 2021. Biochar reinforced the populations of cbbL-containing autotrophic microbes and humic substance formation via sequestrating CO_2 in composting process. *Journal of Biotechnology* 333:39−48
[57] Kayes I, Halim MA, Thomas SC. 2025. Biochar mitigates methane emissions from organic mulching in urban soils: evidence from a long-term mesocosm experiment. *Journal of Environmental Management* 376:124525
[58] Chen L, Liu L, Mao C, Qin S, Wang J, et al. 2018. Nitrogen availability regulates topsoil carbon dynamics after permafrost thaw by altering microbial metabolic efficiency. *Nature Communications* 9:3951
[59] Onwosi CO, Igbokwe VC, Odimba JN, Eke IE, Nwankwoala MO, et al. 2017. Composting technology in waste stabilization: on the methods, challenges and future prospects. *Journal of Environmental Management* 190:140−157
[60] Jindo K, Matsumoto K, García Izquierdo C, Sonoki T, Sanchez-Monedero MA. 2014. Methodological interference of biochar in the determination of extracellular enzyme activities in composting samples. *Solid Earth* 5:713−719
[61] Kato H, Nakatani H, Ichikawa A. 1999. Effect of high electric conductivity (EC) on composting process of poultry manure. *Research Bulletin of the Aichi-ken Agricultural Research Center* 1999:311−116
[62] Zhang H, Wang T, Zhang Y, Sun B, Pan W. 2020. Promotional effect of NH_3 on mercury removal over biochar thorough chlorine functional group transformation. *Journal of Cleaner Production* 257:120598
[63] Liu Q, Meki K, Zheng H, Yuan Y, Shao M, et al. 2023. Biochar application in remediating salt-affected soil to achieve carbon neutrality and abate climate change. *Biochar* 5:45