Received: 28 July 2022 | Revised: 22 September 2022 | Accepted: 23 September 2022

DOI: 10.1111/gcbb.13003

GCB-BIOENERGY Open Access
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY
WILEY

RESEARCH ARTICLE

How much is soil nitrous oxide emission reduced with biochar application? An evaluation of meta-analyses

Navneet Kaur[1] | **Christina Kieffer**[1] | **Wei Ren**[2] | **Dafeng Hui**[1]

[1]Department of Biological Sciences, Tennessee State University, Nashville, Tennessee, USA

[2]Department of Natural Resources & the Environment, University of Connecticut, Storrs, Connecticut, USA

Correspondence
Dafeng Hui, Department of Biological Sciences, Tennessee State University, Nashville, TN 37209, USA.
Email: dhui@tnstate.edu

Funding information
USDA National Institute of Food and Agriculture; National Science Foundation, Grant/Award Number: EiR (2000058), EiR (1900885) and MRI (1919897)

Abstract

Nitrous oxide (N_2O) is the third important long-lived greenhouse gas next to carbon dioxide and methane and croplands are considered biogeochemical hotspots of soil N_2O emissions. To reduce soil N_2O and other greenhouse emissions, climate-smart agricultural practices including biochar application have been applied. Many studies have been conducted with biochar application but results from these studies are not conclusive. To address this issue, meta-analysis, a quantitative review that synthesizes results from multiple independent studies, has been widely used. The results from different meta-analyses also differ but are seldomly evaluated. In this study, we evaluated meta-analyses on the effects of biochar application on soil N_2O emissions. A grand mean response ratio (RR) was further proposed to estimate an overall effect and the impacts of experiment setting, properties of biochar and soil, and agricultural practices. We found 18 meta-analysis papers were published between 2014 and 2022. Sample size (publications or experiments) varied from less than 30 to more than 1000, with a mean sample size of 275. RR was calculated in all studies except one. While four meta-analyses did not find a significant effect of biochar application on soil N_2O emissions, all others reported reductions of soil N_2O emissions, but the magnitude ranged from −10.5% to −54.8%. Synthesizing all results from these meta-analyses, we found that biochar application overall significantly reduced the soil N_2O emissions by 38.8%. The impacts increased with experimental duration till one and half years and reduced after that. Biochar application rate and C:N ratio had large influence on the effects of biochar application on soil N_2O emissions. This study demonstrated that while meta-analysis provides a more comprehensive and better estimation, the inconsistence among these studies may need to be further evaluated. A grand mean RR based on meta-analyses could be more accurate and representative than single meta-analysis.

KEYWORDS
biochar, cropland, greenhouse gas emission, mega-analysis, meta-analysis, response ratio, soil N_2O emission

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access -WILEY

1 | INTRODUCTION

Nitrous oxide (N_2O) is one of the major greenhouse gases that significantly contribute to climate change. It has a global warming potential 296 times higher than carbon dioxide (Dalal et al., 2003) and has an atmospheric life of 114 years which make it more potent and powerful even at low concentrations (Uchida & von Rein, 2018). Agriculture is a key anthropogenic source for atmospheric N_2O. It accounts for the 78% of global N_2O emissions, largely because of the excessive use of nitrogen (N) fertilizer (Maaz et al., 2021). The excess of the applied fertilizer is not used by the plants and is mostly lost through N leaching or into the environment in different gaseous forms of N, particularly N_2O (Bouwman et al., 2013). Soil is the largest source for agricultural emissions of N_2O (Dijkstra et al., 2013). Soil N_2O emission is a result of the biological processes of nitrification and denitrification (Shakoor et al., 2021). The relative contributions of these N_2O-generating process are influenced by soil ammonia and nitrate concentrations, soil labile carbon, soil temperature, water content, and aeration, soil texture, and gaseous diffusion rate (Deng et al., 2015; Huang et al., 2018; Hui, 2020; Snyder et al., 2009; Zhang et al., 2021). To reduce atmospheric N_2O concentration, it is imperative to reduce soil N_2O emissions from croplands.

Several N_2O mitigation strategies have been proposed in the past decades such as the use of enhanced efficiency fertilizer, controlled release fertilizer, nitrification and urease inhibitors, crop rotation, and manure management (Akiyama et al., 2010; Barnard et al., 2005; de Klein & Ledgard, 2005; Hui et al., 2018). Recently, the addition of biochar is recommended as a potential management strategy to mitigate soil N_2O emissions (Case et al., 2015; Feng et al., 2022; Liu et al., 2019; Wu et al., 2019). A global biochar strategy has been projected to be capable of reducing as much as 12% of human CO_2–C equivalent emissions annually (Woolf et al., 2010). Biochar is a carbon-rich substance generated from biomass by the process of pyrolysis in the absence of oxygen (He et al., 2021). The physicochemical properties (e.g., composition, particle and pore size distribution) of the resulting biochar are largely controlled by pyrolysis conditions and feedstock characteristics, which determine its suitability for a given application, as well as its behavior, transport, and fate in the environment (Verheijen et al., 2010). The effect of biochar on agricultural land is influenced by the quality and quantity of biochar (e.g., application rate, feedstock type, and pyrolysis temperature), soil properties (e.g., texture, moisture, pH, soil organic carbon, and C:N ratio), and environmental factors (e.g., temperature and precipitation). Biochar incorporation may change the structure, texture, porosity, particle size distribution, and density of the soil within the plant rooting zone, potentially modifying oxygen concentration, water storage capacity, and microbiological and nutritional condition (Atkinson et al., 2010). It may also affect soil pH, electrical conductivity, and cation exchange capacity. As a result, biochar addition has a high potential to sequester carbon (Borchard et al., 2019; Liu et al., 2019) and regulates soil N dynamics by altering the microbial mediated processes of nitrification and denitrification (Clough et al., 2013; Liu et al., 2014).

Many studies have been conducted on the effects of biochar application on soil N_2O emission. However, there is a high variation and uncertainty in how biochar application influences soil N_2O emissions (Spokas et al., 2012; Yangjin et al., 2021). Effects of biochar application are extremely inconsistent (Liu et al., 2019). It is evident in many cases that soil N_2O emissions are reduced upon addition of biochar (Cayuela et al., 2014). For example, several studies concluded that biochar application greatly reduces soil N_2O emissions (Case et al., 2015; Han et al., 2021; Jia et al., 2012; Van Zwieten et al., 2014). The decrease in soil N_2O emissions mostly resulted from improved soil aeration, pH modification, and N immobilization (He et al., 2021). In contrast, some other studies showed an enhancement in soil N_2O levels after the addition of biochar (Bruun et al., 2011; Sánchez-García et al., 2014). No significant effect of biochar amendment was also seen in studies conducted by Pereira et al. (2015) and Wang et al. (2015). The varied outcomes can be produced because of differences in soil moisture, temperature, and soil type. These findings also reveal that the effects of biochar amendment on soil N_2O emissions depend on the study settings, experiment duration, biochar application rate, biochar feedstock, and pyrolysis processes. The lack of complete knowledge regarding the reduced soil N_2O emissions due to biochar application restricts our understanding of biochar's potential involvement in global climate change mitigation.

Meta-analysis is a promising technique that synthesizing data from individual studies and providing an overall quantification (i.e., an effective size such as response ratio, RR) of treatment effect (Philibert et al., 2012; Shakoor et al., 2021; Song et al., 2016). As numerous data sources are merged into a single dataset by drawing from existing observational data in experimental studies, meta-analysis can reduce experimental errors and provide a better estimation of effective size of treatment (Deng et al., 2015; Hedges et al., 1999; Hui et al., 2021; Luo et al., 2006; Wan et al., 2001; Xu et al., 2021; Young et al., 2021). It is also considered a good approach to resolve the challenge of inconsistence revealed among different individual studies (Hedges et al., 1999; Shakoor et al., 2021). However, as the number of meta-analysis publications increases, the consensus on the overall effects of treatment generated in meta-analyses is not uniform and is highly dependent on the methodology and data selections used (Young et al., 2021). For the impacts of biochar application on soil N_2O emissions, many meta-analysis studies have been conducted (Cayuela et al., 2014; Shakoor et al., 2021; Verhoeven et al., 2017). The results vary significantly in both magnitude and direction among different meta-analysis studies (He et al., 2021; Schmidt et al., 2021; Shakoor et al., 2021; Verhoeven et al., 2017). For example, several meta-analysis studies reveal a significant reduction in soil N_2O emissions when biochar is added to soil (Borchard et al., 2019; Cayuela et al., 2014; Liu et al., 2018), but the magnitude varies among them. Some studies, however, found no significant effect of biochar treatment on soil N_2O emissions (Verhoeven et al., 2017; Zhao et al., 2019). Recently, Young et al. (2021) have conducted a review and synthesis of meta-analysis studies on impacts of agronomic measures on crop, soil, and environmental indicators. However, no studies have compared and evaluated the meta-analysis studies of the impacts of biochar addition on soil N_2O emissions and generated an overall grand effective size with its associated variation (Schmidt et al., 2021). Such a study could provide a better quantification and mechanistic understanding of biochar impacts on soil N_2O emissions.

