

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 (CO₂), methane (CH₄), and nitrous oxide (N₂O), and ammonia (NH₃). Biochar can reduce greenhouse gases and NH₃ 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 CO₂, CH₄, N₂O, and NH₃ emissions during biochar-amended composting. Biochar amendment significantly reduced emissions of CH₄ (53.7%), N₂O (49.8%), and NH₃ (35.9%), but had no significant effect on CO₂ emissions. The application rate of biochar was the key parameter affecting CH₄, N₂O, and NH₃ emissions, demonstrating a dose effect on mitigation efficacy. Biochar decreased CH₄, N₂O, and NH₃ emissions under most parameters, except acidic conditions. Although a high carbon:nitrogen ratio (> 30) and a low moisture content (< 55%) increased CO₂ 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

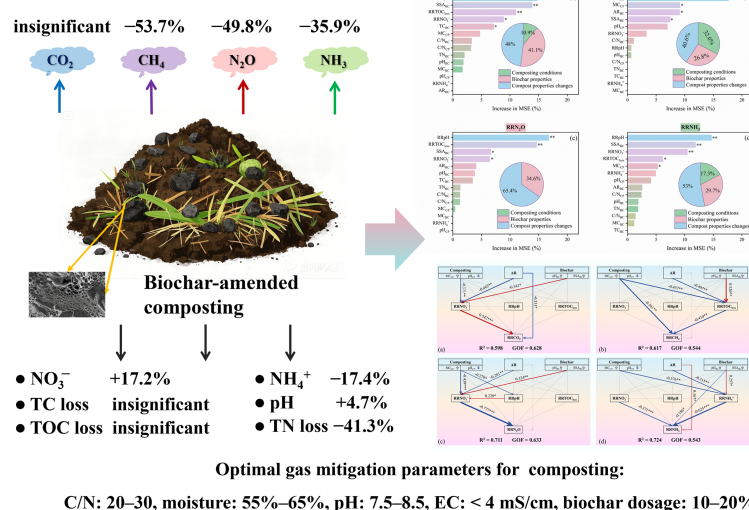
Highlights

- Biochar altered CH₄ (–53.7%), N₂O (–49.8%), NH₃ (–35.9%), but not CO₂ via meta-analysis.
- The application rate of biochar exhibited a dose effect on CH₄, N₂O, NH₃ 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 (CO₂), methane (CH₄), and nitrous oxide (N₂O), and reactive nitrogen (Nr) gases such as ammonia (NH₃) and N₂O will also be emitted during the composting process^[5–7]. These gas emissions are inevitable products of carbon and nitrogen's transformation during composting. CO₂ is mainly released by aerobic metabolism, while CH₄ is more easily generated by methanogenic bacteria under anaerobic conditions^[8,9]. NH₃ produced by the conversion of ammonium (NH₄⁺) will volatilize rapidly and exacerbate nitrogen losses^[10,11]. N₂O 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 NH₃ 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 and a 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 NH₃ 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 CO₂ 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 CO₂ emissions through the adsorption of CO₂ and the sequestration of exogenous organic matter^[40]. So what is the overall effect of biochar amendment on CO₂ emissions, and what is the key mechanism? Similarly, a high biochar application rate (> 8%) was reported to minimize CH₄ 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 N₂O emissions is also controversial. Biochar can reduce N₂O emissions by enhancing the expression of the *nosZ* gene but also may increase N₂O 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 CO₂, CH₄, N₂O, and NH₃ 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 (CO₂, CH₄, N₂O, NH₃, 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 CO₂, CH₄, N₂O, and NH₃ 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 (NH₄⁺) and nitrate (NO₃⁻) 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 CO₂, CH₄, N₂O, and NH₃ gas emissions. The RR was calculated as follows:

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

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:

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

$$w_i = \frac{1}{v_i} \quad (3)$$

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

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:

