



Nitrous oxide emission from agricultural soils: Application of animal manure or biochar? A global meta-analysis

Awais Shakoor^{a,*}, Sher Muhammad Shahzad^b, Nilovna Chatterjee^c, Muhammad Saleem Arif^d, Taimoor Hassan Farooq^e, Muhammad Mohsin Altaf^f, Muhammad Aammar Tufail^{g,h}, Afzal Ahmed Darⁱ, Tariq Mehmood^j

^a Department of Environment and Soil Sciences, University of Lleida, Avinguda Alcalde Rovira Roure 191, 25198, Lleida, Spain

^b Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Sargodha, 40100, Punjab, Pakistan

^c Crop Modeling Scientist; CIBO Technologies, Cambridge, MA, USA

^d Department of Environmental Sciences & Engineering, Government College University Faisalabad, Faisalabad, 38000, Pakistan

^e College of Life Science and Technology, Central South University of Forestry and Technology, Changsha, 410004, Hunan, China

^f State Key Laboratory of Marine Resource Utilization in South China Sea, College of Ecology and Environment, Hainan University, Haikou, 570228, PR China

^g Research and Innovation Centre, Fondazione Edmund Mach, San Michele All'Adige, 38010, Italy

^h Department of Civil, Environmental and Mechanical Engineering, University of Trento, 38123, Trento, Italy

ⁱ School of Environmental Science and Engineering, Shaanxi University of Science and Technology, Xian, China

^j College of Environment, Hohai University, 210098, Nanjing, China

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ABSTRACT

Organic amendments (animal manure and biochar) to agricultural soils may enhance soil organic carbon (SOC) contents, improve soil fertility and crop productivity but also contribute to global warming through nitrous oxide (N₂O) emission. However, the effects of organic amendments on N₂O emissions from agricultural soils seem variable among numerous research studies and remains uncertain. Here, eighty-five publications (peer-reviewed) were selected to perform a meta-analysis study. The results of this meta-analysis study show that the application of animal manure enhanced N₂O emissions by 17.7%, whereas, biochar amendment significantly mitigated N₂O emissions by 19.7%. Moreover, coarse textured soils increased [$\ln RR = 182.6\%$, 95% confidence interval (CI) = 151.4%, 217.7%] N₂O emission after animal manure, in contrast, N₂O emission mitigated by 7.0% from coarse textured soils after biochar amendment. In addition, this study found that 121–320 kg N ha⁻¹ and ≤ 30 t ha⁻¹ application rates of animal manure and biochar mitigated N₂O emissions by 72.3% and 22.5%, respectively. Soil pH also played a vital role in regulating the N₂O emissions after organic amendments. Furthermore, > 10 soil C: N ratios increased N₂O emissions by 121.4% and 27.6% after animal and biochar amendments, respectively. Overall, animal manure C: N ratios significantly enhanced N₂O emissions, while, biochar C: N ratio had not shown any effect on N₂O emissions. Overall, average N₂O emission factors (EFs) for animal manure and biochar amendments were 0.46% and −0.08%, respectively. Thus, the results of this meta-analysis study provide scientific evidence about how organic amendments such as animal manure and biochar regulating the N₂O emission from agricultural soils.

Authors contribution

Awais Shakoor: Conceptualization, Methodology, Formal analysis, Data curation, Software, Writing – original draft Writing – review & editing. Sher Muhammad Shahzad: Project administration, Writing – review & editing. Nilovna Chatterjee: Writing – review & editing. Muhammad Saleem Arif: Writing – review & editing. Taimoor Hassan

Farooq: Software, Data curation. Muhammad Mohsin Altaf: Data curation, review & editing. Muhammad Aammar Tufail: Figures, Writing – review & editing. Afzal Ahmed Dar: Investigation, review & editing. Tariq Mehmood: Review & editing.

* Corresponding author.

E-mail address: awais.shakoor@udl.cat (A. Shakoor).

