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# Antagonistic and synergistic interactions dominate GHGs fluxes, soil properties and yield responses to biochar and N addition

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Applying biochar to soil has been advocated as an effective measure to improve soil fertility and increase carbon (C) sequestration. Biochar is often co-applied with nitrogen (N) fertilizers in agricultural ecosystems, however, the interactive effects of biochar and N addition (BN) on soil greenhouse gases (GHGs) fluxes, soil C and N fractions, and yield has not been investigated. Here, we manipulated a global meta-analysis to explore the effects of biochar and N addition and their interaction on the GHGs, soil C and N fractions, and yield by assembling 75 articles. Results indicate that across all studies, biochar, N, and BN additions all increased soil $CO_2$ emissions (8.5%–29.6%), yield (4.2%–58.2%), soil organic C (SOC, 1.8%–50.4%), dissolved organic C (DOC, 2.7%–30.0%), and total N (TN, 6.8%–15.6%), but had no significant effect on $CH_4$ fluxes. Biochar addition reduced $N_2O$ emissions (–21.3%), global warming potential (GWP, –19.8%), greenhouse gas intensity (GHGI, –28.2%), $NH_4^+$ (–17.8%) and $NO_3^-$ (–10.7%), whereas N addition increased these indexes. The interaction effects of BN on $CO_2$ and $N_2O$ emissions, GWP, TN, and $NH_4^+$ contents were antagonistic, while $CH_4$ emissions, DOC, MBC, $NO_3^-$, and yield exhibited synergistic responses. Notably, soil GHGs responses varied depending on geo-climatic factors, edaphic properties, biochar and N treatment parameters, and experimental scenarios. These findings indicate that the co-addition of biochar and N has the potential to mitigate climate change and improve yield, providing a valuable reference for the improvement of climate-smart agriculture.

KEYWORDS

**biochar, nitrogen, interactive effect, greenhouse gas emissions, C and N cycle, crop yield**

## 1 Introduction

As the three major greenhouse gases (GHGs) resulting from human activities, the annual average concentrations of carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) have risen to alarming levels of 410 ppm, 1866 ppb, and 332 ppb, respectively (IPCC, 2021). Consequently, the excessive GHGs emissions have led to a 1.09°C increase in global surface temperature between the period of 2011–2020 compared to 1850–1900 (IPCC, 2021). Nitrogen (N) addition is a common agricultural practice used to improve soil quality and crop yield (Guo et al., 2010; Shakoor et al., 2020). However, excessive N addition can trigger N leaching and enormous GHGs emissions, leading to further climate warming (Liu and Greaver, 2009; Li and Chen, 2020). Biochar, a chemically stable and highly adsorptive carbon-rich material produced by pyrolysis of biological organic materials, has demonstrated promising results in mitigating GHGs emissions (Woolf et al., 2010; Lehmann et al., 2021). Woolf et al. (2010) estimated that applying biochar to soil can offset 12% of human-induced GHGs emissions. Thus, adding biochar to N-fertilized soils could be an effective strategy to mitigate GHGs emissions while maintaining agricultural productivity.

Numerous independent studies have investigated the responses of soil GHGs to combined biochar and N (BN) addition, including positive, negative, and insignificant effects. One study reported that the application of biochar to mineral N-fertilizer soils caused a 45% increase in $CO_2$ emissions, but had no significant effect on organic N-fertilizer soils (Liu et al., 2016). He et al. (2016) verified that biochar addition significantly promoted $CH_4$ emissions by 11.6% in N-treated plots, but no significant change in bare soils. During the middle and late stages of maize growth, both increased and decreased $N_2O$ emissions were observed due to biochar and N addition, respectively (Edwards et al., 2018). Research has also demonstrated that a low biochar addition rate (20 t $ha^{-1}$) could increase the global warming potential (GWP), whereas a high biochar addition rate (40 t $ha^{-1}$) decreased it in N-fertilized soils (Liu et al., 2019b). Previous studies have suggested that biochar and N applied to soil could improve more yield (35.0%–48.4%) compared to N addition alone (Biederman and Harpole, 2013; Hu et al., 2021). The above contradictory responses may be attributed to heterogeneity in geo-climatic factors, edaphic properties, and experimental conditions of these studies, indicating the importance of considering these factors during the practical application of biochar and N addition.

The impacts of biochar and N addition on soil GHGs fluxes is widely acknowledged to be influenced by both biotic and abiotic pathways (Liu and Greaver, 2009; Zhong et al., 2016; Lehmann et al., 2021). The addition of biochar and N stimulates crop growth, leading to increased root sediments and more litter return, which in turn elevates soil respiration substrates and facilitates $CO_2$ emissions (Alvarez, 2005; Troy et al., 2013; Jia et al., 2020). Conversely, toxic substances present in biochar (phenolic compounds and furans, etc.) and N addition-induced soil acidification may impede microbial and extracellular enzyme activities, ultimately suppressing microbial respiration (Lehmann et al., 2011; Phoenix et al., 2012). The release of $CH_4$ is dependent on the interplay between CH4 production and oxidation, which is governed by both methanogens and methanotrophs (Inubushi et al., 2005). The application of biochar and N to soil provides additional carbon (C) sources for methanogens, resulting in higher $CH_4$ emissions (Liu and Greaver, 2009; Singla and Inubushi, 2014). However, in N-limited regions, N addition may also alleviate the adverse effects of N limitation on methanotrophic activities, thereby accelerating $CH_4$ uptake (Peng et al., 2019; Deng et al., 2020). Studies have also confirmed that microbial autotrophic nitrification and denitrification mechanisms are the primary pathways responsible for $N_2O$ formation (Baggs, 2011; Duan et al., 2019). Most studies suggest that N addition generally stimulates $N_2O$ emissions (Liu and Greaver, 2009; Deng et al., 2020; Du et al., 2021), while biochar addition hinders $N_2O$ production (Song et al., 2016; Liu et al., 2019a; He et al., 2021b). The addition of N fertilizer to the soil can increases the substrate availability for nitrifying and denitrifying bacteria and promote $N_2O$ emissions (Liu and Greaver, 2009), while the adsorption of biochar on soil $NH_4^+$ and $NO_3^-$ reduces their availability and thus suppress $N_2O$ emissions (Cayuela et al., 2013). Therefore, understanding the impact of biochar and N interaction on soil GHGs fluxes and soil properties is critical for accurately predicting C and N cycles in terrestrial ecosystems.