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

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: CO₂, CH₄, N₂O, and NH₃^[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 NH₄⁺, NO₃⁻, pH, TC_{loss}, TN_{loss}, and TOC_{loss} were analyzed in this meta-analysis. However, because of insufficient reporting of the SD or SE values in many studies, the RR and $\overline{RR}$ were calculated using an equal-weighting

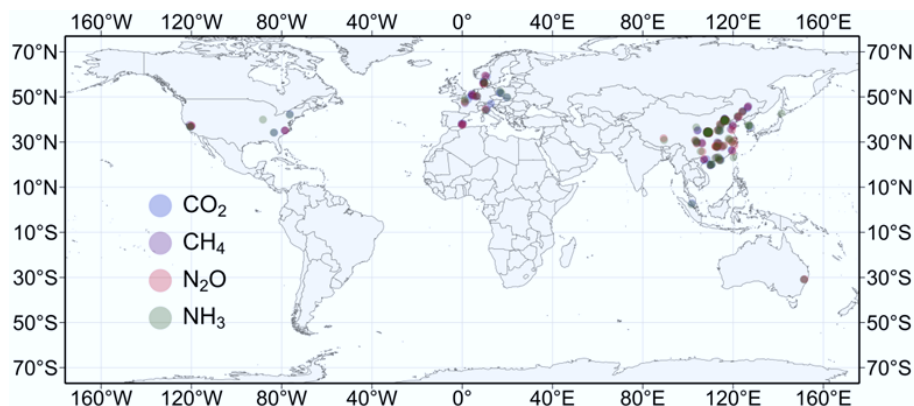


Fig. 1 Global distribution of qualifying studies.

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}	–
Composting conditions	Application rate	AR	%, w/w (dry weight)
	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 RRCO₂, RRCH₄, RRN₂O, and RRNH₃. 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 "plsmpm" R package, we implemented PLS-PM to determine the primary mechanisms by which biochar mitigates CO₂, CH₄, N₂O, and NH₃ 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 R² values of target gas emissions.

Results and discussion

The effects of biochar amendment on compost properties

Biochar amendment significantly reduced the NH₄⁺ content of compost by 17.4% (95% CI: –22.4% to –12.1%, *p* < 0.001), with the mean NH₄⁺ concentration decreasing from 1.94 to 1.59 g/kg (Fig. 2). Biochar amendment significantly increased the NO₃[–] content of compost by 17.2% (95% CI: 5.4%–30.3%, *p* < 0.01), with the mean NO₃[–] 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 CH₄ (53.7%), N₂O (49.8%), and NH₃ (35.9%), while CO₂ emissions showed a marginal increase (4.9%) that was statistically nonsignificant (Fig. 3). Biochar ARs significantly and differentially influenced gas emissions. CO₂ 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 CH₄ emissions, the greatest reduction (–86.1%) occurred at ARs greater than 10.0% (w/w), demonstrating substantially greater mitigation than lower application rates. N₂O 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 N₂O emissions. NH₃ 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 CO₂ 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 CH₄ emissions (reductions of 46.8%–73.8%), except for shell as the FT. The strongest CH₄ mitigation (73.8%) was observed with a PS of >5 mm, while pH 9–10 showed more moderate effects (46.8%). N₂O 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 NH₃, 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 CH₄, N₂O, and NH₃ emissions, which indicates that the AR was the key factor in CH₄, N₂O, and NH₃ emissions. The significant convex relationships between AR and the response ratios of CH₄, N₂O, and NH₃ 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 CO₂ 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 CO₂ emissions by 123.2%, 62.4%, 52.4%, 99.2%, and 93.5%, respectively. For CH₄ 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 N₂O