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1. Introduction

Climate change mitigation and improving food security are considered to be the major challenges worldwide (Zhang et al., 2018). It is estimated that the world population will increase up to 9 to 10 billion by 2050, and over 2 billion already depended on synthetic nitrogen (N) fertilizer (Shakoor et al., 2020b). Mainly, synthetic N fertilizer has been used to increase the crop yield; however, most of the N fertilizer that is applied to agricultural crops are often lost through gaseous forms, particularly in ammonia and nitrous oxide (N_2O) (Li and Chen, 2020). The new global synthesis of N_2O budget (Tian et al., 2020) is considered a major greenhouse gas with over 114 years life span in the atmosphere (Zhang et al., 2016a,b), and it has 298 times more GWP (global warming potential) than carbon dioxide (CO_2) over a 100-year period (Ren et al., 2019; Shakoor et al., 2018). Almost 60% of the total anthropogenic N_2O emission is emitted from agriculture due to excessive use of N fertilizers (Syakila and Kroeze, 2011). Therefore, organic amendments such as animal manure and biochar have been widely adopted to increase soil organic matter (SOM) stocks and to mitigate the greenhouse gases (GHGs) emissions (Clough et al., 2010; Lal, 2004). However, the effect of animal manure and biochar on the mitigation of N_2O emission remains inconsistent and suggests further scientific investigation.

Worldwide, approximately 7 billion tons (annually) of animal manure (cattle, pig, and poultry) is used as an organic amendment for croplands (Thangarajan et al., 2013). The use of animal manure as an organic amendment to agricultural soils not only improved soil fertility and crop yield but also increased soil organic carbon (SOC) contents in the agricultural land that can significantly disturb N_2O emissions (Zhou et al., 2017). Approximately 37% of global N_2O emissions emit through the application and storage of animal manure (Vac et al., 2013). Normally, biological processes for example nitrification as well as denitrification significantly affect the N_2O emission (Barnard et al., 2005; Nelissen et al., 2014; Stinner et al., 1983; Xu et al., 2017). In general, the animal manure amendment to cropland enhances organic carbon (OC) as well as ammonium contents. This may also increase the denitrification process, which ultimately increases N_2O emission (Severin et al., 2015; Velthof and Mosquera, 2011). Because the OC compounds in manure provide a readily available substrate for denitrifiers (Dendooven et al., 1998). The effects of animal manure on N_2O emissions have been intensively debated and significantly vary among individual research studies. Previous research studies showed that animal manure had no significant impact on N_2O emissions (Dendooven et al., 1998; Li et al., 2016). Recently, a global meta-analysis were conducted by Zhou et al. (2017) and Shakoor et al. (2021b) and found that animal manure significantly increased N_2O emissions from agricultural soils. In contrast, N_2O emissions significantly decreased from agricultural soils after the application of animal manure (Velthof et al., 2003).

On the other hand, the application of biochar to agricultural soils as an organic amendment has also been receiving more attention for improving the crop yield (Liu et al., 2019; Qin et al., 2016; Sarfraz et al., 2017) and reducing the emissions of GHGs (Azeem et al., 2019; Lehmann et al., 2006; Liu et al., 2019). Biochar is charcoal used as a soil amendment for both C sequestration as well as soil health benefits. Because soil amendment with biochar can act as soil C storage and, thus, significantly contribute to mitigating GHGs emissions (Van Zwieten et al., 2010; Montanarella and Lugato, 2013).

A study reported that 0.49 Gt of C yearly removed from the atmospheric environment by biochar application to agricultural soils (Woelf et al., 2010). Nevertheless, the application of biochar in croplands to mitigate GHGs emissions remain controversial and varies among research studies (Cayuela et al., 2014; He et al., 2017; Lorenz and Lal, 2014). Some research studies reported the N_2O emission significantly decreased after biochar application in agricultural soils (Case et al., 2015; He et al., 2017). In contrast, enhancement of N_2O emissions was also observed after the biochar amendment by Bruun et al. (2011), Sánchez-García et al. (2014), and Saarnio et al. (2013). While biochar

had no effect on N_2O emission from agricultural soils (Pereira et al., 2015; Wang et al., 2015). The high variability in the results from individual studies is difficult to reveal the main effect of animal manure and biochar on N_2O mitigation.

Meta-analysis is a statistical approach for combining data from multiple studies. Recently, meta-analytical approaches have gained attention in agricultural studies (Ren et al., 2017). In this technique, statistical analysis is performed to integrate as well as compare the final results gathered from multiple research studies to draw the general models at different spatial scales (Freeman et al., 1986).

In recent times, different meta-analysis studies have been conducted to check the individual effect of animal manure (Shakoor et al., 2021b; Zhang et al., 2020; Zhou et al., 2017) and biochar (Cayuela et al., 2014; He et al., 2017) on N_2O emissions. Here, we conducted the first global meta-analysis study to investigate and compare the effect of animal manure and biochar on N_2O emissions from agricultural soils. The main objectives were: (a) to compare the overall effect of animal manure and biochar on N_2O emissions; (b) to examine which soil physicochemical properties (soil texture, soil pH, and C: N ratio), and agricultural management practices are the main driving factors for N_2O emissions after animal manure and biochar application from agricultural soils.