To date, several meta-analyses have primarily focused on the isolated effects of N or biochar addition on soil GHGs fluxes (Ji et al., 2018; Liu et al., 2019a; Deng et al., 2020; Du et al., 2021). Only one study, with certain restriction, investigated the soil GHGs fluxes responses to the interaction between biochar and N (He et al., 2021b). It is noteworthy that soil GHGs reactions are strongly tied to both soil C and N conversion processes, thus, data on soil C and N contents are equally relevant. Additionally, the assessment of yield should not be disregarded since N and biochar additions are frequently utilized in agroecosystems. He et al. (2021b) attempted to explore the impacts of various factors on soil GHGs, but their research did not quantify the relative importance of the involved factors, nor the direct and indirect effects of predictors on soil GHGs. Hence, a global analysis examining the combined effects of biochar and N addition on soil GHGs, as well as soil C and N content, yield, and greenhouse gas intensity (GHGI), while quantifying the key factors, would be more conducive to an accurate assessment of the global soil GHGs budget.

In this study, we synthesized 870 paired observations from 75 peer-reviewed papers to address the following questions: 1) How do soil C and N contents respond to biochar and N additions worldwide? 2) What are the global responses and sensitivities of soil GHGs, yield, and GHGI to biochar and N additions? 3) What is the effect of various factors (geo-climatic factors, edaphic properties, biochar and N treatment parameters, and experimental scenarios) on soil GHGs fluxes?

# 2 Materials and methods

## 2.1 Data preparation

The relevant literature was searched using the Google Scholar, Web of Science, and CNKI databases (2010–2021) using the search terms (char/biochar) AND (nitrogen/N) AND (greenhouse gas/$CO_2$/$CH_4$/$N_2O$). The selection criteria were as follows: 1) included at least four treatments simultaneously (control, N addition, biochar addition, and co-addition of biochar and N at the same site); 2) the means and standard deviations (SDs) could be obtained either directly or indirectly from the text. Ultimately, 75 peer-reviewed papers containing 870 paired observations from 71 sites worldwide were screened and analyzed (Supplementary Figure S1).

Additionally, geo-climatic factors, soil variables, biochar and N treatment parameters, and experimental scenarios were also recorded from the text (Supplementary Table S1, S2). The GWP was assessed by $CH_4$ and $N_2O$ with conversion factors of 25 and 298, respectively (Wang et al., 2012; Liu et al., 2014). The greenhouse gas intensity (GHGI) was evaluated by dividing the GWP by yield (t $ha^{-1}$). The original data in the graphs were obtained using the Get-Data software (ver. 2.20, Russian Federation).

## 2.2 Data analysis

### 2.2.1 Individual effects

The response ratio (RR, natural logs of the ratio of the mean of the treatment group to the control group) were used to evaluate the individual effect of N addition, biochar addition, or both combined (BN) (Hedges et al., 1999). The specific calculation of variance (vi) and weight (w) for each RR and the weighted mean RR ($RR_{++}$) were as described by Jia et al. (2020).

The meta-analysis was conducted using the R (v.4.0.2). The 95% confidence interval (CI) for RR did not overlap with zero, indicating a significant individual effect. The percentage change of $RR_{++}$ was calculated as $(e^{RR++} - 1) \times 100\%$. Additionally, a model selection analysis was performed by using the ‘glmulti’ package within R to specify the relative importance of each predictor. Predictors with a sum of Akaike weights greater than 0.8 were considered to be the most important. Moreover, publication bias was examined by calculating the fail-safe number (Supplementary Table S3).

### 2.2.2 Main and interactive effects

The main effect of a factor represents the difference obtained by comparing its net effect in the presence and absence of a second factor. Following the methods of Gurevitch et al. (1992) and Crain et al. (2008), Hedge’s $d$ was used to assess the main effect sizes of either N ($d_N$) or biochar addition ($d_B$) on the variables as well as their interactions ($d_I$), calculated as follows:

$$d_B = \frac{(\bar{X}_B + \bar{X}_{BN}) - (\bar{X}_N + \bar{X}_C)}{2s} J(m)$$

$$d_N = \frac{(\bar{X}_N + \bar{X}_{BN}) - (\bar{X}_B + \bar{X}_C)}{2s} J(m)$$

$$d_I = \frac{(\bar{X}_{BN} - \bar{X}_B) - (\bar{X}_N - \bar{X}_C)}{2s} J(m)$$

where $\bar{X}_C, \bar{X}_B, \bar{X}_N$, and $\bar{X}_{BN}$ were the means of a variable in the control and treatment groups involving biochar addition, N addition, and their combination, respectively. The degree of freedom (m), correction term for small sample bias (J(m)), and standard deviation (s) were evaluated as follows:

$$\mathrm{m} = n_C + n_B + n_N + n_{BN} - 4$$

$$J(m) = 1 - 3/(4\mathrm{m} - 1)$$

$$s = \sqrt{\frac{(n_C - 1)S_C^2 + (n_B - 1)S_B^2 + (n_N - 1)S_N^2 + (n_{BN} - 1)S_{BN}^2}{m}}$$

The variance of $d_I$ ($v_2$), weighted mean $d_I$ ($d$++), and standard error [s ($d_{++}$)] were calculated as:

$$v_2 = \frac{1}{4}\left[\frac{1}{n_C} + \frac{1}{n_B} + \frac{1}{n_N} + \frac{1}{n_{BN}} + \frac{d_I^2}{2(n_C + n_B + n_N + n_{BN})}\right]$$

$$d_{++} = \sum_{i=1}^{i}\sum_{j=1}^{k} w_{ij} d_{ij} \Big/ \sum_{i=1}^{i}\sum_{j=1}^{k} w_{ij}$$

$$s(d_{++}) = \sqrt{\frac{1}{\sum_{i=1}^{\mathrm{i}}\sum_{j=1}^{\mathrm{k}} \mathrm{w_{ij}}}}$$

$$95\%\ \mathrm{CI} = d_{++} \pm 1.96 s(d_{++})$$

where $i$ was the number of groups, k was the number of comparisons in the $i$th group, and $w$ was the weight (reciprocal of the variances).