In this study, we first compiled a dataset of the effects of biochar addition on soil N_2O emissions from meta-analysis publications. Based on the dataset, this mega-analysis further quantified the overall impacts of biochar application on soil N_2O emissions. We also considered the impacts of biochar properties, soil properties, experimental settings, and agricultural practices on the RRs of soil N_2O emissions in response to biochar application. The main objectives of this study were (1) to evaluate the meta-analyses of the biochar application on soil N_2O emissions; (2) to quantify a grand RR of biochar application on soil N_2O emissions based on meta-analyses; and (3) to explore the impacts of biochar properties, soil properties, crop type, and agricultural practices on the RR of soil N_2O emissions of biochar application.

2 | MATERIALS AND METHODS

2.1 | Literature search

In this study, we conducted a literature search for meta-analytical studies based on the effect of biochar application on soil N_2O emissions. The search was performed through electronic databases, Web of Science, and Google scholar. The keywords used were "soil nitrous oxide" or "soil N_2O" and "biochar" and "meta-analysis." The publication date range was till 2022. We initially found 105 meta-analysis papers related to biochar application. These resulting meta-analysis literature was further screened based on these criteria: (1) the study is a meta-analysis considering biochar application as a treatment; (2) soil N_2O emissions is considered as a response variable; (3) RR is used as effective size; and (4) sample size, RR, and standard error or 95% confident interval are reported or can be derived. A total of 18 meta-analysis publications were screened out from the search results. One meta-analysis using Hedge's d as effective size was not included in the data analysis. Of 18 meta-analyses, 14 studies used MetaWin for data synthesis, one used Open MEE, one used R, and the other two did not specify the software used. The selected 18 meta-analysis papers included those considered biochar as the only treatment factor or as one of several treatment factors. Some papers considered only soil N_2O emissions as a response variable while others included many other response variables. We only focused on soil N_2O emission response to biochar application treatment in this study.

2.2 | Data extraction and compilation

Sample size (n), RR, and 95% confidence interval (CI_{95}: L_1, L_2) were extracted from all meta-analytical studies. If the data were presented in figures, we extracted these data using Webplot Digitizer software (version 3.10, http://arohatgi.info/WebPlotDigitizer/). We collected the RR of biochar application on soil N_2O emissions from each of these meta-analysis papers. To investigate the impacts of experiment type, biochar properties, soil properties, and agricultural practices on the effects of biochar application on soil N_2O emissions, we also extracted the RR, n, and 95% CI of RR for each of these categories. For example, most meta-analyses studies identified experiment type as field, laboratory, or greenhouse. We collected the RR, n, and 95% CI of RR in the field, laboratory, or greenhouse from each meta-analysis paper when data were available.

2.3 | Data analysis

Response ratio and 95% confidence interval in the meta-analysis papers were presented either as RR or as percentage change. When the 95% confidence interval data were presented in percentage change, we first converted them to RR using $RR_{L1} = \ln(1-L_1/100)$ and $RR_{L2} = \mathrm{Ln}(1-L_2/100)$. RR was calculated as $RR = (RR_{L1} + RR_{L2})/2$ if not directly presented. Standard error of RR was estimated as $SE = (RR-RR_{L1})/1.96$. Grand mean of RR was calculated using weighted mean of RR using the equation:

$$RRg = \frac{\sum (ni * RRi)}{\sum ni} \tag{1}$$

where *RRg* is the grand response ratio of soil N_2O emissions across all studies, *RRi* the response ratio of soil N_2O emission from the *i*th meta-analysis study (paper), and n_i the sample size. We took a conservative approach and used the sample size as weight rather than the reverse of variance, as differences in variance, especially some small variances may create heavy weights on a few studies (Eldridge et al., 2016; Sánchez-Meca & Marin-Martinez, 1998; Zhou et al., 2022).

To calculate 95% confidence interval of the grand mean of RR, we calculated weighted standard error using the following equation:

$$SE = \sqrt{\frac{\sum\left((ni-1) * Sei^2\right)}{\sum(ni-1)}} \tag{2}$$

The RR, standard error, and 95% CI expressed in natural log were converted to percentage change while plotting the results. The following equation was used for conversions into percentage change:

$$\mathrm{RR}\,(\%) = \left(e^{\ln RR} - 1\right) \times 100 \tag{3}$$

Similar approach was used to calculate the grand mean RR for different types of experiment, biochar properties, soil properties, and agricultural practices. In the experimental setting category, we considered experiment type (laboratory, field, or greenhouse experiment), ecosystem type (corn, wheat, rice, grassland, forest, etc.), and experimental duration. Biochar properties included type of feedstock used for biochar production, biochar pH, and biochar C:N ratio, and type and temperature of pyrolysis used during biochar production. Soil properties included soil texture, soil organic C, soil C:N ratio, and soil pH. Agricultural practices included application rate of biochar, type of nitrogen fertilization used in combination with biochar, and N application rate. Sub-categories for each category were set based on the settings from most of the meta-analysis studies. For example, duration of experiment included seven sub-categories: <30, 30–60 days, 60–120 days, 120–180 days, 180–360, 360–720, and > 720 days. When different sub-categories were used in meta-analysis papers, we grouped them into closest sub-categories first using weighted mean, then estimated the grand mean RR using the equations (1)–(3). Data analysis was conducted using SAS 9.4 (SAS Institute Inc.). Figures were generated using Sigma Plot (SigmaPlot, 2014. SigmaPlot for windows).

3 | RESULTS

3.1 | Effect of biochar application on soil N_2O emissions

We found 18 meta-analysis papers reported the effects of biochar application on soil N_2O emissions published between 2014 and 2022. Sample size ranged from smaller than 30 to more than 900, with a mean sample size of 275 (Figure 1). Among all meta-analysis studies, four did not find significant effects of biochar application. Three of these studies had sample sizes lower than 40. Of the other 14 studies, RR varied from −0.10 to −0.79 (i.e., soil N_2O emissions was reduced by 10.5% to 54.8%). Based on all studies, we estimated a grand mean RRg and its 95% confidence interval. Our results showed that averaged over all studies, biochar application reduced soil N_2O emissions by

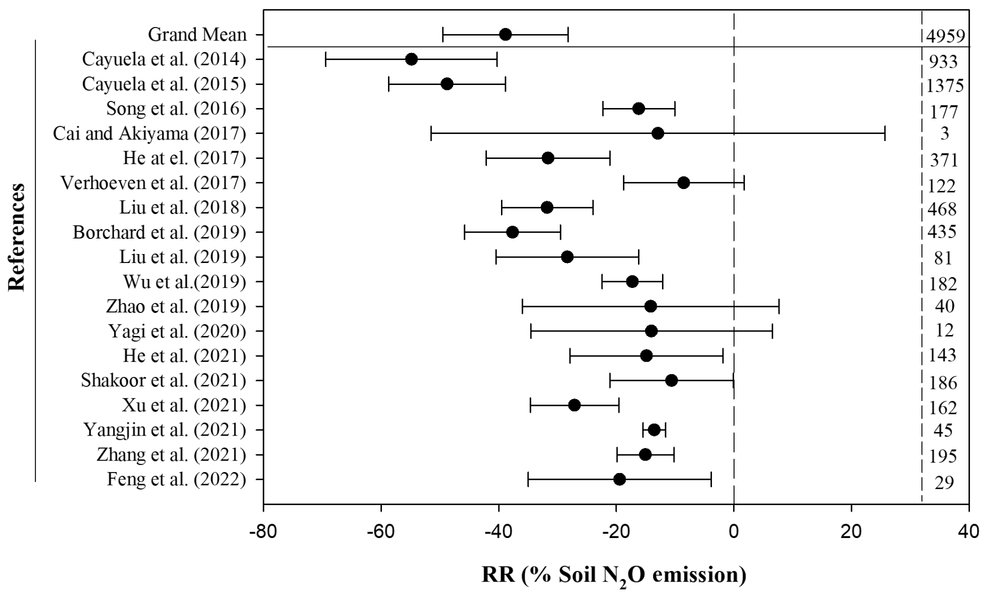

FIGURE 1 Response ratios (RRs) of biochar application on soil N_2O emissions from the meta-analyses and grand mean of RR and its 95% confidence interval. Number on the right side is the total number of experiments used for RR calculation.