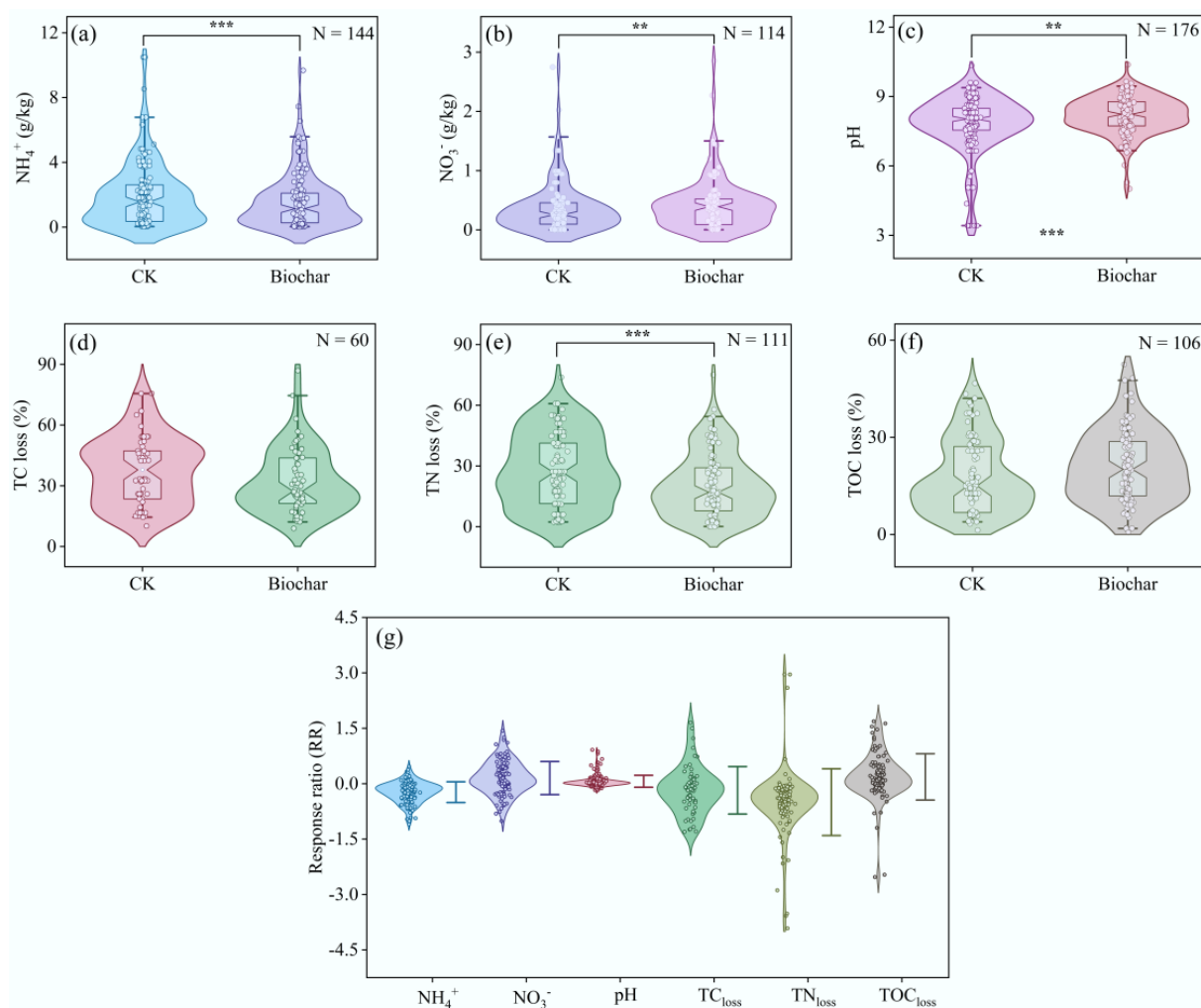


Fig. 2 Violin plots of NH_4^+ , NO_3^- , pH, TC loss, TN loss, and TOC loss in the control (CK) and biochar-amended composting systems (a)–(f). *N* denotes the number of paired samples, with asterisks indicating the statistical significance levels (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$). The response ratios (RR) of NH_4^+ , NO_3^- , pH, TC loss, TN loss, and TOC loss are shown in (g). 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 m³, 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 m³ 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 RR_{CO_2} was negatively correlated with MC (Supplementary Fig. S2). The $\text{RR}_{\text{N}_2\text{O}}$ and RR_{NH_3} exhibited convex and negative relationships with EC, respectively (Supplementary Fig. S2). Additionally, our sub-meta-analysis showed that AR exhibited different effects on RR_{CO_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 RR_{CO_2} were RR_{pH} , SSA_{BC} , MC_{CP} , $\text{RR}_{\text{TOC}_{\text{loss}}}$, $\text{RR}_{\text{NO}_3^-}$, and TC_{BC} (Fig. 5). Among the three categorized drivers, changes in compost properties exhibited the strongest response to RR_{CO_2} (48%). $\text{RR}_{\text{TOC}_{\text{loss}}}$, MC_{CP} , AR_{BC} , and SSA_{BC} played a more important role in RR_{CH_4} , whereas changes in compost properties accounted for the largest proportion at 40.6%. RR_{pH} , $\text{RR}_{\text{TOC}_{\text{loss}}}$, SSA_{BC} , and $\text{RR}_{\text{NO}_3^-}$ were the dominant factors influencing $\text{RR}_{\text{N}_2\text{O}}$, whereas changes in compost properties contributed the largest proportion at 65.4%. RR_{pH} , SSA_{BC} , $\text{RR}_{\text{NO}_3^-}$, $\text{RR}_{\text{TOC}_{\text{loss}}}$, and MC_{CP} governed RR_{NH_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 RR_{CO_2} , whereas composting conditions, AR, and biochar properties all indirectly influenced emissions through $\text{RR}_{\text{NO}_3^-}$ (Fig. 6a). Composting conditions and $\text{RR}_{\text{TOC}_{\text{loss}}}$ directly