The interaction effects of biochar and N addition showed three types: additive, antagonistic, and synergistic. If the 95% CI overlap was zero, the interactive effect was considered additive. When the individual effects were in the opposite direction or both negative, the interactions >0 were denoted antagonistic (<0 were synergistic). If both individual effects were positive, the interactions >0 were denoted synergistic (<0 were antagonistic) (Crain et al., 2008; Yue et al., 2017).

## 3 Results

### 3.1 The impact of biochar and N additions on GHGs fluxes and soil properties

The results showed that the addition of biochar, N, and BN all significantly increased soil $CO_2$ emissions (+8.5%, +28.9%, and +29.6%) and yield (+4.2%, +53.7%, and +58.2%), respectively, but had no significant effect on $CH_4$ fluxes (Figure 1). The soil $N_2O$ emissions and GWP were significantly increased under the N and BN treatments, while biochar addition reduced them.

The addition of biochar, N, and BN also significantly increased the soil SOC, dissolved organic carbon (DOC), and TN (Figure 1). Biochar addition significantly increased soil pH, microbial biomass C (MBC), microbial biomass N (MBN), cation exchange capacity (CEC), ammonia-oxidizing bacteria (AOB), *nirS*, and *nosZ*, but decreased $NH_4^+$-N (Supplementary Figures S1, S2). N addition alone increased soil $NH_4^+$-N and $NO_3^-$-N, but decreased soil pH and *nosZ*. The combined addition of BN significantly increased soil MBC, CEC, AOB, and *nosZ*, but reduced soil bulk density.

### 3.2 Main and interactive effects of two factors on GHGs fluxes and soil properties

The main effects results showed that biochar addition significantly promoted $CO_2$ emissions and yield, while reducing $CH_4$ uptakes, $N_2O$ emissions, GWP, and GHGI (Figure 2). The main effects of N addition were increased $CO_2$ and $N_2O$ emissions, GWP, and yield, in tandem to decreased soil $CH_4$ fluxes and GHGI.

The interactive effects showed that the combined addition of biochar and N had antagonistic effects on $CO_2$ and $N_2O$ emissions and GWP, synergistic effects on $CH_4$ emissions and yield, and additive effects on soil $CH_4$ uptakes and GHGI (Figure 2). The antagonistic effects of $CO_2$ and $N_2O$ emissions and GWP accounted for 46.5%, 51.1%, and 30.0%, respectively. The synergy ratios of $CH_4$ emissions and yield were 2.1% and 36.0%, respectively. Moreover, BN addition produced synergistic effects on DOC, MBC, and $NO_3^-$-N, but produced antagonistic effects on TN and $NH_4^+$-N.

### 3.3 Drivers of soil GHGs, GWP, yield, and GHGI

The results showed that the climate and soil factors, biochar and N treatment parameters, and experimental scenarios (land-use, experimental method, and duration) were closely related to soil

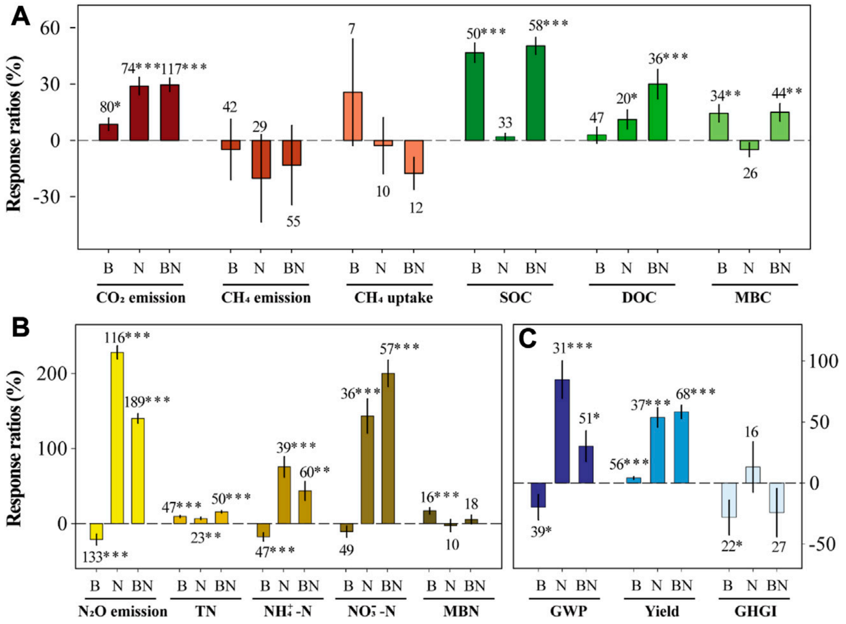

FIGURE 1
Effects of biochar, nitrogen (N), and combined biochar and N (BN) additions on soil carbon cycle **(A)**, N cycle **(B)** and GHGI **(C)**.

GHGs (Figures 3, 4), GWP, yield, and GHGI (Supplementary Table S4 and Supplementary Figure S3). The model selection analysis revealed that the N forms, SOC, STN, biochar pyrolysis temperature, and soil pH were key predictors involved in BN treatment, explaining 47% of the $CO_2$ emissions variability in the structural equation model (SEM) (Figures 5A, D). Additionally, BN addition stimulated higher $CO_2$ emissions in paddy fields added with organic fertilizers (Figure 3A).

The SEM indicated that MAP, soil pH, biochar pH, and STN explained 68% of the variability in $CH_4$ emissions, with STN and MAP being the dominant factors in the context of BN treatment (Figures 5B, E). Similarly, STN was also found to be the key factor determining $CH_4$ emissions under N treatment (Supplementary Figure S4B). In medium-textured soils, BN addition produced more $CH_4$ emissions than N addition alone (Figure 3B). Herbaceous-derived biochar significantly increased $CH_4$ uptakes, while wood-derived biochar suppressed it in N-fertilized soils (Figure 3C).

The MAT, MAP, duration, and STN directly affected 34% of the $N_2O$ emissions variability under BN treatment (Figure 5F). The MAT was a key predictor of $N_2O$ emissions under the N and BN treatments (Figure 5 and Supplementary Figure S4), and a significant relationship between MAT and $N_2O$ emissions was also observed (Figure 4). The results showed that following the addition of BN, the pot experiments resulted in lower $N_2O$ emissions compared to the field experiments (Figure 3D).