38.8% with a 95% confidence interval raged from −32.4% to −44.8%.

3.2 | Impacts of experimental type, ecosystem, and duration of experiment on the effects of biochar application on N_2O emissions

Studies conducted in the laboratory and field condition showed significant impacts of biochar application on soil N_2O emissions (Figure 2a). The highest significant reduction (51.6%, −33.2% to −70.0% $CI_{95\%}$) was observed in the laboratory incubation experiments. Biochar application significantly reduced soil N_2O emissions by 27.1% (−1.0% to −53.2% $CI_{95\%}$) under the field condition. When experiment was conducted in the greenhouse, biochar application had no significant effect on soil N_2O emissions.

Ecosystem type showed different impacts on the effects of biochar application on soil N_2O emissions (Figure 2b). In the uplands, wheat and rice fields, significant reductions of soil N_2O emissions were found. On average, in the wheat fields, soil N_2O emissions were reduced by 23.6% (−6.9% to −40.4% $CI_{95\%}$) and in the rice fields, the reduction was 21.9% (−9.2% to −34.7% $CI_{95\%}$). The upland cropping system showed a reduction of 22.3% (−9.3% to −35.4% $CI_{95\%}$). No significant difference was observed in the fallow, grasslands, and forests. A trend of positive increase in soil N_2O emissions was shown in the grasslands.

Soil N_2O emissions were reduced by biochar application in experiments with all different experimental durations except the longest one (Figure 2c). Soil N_2O emissions were reduced between 18.9% and 44.7% among different durations. The reduction of soil N_2O emissions increased as experimental duration increased up to 180 days when the reduction was the highest (44.7%, −27.2% to −62.2% $CI_{95\%}$), and slightly decreased when the experimental duration was between 180 and 720 days.

3.3 | Impacts of biochar properties on the effect of biochar application on soil N_2O emissions

The response of soil N_2O emissions under biochar application depended upon the elements like feedstock source, pyrolysis temperature, biochar pH, and biochar C:N ratio (Figure 3). The biochar produced from woody and herbaceous materials had the largest reduction of soil N_2O emissions by a mean magnitude of 49.2% (−30.2% to −68.2% $CI_{95\%}$) and 51.0% (−27.2% to −75.0% $CI_{95\%}$), respectively (Figure 3a). Application of biochar produced from crop residues also significantly reduced soil N_2O emissions (27.7%, −12.0% to −43.5% $CI_{95\%}$). In contrast, biochar made from manure, biosolid/biowaste, and lignocellulosic materials as a feedstock source had no significant effect on soil N_2O emissions.

Soil N_2O emissions were significantly reduced by application of biochar with slow pyrolysis and relatively lower pyrolysis temperature (below 600°C; Figure 3b). Application of biochar produced with slow pyrolysis reduced soil N_2O emissions by 56.4% (−33.7% to −79.1% $CI_{95\%}$) while soil N_2O emissions remained unaffected by the

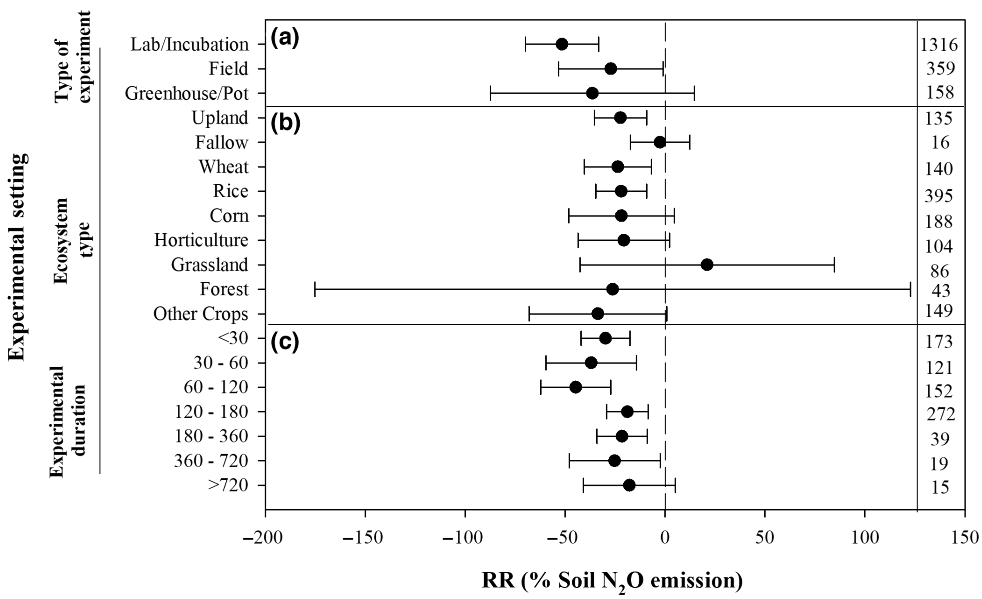

FIGURE 2 Impacts of experimental setting including experiment type (a), ecosystem type (b), and experimental duration (c) on the response ratios (RRs) of biochar application on soil N_2O emissions. Number on the right side is the total number of experiments used for RR calculation.

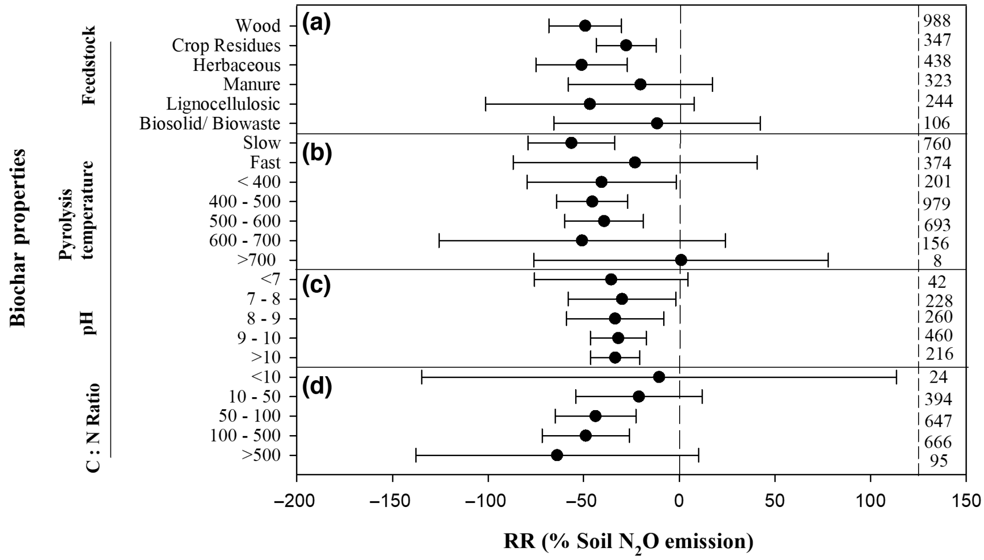

FIGURE 3 Impacts of biochar properties including feedstock (a), pyrolysis temperature (b), pH (c), and C:N ratio (d) on the response ratios (RRs) of biochar application on soil N_2O emission. Number on the right side is the total number of experiments used for RR calculation.

biochar produced by fast pyrolysis. The highest reduction of soil N_2O emissions (45.5%, −27.0% to −64.1% $CI_{95\%}$) was found for the biochar produced at a moderate temperature of 400–500°C. But there was no significant difference in soil N_2O emission reduction by biochar for pyrolysis temperature of 400–500°C, compared to either 300–400°C or 500–600°C. Biochar produced at temperatures higher than 600°C showed a trend of reduction of soil N_2O emissions.