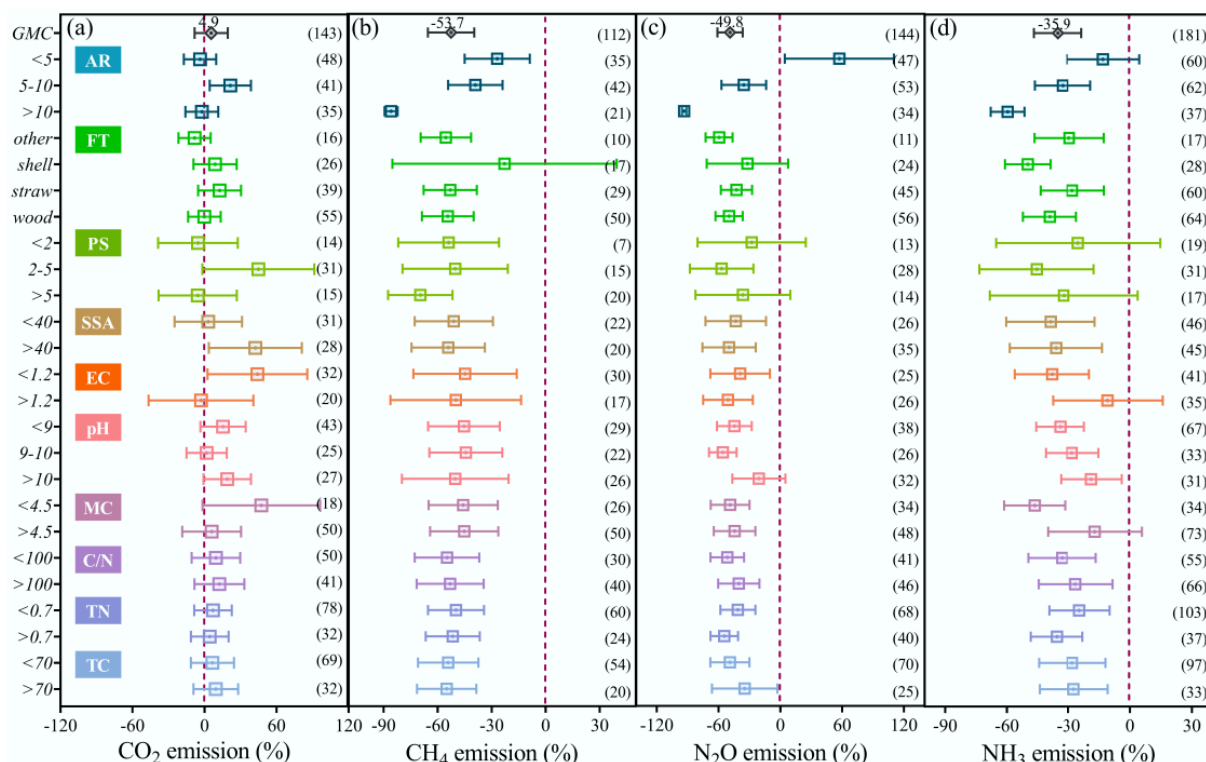


Fig. 3 Effects of biochar properties on CO_2 , CH_4 , N_2O , and NH_3 emissions during composting (a)–(d). The center of the small square represents the average value, and the error line represents the $\pm$ 95% CIs. The numbers in brackets represent sample sizes. TC, total carbon; TN, total nitrogen;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