Both MAP and MAT were significantly negatively correlated with GWP, yield, and GHGI under the N and BN treatments (Supplementary Table S4). The GWP decreased with increasing soil pH under the biochar and BN treatments. Adding biochar and N to paddy fields or fine-textured soil could greatly boost their yield (Supplementary Figure S3).

# 4 Discussion

## 4.1 Individual effects of the single or combined addition of biochar and N on soil GHGs, yield, and GHGI

Overall, biochar addition significantly promoted $CO_2$ emissions, which was a finding consistent with earlier meta-analyses (He et al., 2016; Song et al., 2016). Functioning as exogenous C input, biochar can enrich soil organic matter status, promote the release of inorganic C, and stimulate microbial metabolic activity, thereby augmenting available substrates for soil respiration (Smith et al., 2010; Luo et al., 2011; Omondi et al., 2016; He et al., 2021b). Although our results showed that biochar application significantly increased SOC (46.7%) and MBC (14.4%) and insignificantly increased DOC content (2.7%) (Figure 1), we only observed a significant positive relationship between SOC and $CO_2$ emissions (Figure 4), suggesting that biochar-induced increase in $CO_2$ emissions were mainly related to changes in SOC content in the current study. Compared with biochar addition alone, N and BN additions facilitated more $CO_2$ emissions, potentially due to the significant increase in soil DOC content (11.2% for N addition; 30.0% for BN addition; Figure 1). In addition, our findings indicated that N and BN additions also greatly enriched soil $NH_4^+$-N and $NO_3^-$-N (Figure ), leading to higher N availability and thus, promoting microbial C mineralization in the soil (Lu et al., 2011; Zhou et al., 2013).

The current meta-analysis showed that biochar addition mitigated $N_2O$ emissions, and conversely, N and BN additions greatly stimulated it, consistent with the results of He et al. (2021b). It is well understood that N-fertilized soils provide abundant available substrates for nitrifying and denitrifying

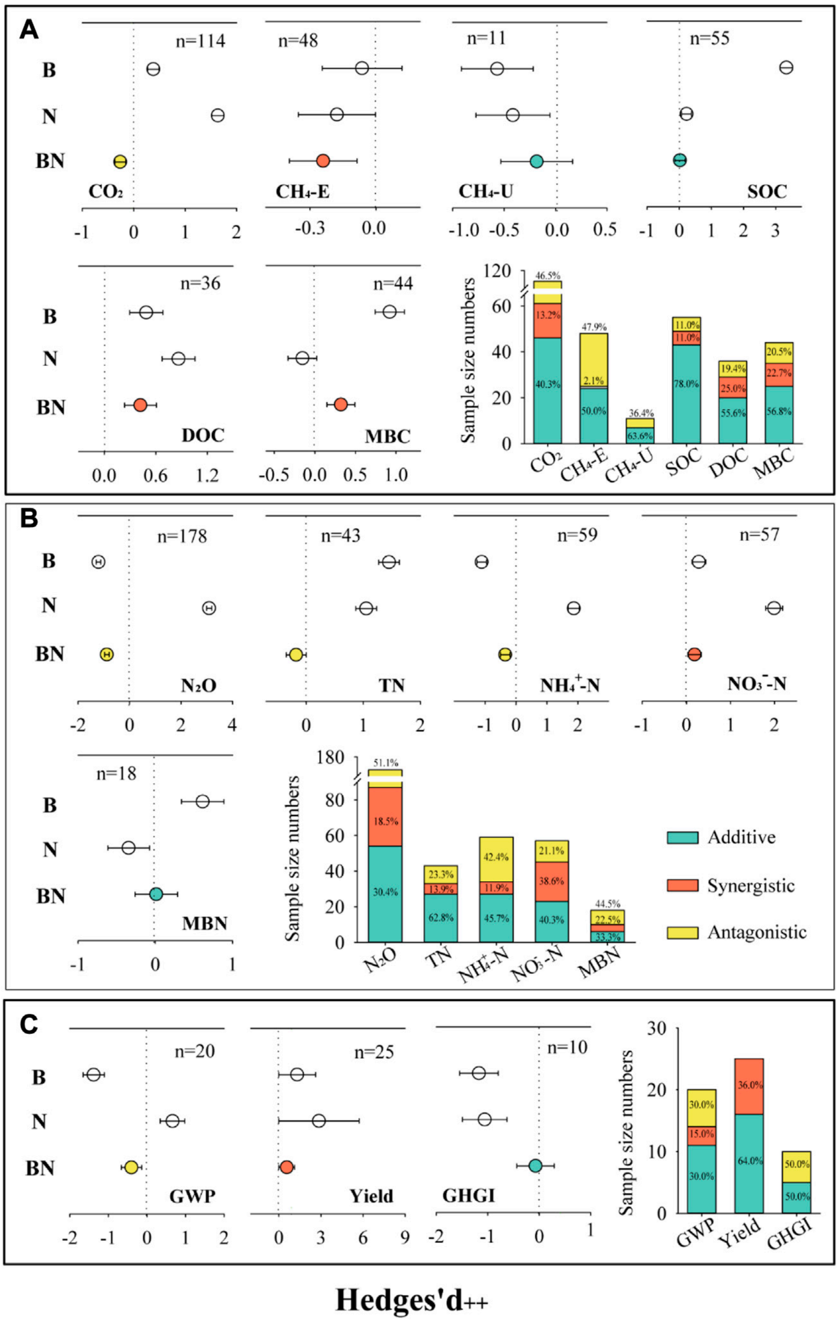

FIGURE 2
Effects of biochar-N interactions on soil carbon cycle **(A)**, N cycle **(B)** and GHGI **(C)**.

bacteria, which ultimately results in increased $N_2O$ emissions (Deng et al., 2020). This possibility is supported by the current positive relationship between the increased soil $NH_4^+$-N contents and $N_2O$ emissions under the N and BN treatments (Figures 1, 4). Moreover, the reduction in $N_2O$ emissions caused by biochar may be attributed to its liming effect. Increased soil pH may promote $N_2O$ reductase activities, resulting in lower $N_2O$ emissions (Clough et al., 2013), and we actually found an increase in *nosZ* (Supplementary Figure S2). Alternatively, biochar adsorbed soil $NH_4^+$-N and $NO_3^-$-N contents, thus reducing the available substrates for soil nitrifying and denitrifying microbes, ultimately hindering soil $N_2O$ emissions rates (Cheng et al., 2008; Cayuela et al., 2013). The results showed that biochar addition alone actually reduced soil $NH_4^+$-N and $NO_3^-$-N (Figure 1), and the RRs of $NH_4^+$-N and $NO_3^-$-N decreased with increasing biochar application rates (Supplementary Figure S5).