The response of soil N_2O emissions also varied with biochar pH (Figure 3c). Biochar with pH of 8–9 induced the highest significant reduction (33.5%, −8.2% to −58.9% $CI_{95\%}$) in soil N_2O emissions. Reductions did not differ significantly when pH was larger than 7. There was no significant effect with biochar having a lower pH (<7).

The reduction of soil N_2O emissions seemed to increase with biochar C:N ratio (Figure 3d). Biochar with a low C:N ratio (<50) showed no impact on soil N_2O emission reduction. The highest reduction (48.9%, −26.1% to −71.7% CI_{95}%) was observed with biochar having C:N ratio of 100–500. However, application of biochar with a very high C:N ratio (>500) showed a trend of high reduction, but not significant due to a relatively low sample size.

3.4 | Impacts of soil properties on the effect of biochar application on soil N_2O emission

The effect of biochar application on soil N_2O emissions varied with soil texture (Figure 4a). In both fine- and medium-textured soils, soil N_2O emissions were significantly reduced when biochar was applied as an amendment. Fine-textured soils showed the most reduction (45.6%, −13.5% to −77.7% $CI_{95\%}$). However, response of soil N_2O emissions in coarse-textured soil showed a trend of reduction but was not significant.

Biochar applications reduced soil N_2O emissions in soils with SOC concentrations <20 g kg^{-1} (Figure 4b). The highest reduction of soil N_2O emissions occurred in soils with 10–20 g kg^{-1} SOC. However, concentrations higher than 20 g kg^{-1} showed no significant effect on soil N_2O emissions by biochar application.

Soil N_2O emissions were reduced by biochar application regardless of the value of soil C:N ratio (Figure 4c). The highest reductions in soil N_2O emissions (−42.1%, −23.2% to 61.1% $CI_{95\%}$) occurred in soil with C:N ratio from 10.2 to 12.4. Soil with low C:N ratio had lower reduction (−24.7%, −7.8% to 41.6% $CI_{95\%}$). Soil with higher C:N ratio (>12.4) showed a significant reduction by −36.3% (−14.5% to −58.2% $CI_{95\%}$).

Response of soil N_2O emissions to biochar application also varied with soil pH (Figure 4d). Soil N_2O emissions were not changed by biochar application when soil was acidic with pH of 3–5 but reduced when soil pH >5. The largest reductions (45.1%, −22.0% to −68.5% $CI_{95\%}$) of soil N_2O emissions by biochar application occurred in soil with a neutral pH (6.5–7.5).

3.5 | Impacts of agricultural practices on the effect of biochar application on soil N_2O emissions

The reduction of soil N_2O emissions increased with biochar application rate (Figure 5a). It increased from

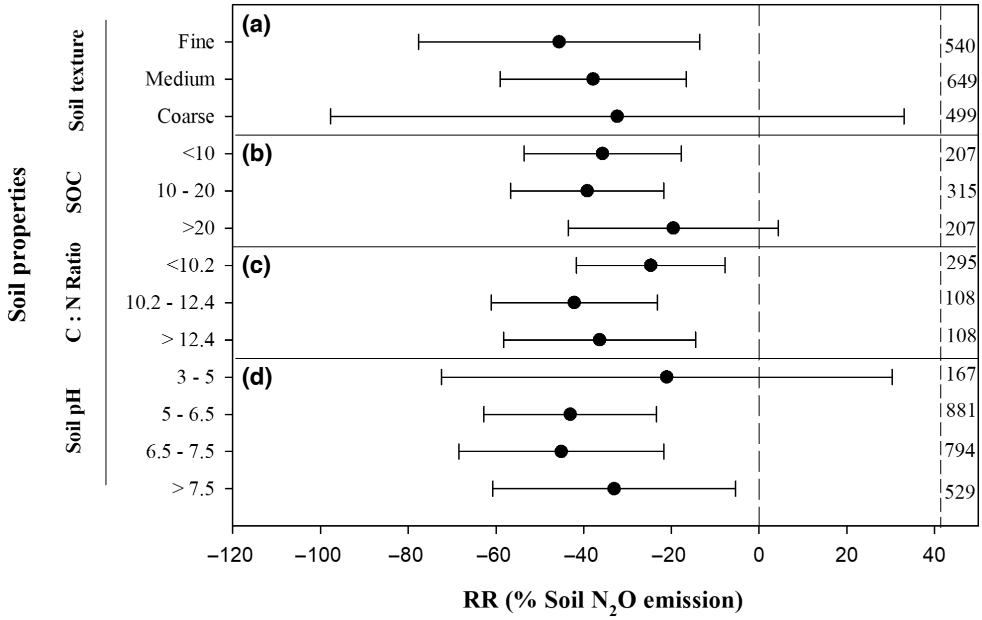

FIGURE 4 Impacts of soil properties including soil texture (a), soil organic carbon (SOC, b), C:N ratio (c), and soil pH (d) on the response ratios (RRs) of biochar application on soil N_2O emissions. Number on the right side is the total number of experiments used for RR calculation.

−15.8% (−2.9% to −27.0% $CI_{95\%}$) when biochar was applied at 10 t ha^{-1} to −86.6% (−41.7% to −131.5% $CI_{95\%}$) when biochar was applied at more than 120 t ha^{-1}. When an application of 10–20 t ha^{-1} of biochar was conducted, it showed a trend of reduction, but not a significant effect on soil N_2O emissions. All other biochar application rates showed significant reduction in soil N_2O emissions.

Regarding to different fertilizer types, significant reduction was observed only when either there was no fertilization or urea was applied. Biochar application reduced soil N_2O emissions by 50.7% (−28.1% to −73.4% $CI_{95\%}$) with no N application, and 51.7% (−3.8% to −99.6% $CI_{95\%}$) when urea was applied. When synthetic/mineral N fertilizer was applied, there was a high reduction tendency of soil N_2O emissions by biochar but was not statistically significant (Figure 5b).

The reduction of soil N_2O emissions by biochar application varied with N fertilization rate (Figure 5c). When no fertilizer was applied, biochar application did not influence soil N_2O emissions. Low application rates of nitrogen fertilizer (0–150 kg ha^{-1}, 150–300 kg ha^{-1}) reduced N_2O emissions by −36% and the difference between two application rates was not significant. Higher application rates of the N fertilizer (>300 kg ha^{-1}) showed a slightly decrease in soil N_2O emissions.

4 | DISCUSSION

Based on 18 meta-analyses, we evaluated the impacts of biochar application on soil N_2O emissions. We found that (1) soil N_2O emission was reduced by 38.9% with a 95% confidence interval of −32.4% to −44.8%. (2) Laboratory studies showed more soil N_2O emission reductions (51.6%) than the field experiments (27.1%). More soil N_2O emission reductions were observed in the wheat and rice fields, and studies lasted 120 days showed more soil N_2O reductions. (3) Biochar produced from woody and herbaceous materials, at moderate temperature (400–500°C), or with slow pyrolysis showed more soil N_2O emissions when applied to soil; fine- to medium-textured soils with neutral pH values (6.5–8.5) had larger soil N_2O reduction. (4) Soil N_2O emissions decreased with an increase in biochar application rate increased. When N fertilizer is applied as urea or at a rate of less than 300 kg N ha^{-1}, biochar application reduced more soil N_2O emissions. Our results demonstrated that biochar application as soil amendment could significantly reduce soil N_2O emissions. Utilizing adequately processed biochar together with urea as N fertilizer could produce more crop yields while releasing less N_2O from soils.