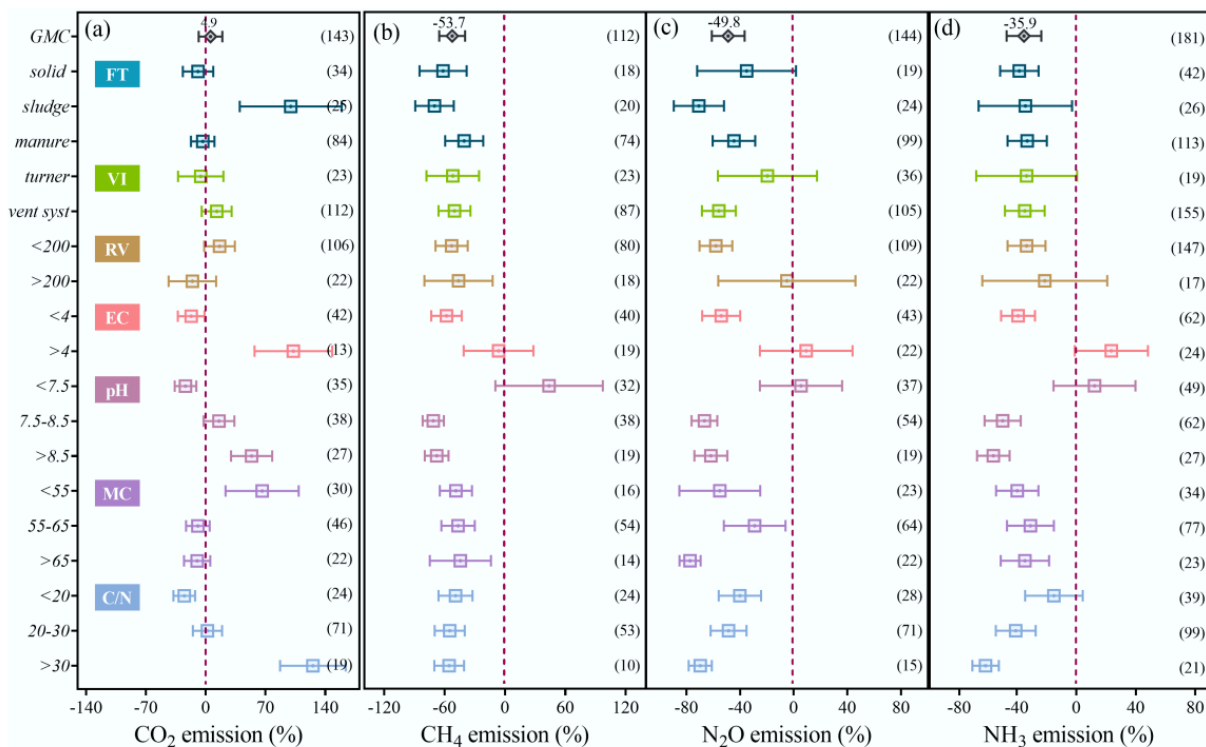


Fig. 4 Effects of composting conditions on CO_2 , CH_4 , N_2O , and NH_3 emissions during composting (a)–(d). The center of the small square represents the average value, and the error line represents the $\pm$ 95% CIs. The numbers in brackets represent the sample sizes. C/N, carbon : nitrogen ratio;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