The soil GWP was assessed jointly by the $CH_4$ and $N_2O$ fluxes, and the results suggest that biochar addition did not significantly alter $CH_4$ fluxes (Figure 1), thus, the reduction in biochar-induced GWP was mainly due to less $N_2O$ emissions. Similarly, the increase

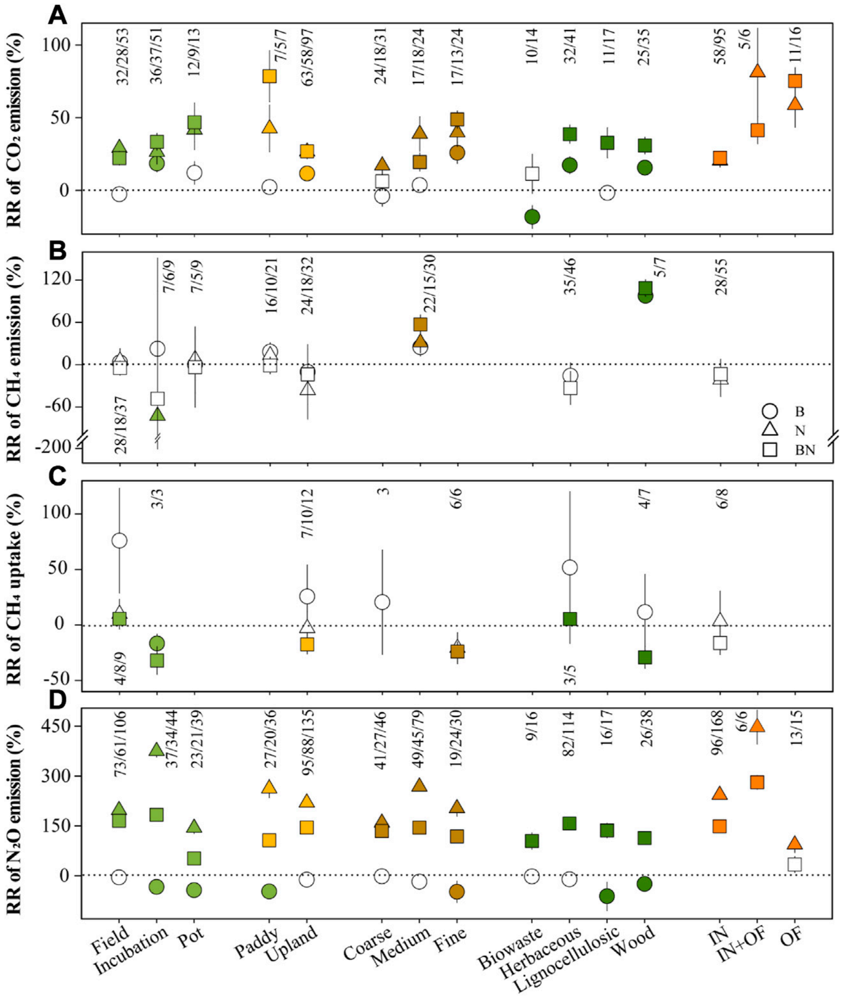

FIGURE 3
The responses of soil $CO_2$ emission **(A)**, $CH_4$ emission **(B)**, $CH_4$ uptake **(C)** and $N_2O$ emission **(D)** to predictors under BN addition.

in GWP resulting from the addition of N or BN stems from higher $N_2O$ emissions (Figure 1). Moreover, the results found that the addition of biochar, N, and BN all significantly boosted crop yield, which was closely related to improved N availability (Supplementary Table S4). Consequently, the positive effects of crop yield (4.2%) coupled with decreased soil GWP (−19.8%) led to lower soil GHGI (−28.2%) in the biochar-amended plots.

## 4.2 Interactive effects of biochar and N application on soil GHGs, yield, and GHGI

Antagonistic effects indicate that the combined effect of two factors is weaker than the sum of their individual effects (Coors and Meester, 2010; Zhou et al., 2016). Our study showed that combined BN addition promoted $CO_2$ emissions by 29.6%, which was less than the sum of the two individual effects (37.4%, Figure 1). Antagonistic effects of the biochar-N interaction on $CO_2$ emissions aligned with the meta-analysis of He et al. (2021b), which may be attributable to accompanying reduced soil microbial respiration rates (Iqbal et al., 2009; Zhang et al., 2012; Zhang et al., 2021). Previous research has found that N inhibition of white-rot fungi could reduce phenoloxidase activity, thereby impairing soil microbial respiration (Frey et al., 2004). The adsorption of inorganic N by biochar can reduce N availability for microbes (Steiner et al., 2008; Clough et al., 2013). The current indeed found a significant decrease in soil $NH_4^+$-N content due to the biochar-N interaction (Figure 2).

Our findings reveal a synergistic effect of biochar-N interaction on $CH_4$ emissions, contradicting those of a recent meta-analysis (He et al., 2021b). This discrepancy may be attributed to the differences in sample size between the studies, and our results may be more convincing science our observations (n = 48) are larger than theirs (n = 33). Nonetheless, there were some similar results where the interaction of biochar with N significantly reduced $CH_4$ emissions. Other studies also demonstrated that biochar reduced $CH_4$ emissions in rice fields, especially in N-fertilized plots (Xie et al., 2013; Qin et al., 2016; Liu et al., 2019b). The existing empirical evidence suggests that biochar-induced increases in soil pH and aeration favor methanotrophs, thereby reducing *mcrA*/*pmoA* and ultimately suppressing $CH_4$ emissions (Feng et al., 2012). Our study demonstrated that BN addition slightly