4.1 | Overall effect of biochar application on soil N_2O emissions and potential mechanisms

Application of soil organic amendments such as biochar not only influences the soil fertility and ecosystem productivity but also has a major impact on soil N_2O emissions. Our analysis showed that biochar application significantly

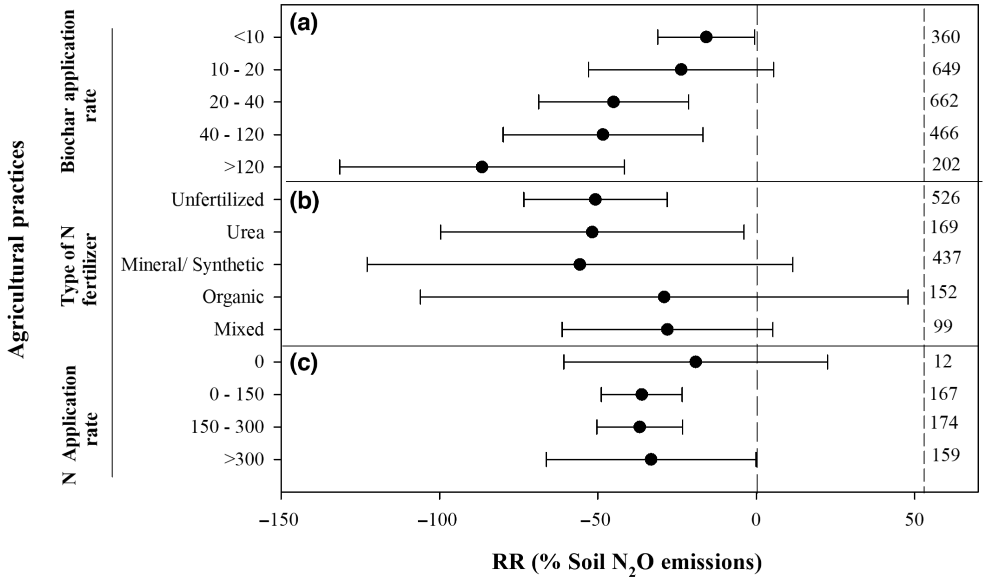

FIGURE 5 Impacts of agricultural practices including biochar application rate (a), type of fertilizer (b), and nitrogen (N) application rate (c) on the response ratios (RRs) of biochar application on soil N_2O emissions. Number on the right side is the total number of experiments used for RR calculation.

reduced soil N_2O emissions by 38.8%. This result is consistent with most of the meta-analysis studies that reported reductions of soil N_2O emissions (e.g., Shakoor et al., 2021; Song et al., 2016). The biochar-induced reduction of soil N_2O emissions could be caused by physiochemical changes in soil properties and biological changes in soil N processes with biochar application as demonstrated by previous studies (Liu et al., 2018; Shakoor et al., 2021). At least four mechanisms have been proposed to explain the changes in soil N_2O emissions. (1) Biochar application to agricultural soils could promote soil porosity and aeration. The increased availability of oxygen may prevent the denitrification process and reduce soil N_2O emissions. (2) Biochar application may limit the amount of inorganic N available to nitrifiers as well as denitrifies through immobilization and therefore suppresses soil N_2O emissions (He et al., 2017; Shakoor et al., 2021). (3) Biochar application increases the transcription of N_2O reductase genes of denitrifiers (nosZ) which results in a complete reduction to N_2 (Xu et al., 2014). Biochar also enhances the reduction of N_2O to N_2 by facilitating the transport of electrons to soil denitrifying microbes and hence it serves as an electron shuttle (Cayuela et al., 2014). (4) Biochar application increases a fraction of readily degradable organic C resulting in a reduction in soil N_2O emissions (Wang et al., 2015). The non-significant change in soil N_2O emission reported in four meta-analyses included one with a small sample size, one included 52 flooded rice field studies of 122 studies, and the other two only considered the paddy rice fields (Cai & Akiyama, 2017; Yagi et al., 2020; Zhao et al., 2019). Water conditions in the paddy rice fields might cause large pulses of soil N_2O emission in some studies and weaken the benefits of biochar application such as changes in soil porosity and aeration, which resulted in no significant change in soil N_2O emission.

4.2 | Effects of experimental setting (i.e., type of experiment, ecosystem type, and experimental duration) on soil N_2O emissions

This study showed that high reduction was observed in experimental setup in the laboratory (51.6%) as compared to the field (27.1%). Similar results were published in a meta-analysis conducted by Cayuela et al. (2015). The possible explanation for this could be due to the relatively lower application rate of biochar in the field compared to the laboratory studies. Another factor contributing to the lesser mitigation in the field could be the less uniform mixing of biochar with the soil (Cayuela et al., 2015).

Crop species may influence the impacts of biochar application on soil N_2O emissions. In this study, in the wheat, rice, corn, and upland fields, biochar application showed a significant reduction in soil N_2O emissions. Similar results were found in Xu et al. (2021) and Song et al. (2016). However, other cropping systems including grasslands, forest, and horticultural crops showed no significant impact. The differences could be due to different N nutrient status and different soil environment conditions prevailing in each ecosystem. Further research needs to be conducted to understand the mechanistic controls of soil N_2O emissions under biochar application in different cropland ecosystems (Shakoor et al., 2021).

We found that the effect of biochar application on soil N_2O emission reduction increased with the duration of experiment up to 120 days. Longer studies showed lower reduction in soil N_2O emissions or even complete absence after 2 years of biochar application (Figure 2c). Song et al. (2016) also found that the considerable reductions in soil N_2O emissions occur during the initial stages of biochar application and weakened over time. This could be because biochar's liming effect wears off over time and reduced nitrate sorption potential of the biochar because of oxidation (Song et al., 2016). Biochar aging in soil leads to surface property changes via oxidation and formation of oxygen-containing functional groups and sorption of natural organic matter, which leads to clogged biochar pores, and formation of organo-mineral complexes coating biochar surfaces (Wang et al., 2020; Yuan et al., 2019). Therefore, the stability of biochar would steadily deteriorate as the experiment progressed, and the effect of biochar application on soil N_2O emissions would become weaker over time (Song et al., 2016; Yuan et al., 2019).

4.3 | Effects of biochar properties (i.e., feedstock type, pyrolysis temperature, pH, and C: ratio) on soil N_2O emissions

The biochar feedstock is an important factor influencing the compositional constituents of biochar (Liu et al., 2019). The results from our analysis showed that the significant decreases in soil N_2O emissions were found in soils with biochar derived from herbaceous materials (51%), wood (49%), and crop residues (28%) (Figure 3a), and biochar derived from other sources did not influence soil N_2O emissions. Our results are consistent with some previous studies (Cayuela et al., 2014; Liu et al., 2019; Song et al., 2016). Biochar derived from manure and biowaste has less developed pore structure compared to the woody and crop residues derived biochar. Therefore, biochar made from woody, herbaceous, or crop residue as a feedstock offers more retention of available N (NH_4^+, NO_3^-) and greater increases in soil porosity, hence altering the stichometry of nitrification and denitrification processes.

Another key element that impacts biochar characteristics is the temperature at which it is pyrolyzed. The physicochemical features of biochar, such as pH, bioavailable C and N concentrations, and porosity and pore size distribution, may be affected by the pyrolysis temperature (Lan et al., 2018). For example, surface area of biochar increases with increasing pyrolysis temperature. We found an increased trend in the reduction of soil N_2O emissions as pyrolysis temperature increased (Figure 3b). Biochar produced at lower temperatures (<400°C) would have reduced surface area and weaker aromatic structure resulting in decreased electric conduction capability and less surface functionality for interacting with N_2O turnover (Liu et al., 2018). Pyrolysis at 400–600°C yields biochar with a moderate surface area and functional groups and showed largest reductions in soil N_2O emissions. A further increase in temperature beyond 600°C did not influence biochar-induced soil N_2O mitigation (Lee et al., 2021). Although pyrolysis temperature is a simple metric to define the pyrolysis process, numerous pyrolysis circumstances, such as rate of temperature increase and time at the highest treatment temperature might also influence the carbonization degree and molecular structure of biochar and its impact on soil N_2O emissions (Cayuela et al., 2014; Lee et al., 2021).

Results showed that biochar application with pH <7 had no significant effect on soil N_2O emissions (Figure 3c). However, a great reduction in magnitude was seen in biochar with higher pH. Large number of soluble base cations present in biochar can increase soil pH by neutralizing soil acidity. This would result in an increased production of N_2 relative to N_2O by altering the stoichiometry of denitrification process (Song et al., 2016).