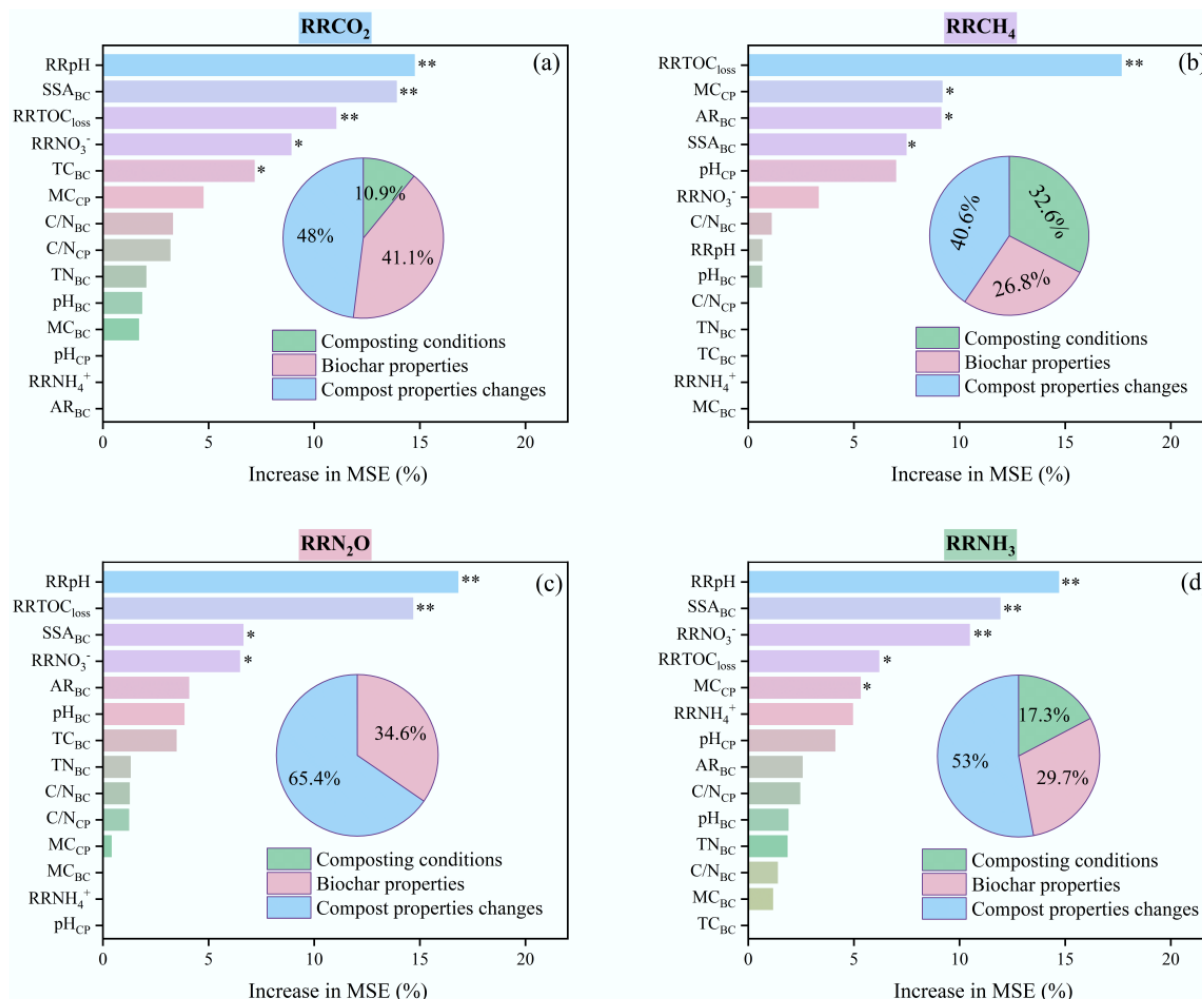


Fig. 5 Random Forest models used to rank the predictive variables of response ratios (RR) of CO₂, CH₄, N₂O, and NH₃ emissions (a)–(d). The percentage increase in the mean squared error (%IncMSE) represents the importance of the main predictors; negative values of %IncMSE are not shown. Statistical significance 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 NH₄⁺, NO₃⁻ final pH, and TOC loss.

regulated CH₄ emissions, whereas RRTOC_{loss} is governed by composting conditions, AR, and biochar properties (Fig. 6b). Similarly, composting conditions, AR, and biochar properties indirectly influenced N₂O emissions by controlling RRpH and RRNO₃⁻ (Fig. 6c). The key factors influencing NH₃ emissions included AR, RRNO₃⁻, and RRNH₄⁺, whereas RRNH₄⁺ governed NH₃ emissions (Fig. 6d). Above all, RRNO₃⁻ was the dominant factor driving RRCO₂ and RRN₂O, whereas RRTOC_{loss} and RRNH₄⁺ were the dominant factors driving RRCH₄ and RRNH₃, respectively, as illustrated in the PLS-PM model (Fig. 6a–d).

Discussion

Biochar facilitates nitrogen conservation, carbon stability, and synergistic mitigation of CH₄, N₂O, and NH₃ during composting

Biochar amendment demonstrated multiple benefits in composting systems by mitigating gas emissions (CH₄, N₂O, and NH₃), conserving nitrogen nutrients, and contributing to carbon stability. Our analysis confirmed that biochar significantly reduced NH₄⁺, increased NO₃⁻,

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 CH₄, N₂O, and NH₃ emissions, with no significant influence on CO₂ 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 CH₄, N₂O, and NH₃ emissions during composting

Our results indicated that biochar amendment significantly reduced CH₄, N₂O, and NH₃ emissions, with the efficiency of mitigation strongly