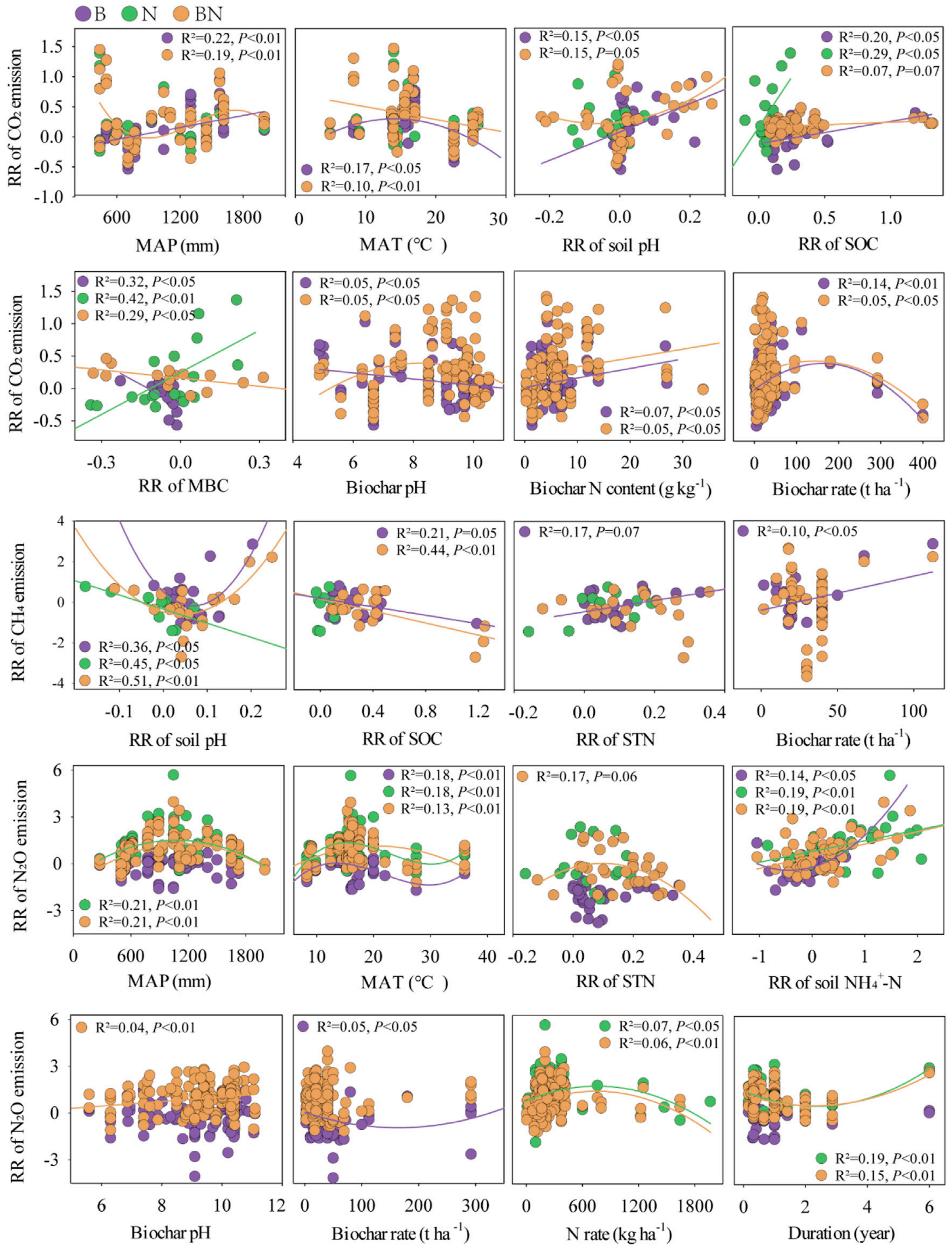

FIGURE 4
Relationships between the predictors and the responses of soil GHGs. MAP, mean annual precipitation; MAT, mean annual temperature.

increased the soil pH by 2.0% and significantly decreased the soil bulk density by 4.7% (Supplementary Figure S2).

The observed mitigative and antagonistic effects of the biochar-N interaction on $N_2O$ emissions indicate that the biochar-induced reduction in $N_2O$ emissions exceeded the N-induced increase in $N_2O$ emissions, possibly due to the alteration in soil pH and $NH_4^+$-N levels (Figure 2). The abundant alkaline cations provided by biochar raised the soil pH, which stimulated $N_2O$ reductase activities and facilitated the complete denitrification of $N_2O$ to $N_2$ (Cayuela et al., 2013). Our results showed that BN addition slightly increased soil