Biochar C:N ratio is also an important parameter that significantly influences the soil N_2O emissions. In this study, biochar with <10 C:N ratio and >500 showed no significant results on soil N_2O emissions. But the extent of the reduction of soil N_2O emissions increased with an increase in C:N ratio (≤500). Similar results were reported by Cayuela et al. (2014) and Borchard et al. (2019). Due to microbial N immobilization, biochar amendments with greater C:N ratios considerably reduced N_2O emissions. As a result, the amount of soil N accessible for microbial processes that produce N_2O is drastically reduced.

4.4 | Impacts of soil physiochemical properties (i.e., soil texture, SOC, C:N ratio, and soil pH) on the effects of biochar application on soil N_2O emissions

Soil texture is closely related to soil aeration and soil water and nutrient availabilities. Previous studies showed that the type of soil has a significant impact on soil N_2O emissions (He et al., 2017) as biochar application changes soil physical qualities, such as reducing soil compaction and bulk density or adsorbing excess soil moisture. Therefore, soil texture primarily influences N_2O emissions by regulating which of the aerobic or anaerobic conditions in the soil are more likely to occur (Wang et al., 2021). We found that soils with fine and medium soil texture reduced more soil N_2O emissions with biochar application, probably because these types of soils had high water-filled pore space (WFPS) and high soil water content and, as a result, nitrifier and denitrifier activity could be influenced (Cayuela et al., 2014). Nitrification is the primary source of N_2O between 35% and 60% WFPS, while denitrification is the primary source of N_2O above 70% WFPS. The reductions of soil N_2O emission were probably due to the denitrification rate dropping most rapidly in fine-textured soils with the biochar-induced WFPS decrease (Wang et al., 2021).

Soil C availability offers an energy source for soil microorganisms resulting in increased microbial activity. A readily available C source is required by the denitrifying microbes for carrying out the reduction of NO_3^-. The amount of organic C available to bacteria as a food source will determine whether N_2 or N_2O is produced. The addition of biochar increased SOC and soil stability was improved when there was a high level (10–20 $g\,kg^{-1}$) of SOC with more aeration and improved water drainage. Good soil aeration interferes with the process of denitrification, thereby reducing the N_2O emissions (Figure 4b). However, when SOC was greater than 20 $g\,kg^{-1}$, no substantial effect of biochar addition on soil N_2O emissions was observed, probably due to that high SOC stimulated soil microbial activity and N_2O production, and reduced the impacts of biochar.

Soil C:N ratio is a key factor in governing soil N activities such mineralization, nitrification, and immobilization, all of which influence N_2O generation by regulating NH_4^+ and organic C availability (Lee et al., 2021). Application of biochar increased C:N ratio which further increased SOC and thus influenced soil N_2O emissions. Because nitrification not only produces N_2O but also supplies NO_3^-, a substrate for denitrifiers to produce N_2O, soils with adequate C:N ratio have more N_2O emission than soils with higher C:N ratio due to higher nitrification (Liimatainen et al., 2018).

Soil pH influences soil N_2O production and consumption. Changing the nitrification and denitrification product ratios by raising soil pH to an appropriate range is important for developing solutions for lowering soil N_2O emissions from agricultural soils (Cayuela et al., 2014). Biochar was not effective at mitigating soil N_2O emissions in acid soils (pH <5) (Figure 4a). In acidic soils, soil N_2O is the sole denitrification product (Rochester, 2003). Low pH inhibits the formation of functional soil N_2O reductase (N_2OR), an enzyme that converts soil N_2O to N_2 during denitrification. Increased N_2OR activity because of the pH rise due to biochar application could be one of the key factors for the observed inhibition of soil N_2O emission in soils close to neutral pH (Figure 4d; Obia et al., 2015). The liming effect induced by biochar application may generate a suitable environment for N_2O reductase and create a higher proportion of soil N_2O is evolved into N_2. Biochar application suppressed soil N_2O emissions because of its alkalizing action in soils, which might have an impact on denitrification.

4.5 | Effects of agricultural practices (i.e., biochar application rate, nitrogen fertilizer type, and application rate) on soil N_2O emissions

The ability of biochar to reduce soil N_2O emissions is a function of its quality and the effects on soil properties that are cumulative and may grow more prominent as biochar's content and dominance in soil increase (Cayuela et al., 2014). Therefore, a clear correlation can be predicted between biochar application rate and reduced soil N_2O emissions. Indeed, we found the magnitude of the reductions increased as the application rate increased (Figure 5a). The maximum reductions were observed when biochar was applied at the rate of 120 $t\,ha^{-1}$ to the soil. Similar results were reported by Borchard et al. (2019). A large amount of biochar could limit the availability of N, which is the main source of N_2O emissions, resulting in lower N_2O emissions (Shakoor et al., 2021). Also, the surface of biochar might easily absorb nitrate contents, resulting in lower soil N_2O emissions.

Application of N fertilizer to agricultural soils is considered as a potent source for soil N_2O emissions. Soil N_2O emissions are supposed to increase with the application of high doses of N fertilizer. But when applied in combination with the biochar, mitigation of the soil N_2O emissions can be observed. Biochar reduced soil N_2O emissions when N was applied as urea, as well as in unfertilized soil (Figure 5b). No significant reduction was observed when N was applied as mineral N fertilizer, or organic N. Biochar application could increase N use efficiency because of adsorption of nitrate and ammonium on its surface. Therefore, the availability of these N forms for nitrification or denitrification reduces, resulting in reduction of magnitude of soil N_2O emissions (Clough et al., 2013). These results seem to be in consistence with studies conducted by Liu et al. (2019). Biochar's ability to reduce N_2O emissions could also be affected by the N application rate. Reduction of soil N_2O emissions (from 33.2% to 36.8%) by biochar application was similar when N was applied from 0 to $150\,kg\,N\,ha^{-1}$ to more than $300\,kg\,N\,ha^{-1}$.

4.6 | Limitations of the study

Like any data synthesis study, results of this mega-analysis could be restricted/affected by several factors. One was the quality of meta-analyses. Existing meta-analyses are often highly focused on specific ecosystems or regions such as temperate areas with little attention to tropical area (Young et al., 2021). These biases might create certain bias in the result of mega-analysis. Another was the category of mediator factors. Different meta-analyses used different categories for grouping studies, particularly when mediator factor was a numerical variable such as N application rate. The other one was the potential overlap of individual studies used in meta-analyses. We checked 10 meta-analyses based on a total of 321 papers and found that 217 papers were included in only one meta-analysis, 49, 35, 13, and 4 papers were included in 2, 3, 4, 5, and 6 meta-analyses. While the overlap was low, it would create some biases. Thus, mega-analysis based on these meta-analyses would provide a more comprehensive yet conservative result. A cumulative meta-analysis needs to be conducted to verify the result of the mega-analysis.

5 | CONCLUSIONS

Meta-analysis has become an increasing important tool to synthesize individual studies in ecology over the past several decades. Many meta-analyses have been conducted on the same research issue such as the impacts of biochar application on soil N_2O emissions, but an evaluation and data synthesis of these meta-analyses have rarely been conducted. Synthesizing 18 meta-analytic studies, this mega-analysis showed that biochar application significantly reduced soil N_2O emissions by 38.8%, implying that biochar could be a useful soil amendment for reducing greenhouse gas emissions. The magnitude of the reductions varied depending on biochar qualities, soil properties, experimental setting, and agronomic practices. Considering the effects of biochar properties on N_2O emissions, biochar generated from herbaceous or woody feedstock, pyrolyzed at temperatures between 400 and 700°C, and with a high pH (8–9) of biochar are all effective. Fine-textured soils with a neutral pH (6.5–7.5), having C:N ratio around 10.2–12.4 and moderate amount of SOC, demonstrated the greatest decreases in soil N_2O emissions. Nitrogen fertilizers are a major source of soil N_2O emissions; however, combining these fertilizers with biochar could reduce soil N_2O emissions. This study provides a comprehensive analysis on how various factors influence the response of soil N_2O emissions to biochar application. Despite numerous useful reviews and meta-analyses, there is still a great deal of uncertainty in the impact of biochar application on variations in soil N_2O emissions. Therefore, the potential of biochar application to cropland to mitigate climate change needs to be further investigated.

AUTHOR CONTRIBUTIONS

Dafeng Hui developed the ideas for this manuscript. Navneet collected the data. Navneet and Dafeng Hui performed the data analysis. All authors contributed to the writing of the manuscript.