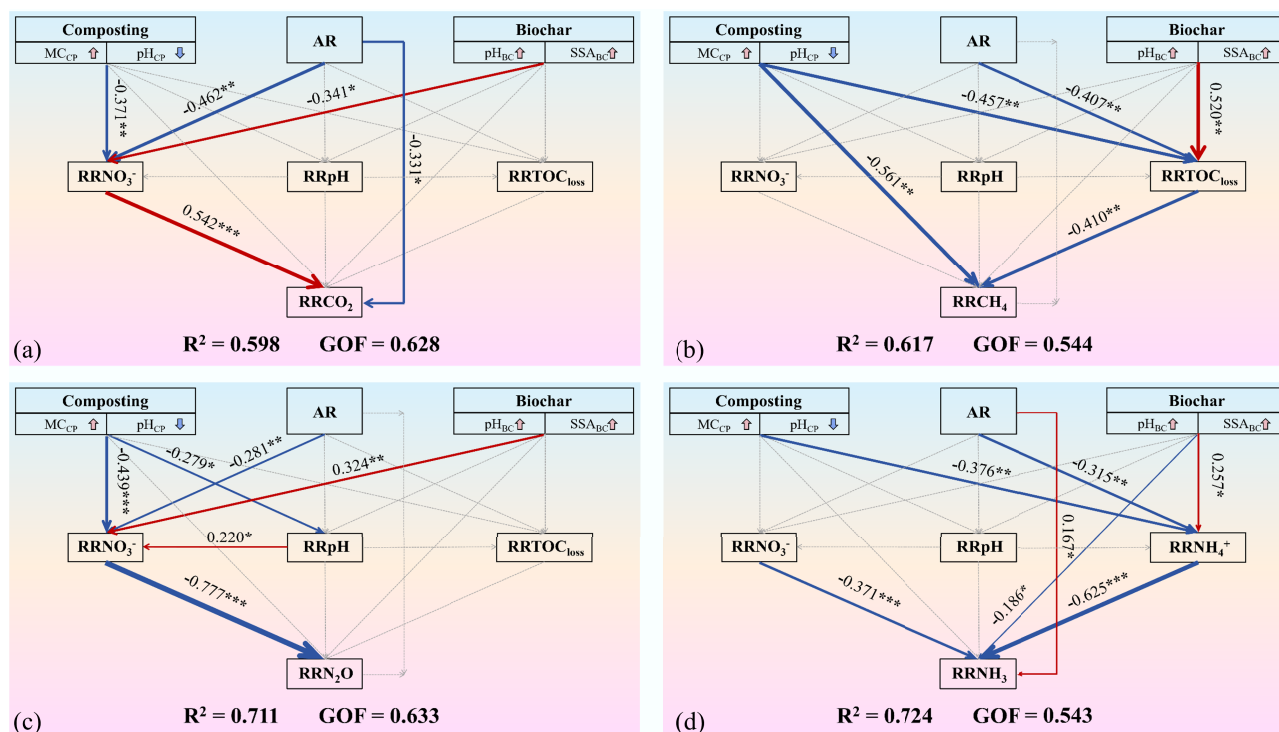


Fig. 6 Partial least squares path models (PLS-PMs) demonstrating how composting conditions (MC_{cp} , moisture content of compost; pH_{cp} , initial pH of compost), the application rate of biochar (AR), biochar properties (pH_{bc} , pH of biochar; SSA_{bc} , specific surface area of biochar), and changes 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 CO₂, CH₄, N₂O, and NH₃ 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 CH₄, N₂O, and NH₃ 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 CH₄, N₂O, and NH₃ (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 CO₂ emissions under high C/N ratios (> 30), but reduces CO₂ 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 CO₂ 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 CO₂ emissions shifts from promoting to inhibiting (Fig. 4 and Supplementary Fig. S2). This transition suggests that biochar stabilizes CO₂ 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 CH₄ and N₂O emissions (Fig. 4). Because biochar regulates an appropriate aerobic environment, there were significant mitigation effects on CH₄ and N₂O 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 CH₄, N₂O, and NH₃ 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 NH₃ 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 CO₂ 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 (CH₄, N₂O, and NH₃), conserving nitrogen nutrients, and contributing to carbon stocks' stability in composting. Biochar could significantly reduce CH₄ (53.7%), N₂O (49.8%), and NH₃ (35.9%) emissions during composting. Biochar amendment could reduce NH₄⁺ (17.4%), increase NO₃⁻ (17.2%), elevate pH (4.7%), and decrease TN losses (41.3%) in composting. There were no significant changes in CO₂ 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 CH₄, N₂O and NH₃ emissions, demonstrating dose-dependent effects on the efficacy of mitigation. Biochar decreased CH₄, N₂O, and NH₃ emissions under most parameters except acidic conditions. High C/N ratios (> 30) and low MC (< 55%) increased CO₂ 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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Ethical statements

Not applicable.

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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