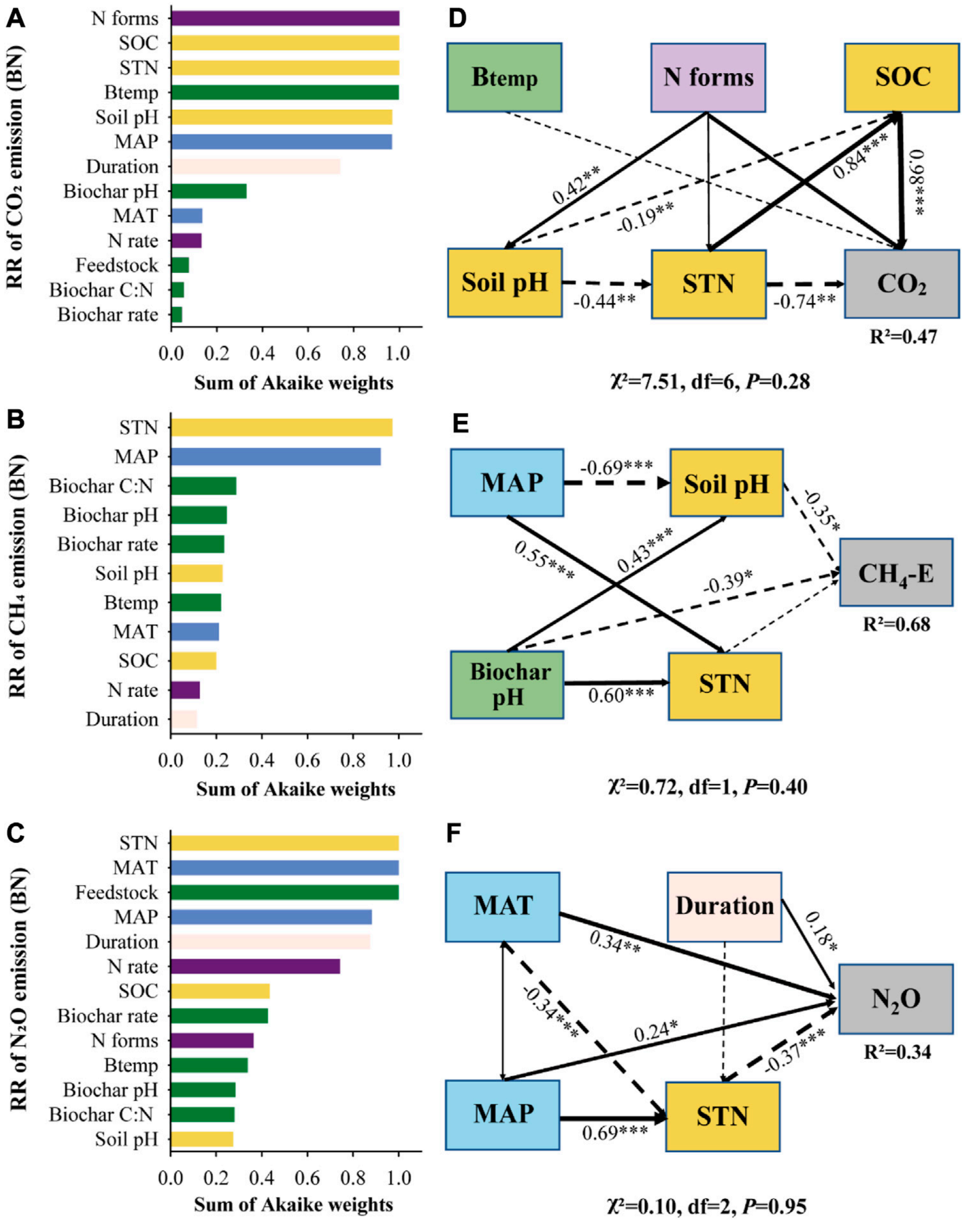

FIGURE 5
Model-averaged importance of the predictors of BN addition impacts on soil GHGs **(A–C)**. The structural equation model (SEM) examining the indirect and direct effects of predictors on soil GHGs **(D–F)**. MAP, mean annual precipitation; MAT, mean annual temperature; SOC: soil organic carbon; B temp: biochar pyrolysis temperature.

pH and greatly increased *nosZ* by 40.3% (Supplementary Figure S2). The above-mentioned immobilization of soil $NH_4^+$-N by biochar also reduced the available substrates for soil nitrifying bacteria, ultimately hindering the $N_2O$ emissions rate (Cheng et al., 2008). The reduced soil bulk density caused by the biochar-N interaction increased the soil aeration (Supplementary Figure S2), thereby inhibiting the soil denitrification process and slowing down $N_2O$ production (Simek et al., 2002).

The biochar-N interaction exhibited an antagonistic effect on GWP, but a synergistic effect on yield. It is well understood that reduced soil GWP results from lower $CH_4$, and $N_2O$ emissions (Figure 2). Adding N fertilizer to biochar-treated soil can enrich the nutrient supply and improve nutrient use efficiency, thus promoting crop yield (Hu et al., 2021; Kotuš et al., 2022). In this study, the findings of increased DOC, MBC, and $NO_3^-$-N provide some support for this explanation under the interactive addition of biochar and N (Figure 2).

## 4.3 Factors affecting the response of soil GHGs fluxes

Existing empirical evidence suggests that the effects of N and biochar addition on soil GHGs fluxes are diverse, with the degree

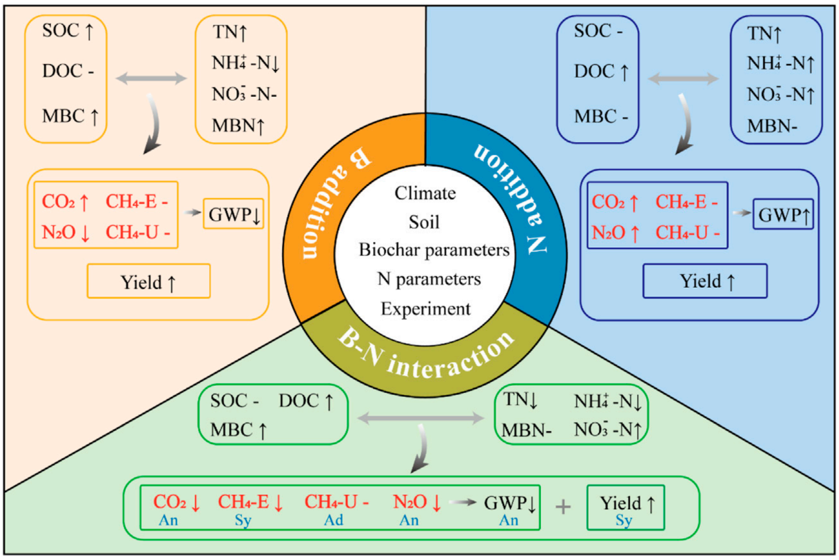

FIGURE 6
Potential mechanisms for the effects of biochar-N interactions on soil GHGs fluxes. An, Sy, and Ad indicate antagonistic, synergistic, and additive, respectively.

and direction of responses varying with geo-climatic factors, edaphic properties, biochar and N treatment parameters, and experimental scenarios (Liu et al., 2018; Deng et al., 2020; He et al., 2021b).

### 4.3.1 Climates and edaphic factors

Model selection analysis revealed that the MAP and MAT were key predictors of soil GHGs emissions under BN treatment (Figure 5). The MAP and MAT could change the soil microhabitats by altering the soil temperature and moisture, thus affecting GHGs fluxes (Yan et al., 2022; Yang et al., 2022). Most preexisting studies have concluded that SOC decreases with increasing temperature (Hontoria et al., 1999; Lal, 2004), leading to reduced available substrates for soil respiration (Brye et al., 2016). Similarly, we observed that $CO_2$ emissions decreased with increasing MAT under BN treatment (Figure 4), possibly related to temperature-induced changes in SOC. The emission and uptake of CH4 are influenced by the joint activities of methanotrophs and methanogens (Inubushi et al., 2005), and changes in soil moisture caused by rainfall affect soil aeration status (Yang et al., 2022). The SEM showed that MAP and MAT directly affected $N_2O$ emissions (Figure 5), and both displayed a parabolic relationship with $N_2O$ emissions (Figure 4), indicating the threshold effects of MAP and MAT on $N_2O$ emissions under the BN treatment.