ACKNOWLEDGMENTS

We thank the original researchers and authors of the meta-analysis papers that made this study possible. This research was supported by the National Science Foundation (NSF) MRI (1919897) and EiR projects (2000058; 1900885) and USDA projects.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.vmcvdncwz.

ORCID

Wei Ren https://orcid.org/0000-0003-0271-486X
Dafeng Hui https://orcid.org/0000-0002-5284-2897

REFERENCES

Akiyama, H., Yan, X., & Yagi, K. (2010). Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis. *Global Change Biology*, *16*(6), 1837–1846.

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant and Soil*, *337*(1), 1–18.

Barnard, R., Leadley, P. W., & Hungate, B. A. (2005). Global change, nitrification, and denitrification: A review. *Global Biogeochemical Cycles*, *19*(1), 1–13.

Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis. *Science of the Total Environment*, *651*, 2354–2364.

Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H., Van Vuuren, D. P., Willems, J., Rufino, M. C., & Stehfest, E. (2013). Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900-2050 period. *Proceedings of the National Academy of Sciences of the USA*, *110*(52), 20882–20887.

Bruun, E. W., Müller-Stöver, D., Ambus, P., & Hauggaard-Nielsen, H. (2011). Application of biochar to soil and N_2O emissions: Potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry. *European Journal of Soil Science*, *62*(4), 581–589.

Cai, Y., & Akiyama, H. (2017). Effects of inhibitors and biochar on nitrous oxide emissions, nitrate leaching, and plant nitrogen uptake from urine patches of grazing animals on grasslands: A meta-analysis. *Soil Science and Plant Nutrition*, *63*(4), 405–414.

Case, S. D., McNamara, N. P., Reay, D. S., Stott, A. W., Grant, H. K., & Whitaker, J. (2015). Biochar suppresses N_2O emissions while maintaining N availability in a sandy loam soil. *Soil Biology and Biochemistry*, *81*, 178–185.

Cayuela, M. L., Jeffery, S., & van Zwieten, L. (2015). The molar H: Corg ratio of biochar is a key factor in mitigating N_2O emissions from soil. *Agriculture, Ecosystems & Environment*, *202*, 135–138.

Cayuela, M. L., Van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., & Sánchez-Monedero, M. A. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, *191*, 5–16.

Clough, T. J., Condron, L. M., Kammann, C., & Müller, C. (2013). A review of biochar and soil nitrogen dynamics. *Agronomy*, *3*(2), 275–293.

Dalal, R. C., Wang, W., Robertson, G. P., & Parton, W. J. (2003). Nitrous oxide emission from Australian agricultural lands and mitigation options: A review. *Soil Research*, *41*(2), 165–195.

de Klein, C. A. M., & Ledgard, S. F. (2005). Nitrous oxide emissions from New Zealand agriculture – Key sources and mitigation strategies. *Nutrient Cycling in Agroecosystems*, *72*(1), 77–85.

Dijkstra, F. A., Morgan, J. A., Follett, R. F., & Lecain, D. R. (2013). Climate change reduces the net sink of CH_4 and N_2O in a semiarid grassland. *Global Change Biology*, *19*(6), 1816–1826.

Deng, Q., Hui, D., Wang, J., Iwuozo, S., Yu, C.-L., Jima, T., Smart, D., Reddy, C., & Dennis, S. (2015). Corn yield and soil nitrous oxide emission under different fertilizer and soil management: A three-year field experiment in middle Tennessee. *PLoS One*, *10*(4), e0125406. https://doi.org/10.1371/journal.pone.0125406

Eldridge, D. J., Poore, A. G., Ruiz-Colmenero, M., Letnic, M., & Soliveres, S. (2016). Ecosystem structure, function, and composition in rangelands are negatively affected by livestock grazing. *Ecological Applications*, *26*(4), 1273–1283.

Feng, Y., Feng, Y., Liu, Q., Chen, S., Hou, P., Poinern, G., Jiang, Z., Fawcett, D., Xue, L., Lam, S. S., & Xia, C. (2022). How does biochar aging affect NH_3 volatilization and GHGs emissions from agricultural soils? *Environmental Pollution*, *294*, 118598.

Han, Z., Wang, J., Xu, P., Li, Z., Liu, S., & Zou, J. (2021). Differential responses of soil nitrogen-oxide emissions to organic substitution for synthetic fertilizer and biochar amendment in a subtropical tea plantation. *GCB Bioenergy*, *13*(8), 1260–1274.

He, Y., Yao, Y., Jia, Z., Chen, X., Zhou, L., Shao, J., Liu, R., Zhou, G., Fu, Y., Sun, X., Zhou, X., & Bai, S. H. (2021). Antagonistic interaction between biochar and nitrogen addition on soil greenhouse gas fluxes: A global synthesis. *GCB Bioenergy*, *13*(10), 1636–1648.

He, Y., Zhou, X., Jiang, L., Li, M., Du, Z., Zhou, G., Shao, J., Wang, X., Xu, Z., Bai, S. H., Wallace, H., & Xu, C. (2017). Effects of biochar application on soil greenhouse gas fluxes: A meta-analysis. *GCB Bioenergy*, *9*(4), 743–755.

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, *80*(4), 1150–1156.

Huang, Y., Ren, W., Wang, L., Hui, D., Grove, J. H., Yang, X., Tao, B., & Goff, B. (2018). Greenhouse gas emissions and crop yield in no-tillage systems: A meta-analysis. *Agriculture, Ecosystems & Environment*, *268*, 144–153.

Hui, D. (2020). Effects of biochar application on soil properties, plant biomass production, and soil greenhouse gas emissions: A mini-review. *Agricultural Sciences*, *12*(3), 213–236.

Hui, D., Deng, Q., Tian, H., & Luo, Y. (2021). Global climate change and greenhouse gases emissions in terrestrial ecosystems. In M. Lackner, B. Sajjadi, & W. Y. Chen (Eds.), *Handbook of climate change mitigation and adaptation* (pp. 1–54). Springer International Publishing.

Hui, D., Yu, C. L., Deng, Q., Saini, P., Collins, K., & Koff, J. D. (2018). Weak effects of biochar and nitrogen fertilization on switchgrass photosynthesis, biomass, and soil respiration. *Agriculture*, *8*(9), 143.

Jia, J., Li, B., Chen, Z., Xie, Z., & Xiong, Z. (2012). Effects of biochar application on vegetable production and emissions of N_2O and CH_4. *Soil Science and Plant Nutrition*, *58*(4), 503–509.

Lan, Z., Chen, C., Rezaei Rashti, M., Yang, H., & Zhang, D. (2018). High pyrolysis temperature biochars reduce nitrogen availability and nitrous oxide emissions from an acid soil. *GCB Bioenergy*, *10*(12), 930–945.

Lee, S. I., Park, H. J., Jeong, Y. J., Seo, B. S., Kwak, J. H., Yang, H. I., Xu, X., Tang, S., Cheng, W., Lim, S. S., & Choi, W. J. (2021). Biochar-induced reduction of N_2O emission from East Asian soils under aerobic conditions: Review and data analysis. *Environmental Pollution*, *291*, 118154.

Liimatainen, M., Voigt, C., Martikainen, P. J., Hytönen, J., Regina, K., Oskarsson, H., & Maljanen, M. (2018). Factors controlling nitrous oxide emissions from managed northern peat soils with low carbon to nitrogen ratio. *Soil Biology and Biochemistry*, *122*, 186–195.

Liu, L., Shen, G., Sun, M., Cao, X., Shang, G., & Chen, P. (2014). Effect of biochar on nitrous oxide emission and its potential mechanisms. *Journal of the Air & Waste Management Association*, *64*(8), 894–902.

Liu, Q., Liu, B., Zhang, Y., Hu, T., Lin, Z., Liu, G., Wang, X., Ma, J., Wang, H., Jin, H., Ambus, P., Amonette, J. E., & Xie, Z. (2019). Biochar application as a tool to decrease soil nitrogen losses (NH_3 volatilization, N_2O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective. *Global Change Biology*, *25*(6), 2077–2093.

Liu, Q., Zhang, Y., Liu, B., Amonette, J. E., Lin, Z., Liu, G., Ambus, P., & Xie, Z. (2018). How does biochar influence soil N cycle? A meta-analysis. *Plant and Soil*, *426*(1), 211–225.