2. Materials and methods

2.1. Database

For this study, data were collected from previous peer-reviewed published publications and searched through Scopus, Google Scholar, and Web of Science search engines from 1980 to 2020. The main keywords used to search the relevant publications were “animal manure”, “swine”, “pig”, “dairy”, “cattle”, “poultry”, “biochar”, “charcoal”, “GHGs”, and “nitrous oxide” “ N_2O ”. To fulfill the objectives, peer-reviewed publications were further screened to meet the following criteria: (i) research studies must reported at least one control as well as treatment; (ii) studies measured cumulative N_2O emissions (kg ha^{-1}) after animal manure, and/or biochar application from agricultural soils; (iii) means and standard deviations/errors; and (iv) physicochemical properties of soil, animal manure and biochar; (v) application rate of animal manure and biochar and crop type were also clearly presented. Keeping these criteria, we collected 85 publications for this meta-analysis (Table S1). Fig. 1 shows the geographic distribution of all the selected research studies around the world. Flux data that were presented in the graphs retrieved using GetData Graph Digitizer (version 2.26) software.

To better understand the impact of animal manure and biochar on N_2O emission, datasets are further divided into different groups. Soil texture subdivided into coarse (sandy clay loam, sandy loam, loamy sand), fine (silt clay, clay, sandy clay), and medium (loam, clay loam, silt, silty clay loam, silt loam) textured soils (USDA, 1999); soil pH categorized as ≤ 6.5 (acidic), 6.6–7.3 (neutral), and > 7.3 (alkaline); and soil C: N ratio subdivided into ≤ 10 and > 10 (Shakoor et al., 2021a). Furthermore, manure and biochar rates categorized as $\leq 120 \text{ kg N ha}^{-1}$, 121–320 kg N ha^{-1} and $> 320 \text{ kg N ha}^{-1}$ (Cayuela et al., 2017), and biochar application rate subdivided as $\leq 10 \text{ T ha}^{-1}$, $\leq 20 \text{ T ha}^{-1}$, $\leq 30 \text{ T ha}^{-1}$, $\leq 40 \text{ T ha}^{-1}$, and $> 40 \text{ T ha}^{-1}$ (Song et al., 2016), respectively. Manure C: N ratio sub grouped into ≤ 10 , ≤ 30 , and > 30 , while biochar C: N ratio categorized as ≤ 100 , ≤ 200 , and > 200 . On the other hand, crop type is divided into barley, maize, rice, fallow, grassland, and vegetable categories (Shakoor et al., 2021b).

2.2. Meta-analysis and statistical analysis

A natural log-transformed response ratio (lnRR) was used to calculate the effect size of N_2O emissions after animal manure and biochar amendments (Hedges et al., 1999).



Fig. 1. General data information ($n = 85$) obtained from 43 studies in animal manure and 42 studies in biochar application used in the meta-analysis according to the location of experiments.

$$\ln RR = \ln(x_T / x_C) = \ln(x_T) - \ln(x_C) \quad (1)$$

where, the subscript of x_T and x_C denotes the mean of treatment and control for both animal manure and biochar amendments, respectively. If the value of $RR < 1$, $RR = 0$, and/or $RR > 1$, it shows that treatment had negative, no, and positive effects on N_2O emissions, respectively.

If only the standard error (SE) was calculated, then the following equation was used to calculate the standard deviation (SD);

$$SD = SE\sqrt{n} \quad (2)$$

n represents the number of replications.

The following equation was used to convert the effect sizes into percentage changes;

$$(e^{\ln RR} - 1) \times 100\% \quad (3)$$

Here, we also calculated the emission factors (EFs, %) of N_2O following the application of animal manure and biochar to check the net effect using the following equation;

$$EFs \text{ (\%)} = (x_T - x_C) / N \times 100 \quad (4)$$

where x_T and x_C shows the mean of treatment and control, while N is the application rate of animal manure and biochar (kg N ha^{-1}).

The effect sizes were calculated using METAWIN (2.1), and 95% bootstrapped confidence intervals (CIs) were measured using 4999 iterations (Rosenberg et al., 2000). The relationship between the variables is significant if $P < 0.05$.