The addition of biochar and N each stimulated greater $CO_2$ emissions in fine-textured soils compared to coarse-textured soils (Figure 3), consistent with the finding of He et al. (2021b). Existing empirical evidence posits that SOC increases with silt and clay contents but decreases with sand content (Zinn et al., 2005; Gami et al., 2009). Consequently, fine-textured soil can provide more available substrates for soil organic matter mineralization and microbial survival, thereby resulting in higher $CO_2$ emissions (Figure 4), and the SEM actually revealed the direct impact of SOC on $CO_2$ emissions (Figure 5A). Our results showed that the initial N content of the soil was also a key factor affecting $CH_4$ emissions under biochar and BN additions (Figure 5 and Supplementary Figure S4), and higher soil N content resulted in more $CH_4$ emissions (Figure 4), as N-rich soil provides a greater nutrient supply for methanogens. It is well understood that $N_2O$ emissions increase with increasing soil $NH_4^+$-N due to more available substrates for the nitrification process (Figure 4).

### 4.3.2 Biochar and N treatment parameters

Biochar feedstock and its application rates can modulate soil feedback, thereby affecting soil GHGs fluxes (Li et al., 2018; Zhang et al., 2019). Our results showed that biowaste-derived biochar suppressed $CO_2$ emissions, whereas biochar produced from herbaceous or wood pyrolysis stimulated it (Figure 3). The poor C content of biowaste-derived biochar can impair the mineralization rate of easily decomposable C from this biochar itself (Liu et al., 2019a). We observed a threshold effect of the biochar application rates on $CH_4$ emissions, with biochar application rates exceeding 22.7 t $ha^{-1}$ promoting $CH_4$ emissions (Figure 4), as more biochar supply enriches the available substrates for methanogens (Singla and Inubushi, 2014). Additionally, the lignocellulosic/wood-derived biochar mitigated $N_2O$ emissions, but biowaste-derived biochar had no significant effect on it, which is likely attributable to the lesser surface area and weaker aromatic structure of biowaste-derived biochar (Mandal et al., 2016).

Moreover, N forms and their application rates were also crucial predictors of GHGs responses (Figure 5 and Supplementary Figure S4). The combined addition of organic and inorganic N greatly promoted $CO_2$ and $N_2O$ emissions compared to inorganic N addition alone (Figure 3). The abundant C produced by the decomposition of organic fertilizers can provide nutrient and cellular energy for microbial respiration and denitrifying bacteria, thereby promoting the rate of denitrification (Clough et al., 2013; Xie et al., 2013). Furthermore, the meta-regression analysis showed a significant negative relationship between $CH_4$ uptake and the N application rates (data not shown), which is similar to previous findings (Robertson, 2006; Zhang et al., 2008). The accumulation of soil $NO_3^-$-N and $NH_4^+$-N due to high N input reduces soil pH, which is toxic to methanotrophs, and thus inhibits $CH_4$ uptakes (Gulledge et al., 2004; Deng et al., 2020).

### 4.3.3 Experimental scenarios

Different experimental scenarios (including alterations in the experimental method, duration, and land use) affect the soil bulk density, oxygen partial pressure, and nutrient availability, and ultimately alter soil GHGs (Vargas et al., 2012; Li et al., 2018). Our results showed that BN addition stimulated more $CO_2$ emissions in incubation/pot experiments than in the fields (Figure 3), which is in line with the findings of Song et al. (2016), suggesting that the increased $CO_2$ emissions was mainly contributed by the incubation/pot experiment. This discrepancy may be attributed to differences in fertilizer application rates, experimental durations, and soil hydrology between the field and incubation/pot experiments.

The result showed that $CH_4$ uptake decreased with increasing trial duration (data not shown). Spokas (2013) found that the stable structure of field-aged biochar was partially destroyed, making it easier for methanogens to decompose and utilize, thus promoting $CH_4$ production and reducing $CH_4$ absorption. Similarly, a longer experimental duration was found to be not conducive to $N_2O$ emissions mitigation (Figure 4). He et al. (2021a) found that continuous N application for 30 years had a stronger stimulating effect on the gross rate of nitrogen mineralization and autotrophic nitrification. Conversely, The destruction of the aromatic structure of the weathered biochar and the increased content of acidic functional groups weakened the electron transfer ability in the denitrification process (Jose et al., 2018). Therefore, the stimulation of $N_2O$ emissions by aging biochar may be attributed to the nitrification pathway.

Moreover, adding biochar and N to the paddy field stimulated more $CO_2$ emissions than in upland fields (Figure 3), which is consistent with an earlier meta-analysis (Liu et al., 2016). It is generally accepted that paddy field soils have higher initial organic matter and N application rates, which may account for the more positive $CO_2$ emissions response. Consequently, high N addition alone stimulated more $N_2O$ emissions in paddy fields compared to upland fields. However, adding N to biochar-treated soil produced more $N_2O$ in the upland. These heterogeneous results imply that both fertilization methods and land use types need to be considered when formulating effective climate mitigation strategies.

## 5 Conclusion

In the current meta-analysis, the individual effects, main effects, and interaction effects of biochar and N addition were examined simultaneously (Figure 6). The results showed that biochar, N, and BN additions all increased $CO_2$ emissions, SOC, DOC, TN, and yield, respectively, but caused no change in $CH_4$ fluxes. N and BN additions stimulated $N_2O$ emissions and GWP, while biochar addition inhibited them. In addition, the effect of the biochar-N interaction on the soil GHGs was mainly antagonistic, while its effect on yield was synergistic. It is worth noting that the responses of soil GHGs were also affected by geo-climatic factors, edaphic properties, biochar and N treatment parameters, and experimental scenarios. Applying herbal biochar and N to fine-textured soils may produce better economic and environmental benefits. Furthermore, global climate change factors (such as warming, drought events, and elevated $CO_2$ concentrations) could interact with biochar/N addition to jointly affect soil GHGs, and the long-term persistence of biochar-N interactions also needs to be further verified.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the first author.

## Author contributions

XJ: Conceptualization, Methodology, formal analysis, investigation, writing—original draft. WY: Software, validation, supervision, writing—review and editing. HM: Investigation, resources. ZS: Conceptualization, investigation, writing—review and editing.

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## Conflict of interest

## Publisher's note

## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1123897/full#supplementary-material

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