Luo, Y., Hui, D., & Zhang, D. (2006). Elevated CO_2 stimulates net accumulations of carbon and nitrogen in land ecosystems: A meta-analysis. *Ecology*, *87*(1), 53–63.

Maaz, T. M., Sapkota, T. B., Eagle, A. J., Kantar, M. B., Bruulsema, T. W., & Majumdar, K. (2021). Meta-analysis of yield and nitrous oxide outcomes for nitrogen management in agriculture. *Global Change Biology*, *27*(11), 2343–2360.

Obia, A., Cornelissen, G., Mulder, J., & Dörsch, P. (2015). Effect of soil pH increase by biochar on NO, N_2O and N_2 production during denitrification in acid soils. *PLoS One*, *10*(9), e0138781.

Pereira, E. I. P., Suddick, E. C., Mukome, F. N. D., Parikh, S. J., Scow, K., & Six, J. (2015). Biochar alters nitrogen transformations but has minimal effects on nitrous oxide emissions in an organically managed lettuce mesocosm. *Biology and Fertility of Soils*, *51*(5), 573–582.

Philibert, A., Loyce, C., & Makowski, D. (2012). Assessment of the quality of meta-analysis in agronomy. *Agriculture, Ecosystems & Environment*, *148*, 72–82.

Rochester, I. J. (2003). Estimating nitrous oxide emissions from flood-irrigated alkaline grey clays. *Soil Research*, *41*, 197–206.

Sánchez-García, M., Roig, A., Sánchez-Monedero, M. A., & Cayuela, M. L. (2014). Biochar increases soil N_2O emissions produced by nitrification-mediated pathways. *Frontiers in Environmental Science*, *2*, 1–10.

Sánchez-Meca, J., & Marin-Martinez, F. (1998). Weighting by inverse variance or by sample size in meta-analysis: A simulation study. *Educational and Psychological Measurement*, *58*(2), 211–220.

Schmidt, H. P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Sánchez Monedero, M. A., & Cayuela, M. L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. *GCB Bioenergy*, *13*(11), 1708–1730.

Shakoor, A., Shahzad, S. M., Chatterjee, N., Arif, M. S., Farooq, T. H., Altaf, M. M., Tufail, M. A., Dar, A. A., & Mehmood, T. (2021). Nitrous oxide emission from agricultural soils: Application of animal manure or biochar? A global meta-analysis. *Journal of Environmental Management*, *285*, 112170.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., & Fixen, P. E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, *133*(3–4), 247–266.

Song, X., Pan, G., Zhang, C., Zhang, L., & Wang, H. (2016). Effects of biochar application on fluxes of three biogenic greenhouse gases: A meta-analysis. *Ecosystem Health and Sustainability*, *2*(2), e01202.

Spokas, K. A., Novak, J. M., & Venterea, R. T. (2012). Biochar's role as an alternative N-fertilizer: Ammonia capture. *Plant and Soil*, *350*(1), 35–42.

Uchida, Y., & von Rein, I. (2018). Mitigation of nitrous oxide emissions during nitrification and denitrification processes in agricultural soils using enhanced efficiency fertilizers. In D. Vázquez-Luna & M. D. C. Cuevas-Dáaz (Eds.), *Soil contamination and alternatives for sustainable development*. IntechOpen.

Van Zwieten, L., Singh, B. P., Kimber, S. W. L., Murphy, D. V., Macdonald, L. M., Rust, J., & Morris, S. (2014). An incubation study investigating the mechanisms that impact N_2O flux from soil following biochar application. *Agriculture, Ecosystems and Environment*, *191*, 53–62.

Verheijen, F., Jeffery, S., Bastos, A. C., Van der Velde, M., & Diafas, I. (2010). Biochar application to soils—A critical scientific review of effects on soil properties, processes, and functions. *EUR*, *24099*, 162.

Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., & Six, J. (2017). Toward a better assessment of biochar–nitrous oxide mitigation potential at the field scale. *Journal of Environmental Quality*, *46*(2), 237–246.

Wan, S., Hui, D., & Luo, Y. (2001). Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis. *Ecological Applications*, *11*(5), 1349–1365.

Wang, C., Amon, B., Schulz, K., & Mehdi, B. (2021). Factors that influence nitrous oxide emissions from agricultural soils as well as their representation in simulation models: A review. *Agronomy*, *11*(4), 770.

Wang, J., Chen, Z., Xiong, Z., Chen, C., Xu, X., Zhou, Q., & Kuzyakov, Y. (2015). Effects of biochar amendment on greenhouse gas emissions, net ecosystem carbon budget and properties of an acidic soil under intensive vegetable production. *Soil Use and Management*, *31*, 375–383.

Wang, L., O'Connor, D., Rinklebe, J., Ok, Y. S., Tsang, D. C., Shen, Z., & Hou, D. (2020). Biochar aging: Mechanisms, physicochemical changes, assessment, and implications for field applications. *Environmental Science & Technology*, *54*(23), 14797–14814.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(1), 1–9.

Wu, Z., Zhang, X., Dong, Y., Li, B., & Xiong, Z. (2019). Biochar amendment reduced greenhouse gas intensities in the rice-wheat rotation system: Six-year field observation and meta-analysis. *Agricultural and Forest Meteorology*, *278*, 107625.

Xu, H., Cai, A., Wu, D., Liang, G., Xiao, J., Xu, M., Colinet, G., & Zhang, W. (2021). Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C: N ratio and soil pH: A global meta-analysis. *Soil and Tillage Research*, *213*, 105125.

Xu, H. J., Wang, X. H., Li, H., Yao, H. Y., Su, J. Q., & Zhu, Y. G. (2014). Biochar impacts soil microbial community composition and nitrogen cycling in an acidic soil planted with rape. *Environmental Science & Technology*, *48*(16), 9391–9399.

Yagi, K., Sriphirom, P., Cha-un, N., Fusuwankaya, K., Chidthaisong, A., Damen, B., & Towprayoon, S. (2020). Potential and promisingness of technical options for mitigating greenhouse gas emissions from rice cultivation in southeast Asian countries. *Soil Science and Plant Nutrition*, *66*(1), 37–49.

Yangjin, D., Wu, X., Bai, H., & Gu, J. (2021). A meta-analysis of management practices for simultaneously mitigating N_2O and NO emissions from agricultural soils. *Soil and Tillage Research*, *213*, 105142.

Young, M. D., Ros, G. H., & de Vries, W. (2021). Impacts of agronomic measures on crop, soil, and environmental indicators: A review and synthesis of meta-analysis. *Agriculture, Ecosystems & Environment*, *319*, 107551.

Yuan, H., Zhang, Z., Li, M., Clough, T., Wrage-Mönnig, N., Qin, S., Ge, T., Liao, H., & Zhou, S. (2019). Biochar's role as an electron shuttle for mediating soil N_2O emissions. *Soil Biology and Biochemistry*, *133*, 94–96.

Zhang, L., Jing, Y., Chen, C., Xiang, Y., Rezaei Rashti, M., Li, Y., Deng, Q., & Zhang, R. (2021). Effects of biochar application on soil nitrogen transformation, microbial functional genes, enzyme activity, and plant nitrogen uptake: A meta-analysis of field studies. *GCB Bioenergy*, *13*(12), 1859–1873.

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access

Zhao, X., Pu, C., Ma, S. T., Liu, S. L., Xue, J. F., Wang, X., Wang, Y. Q., Li, S. S., Lal, R., Chen, F., & Zhang, H. L. (2019). Management-induced greenhouse gases emission mitigation in global rice production. *Science of the Total Environment*, *649*, 1299–1306.

Zhou, G., Zhou, X., Eldridge, D.J., Han, X., Song, Y., Liu, R., Zhou L, He Y, Du Z & Delgado-Baquerizo, M. (2022). Temperature and rainfall patterns constrain the multidimensional rewilding of global forests. *Advanced Science*, *9*(18), e2201144.

How to cite this article: Kaur, N., Kieffer, C., Ren, W., & Hui, D. (2023). How much is soil nitrous oxide emission reduced with biochar application? An evaluation of meta-analyses. *GCB Bioenergy*, *15*, 24–37. https://doi.org/10.1111/gcbb.13003