3. Results

3.1. The response of N_2O emissions to animal manure and biochar application

The overall effect size ($n = 417$) ($\ln RR$) of animal manure ($n = 231$) and biochar ($n = 186$) on N_2O emissions is shown in Fig. 2. According to this study, overall $[\ln RR = 7.1\%$, 95% CI = -10.5% , 28.2%], organic amendments (animal manure and biochar) had no significant effect on N_2O emissions because 95% CI overlapped with zero. On average,

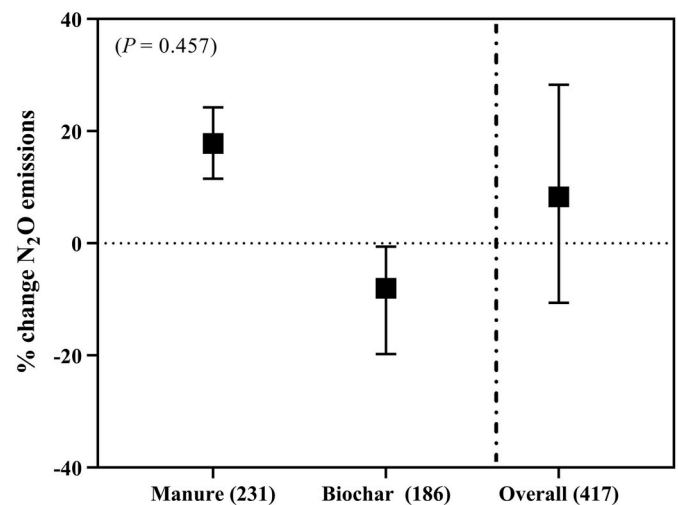


Fig. 2. The overall effects of organic amendments (animal manure and biochar) on N_2O emissions. Numbers in parentheses indicate the sample size and error bars represent 95% bootstrap confidence intervals. The P values are presented in the panel.

animal manure significantly increased N_2O emissions by 17.7% [95% CI = 11.5%, 24.2%]. In contrast, biochar application significantly mitigated N_2O emissions by 19.7% [95% CI = -3.7% , -0.5%] (Fig. 2).

3.2. Effects of soil physiochemical properties on N_2O emissions

3.2.1. Soil texture

Fig. 3 shows the effect sizes of animal manure and biochar on N_2O emissions. For animal manure, from the total ($n = 204$), 41, 149, and 18 observations (paired wise) were selected for coarse, medium, and fine textured soils, respectively. On the other hand, for biochar ($n = 127$), 63, 50, and 14 observations (paired wise) were chosen for coarse, medium, and fine soils, respectively.

Overall, both animal manure $[\ln RR = 25.8\%$, 95% CI = -72.9% ,

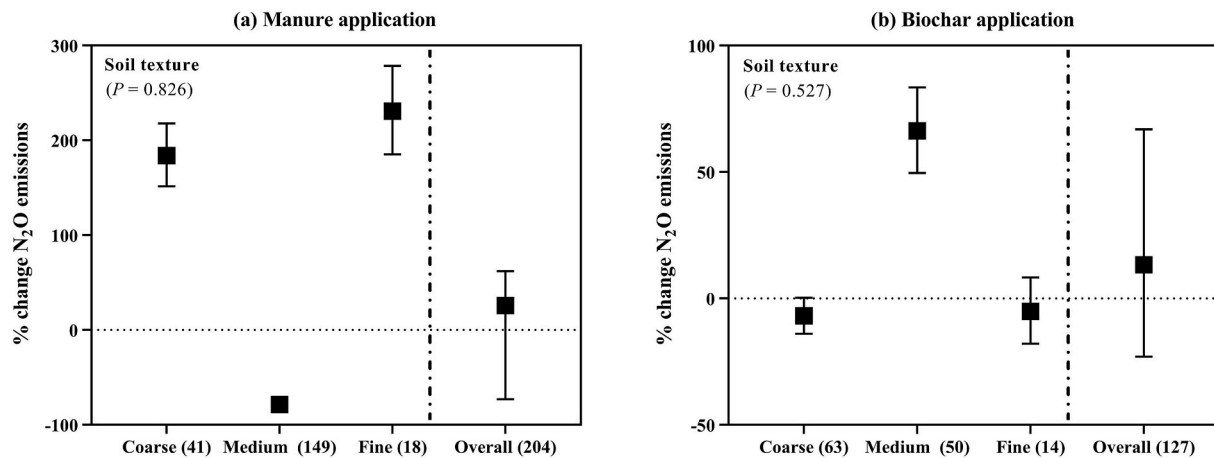


Fig. 3. Influence of organic amendments ((a) animal manure and (b) biochar) on N_2O emissions in response to soil texture. Numbers in parentheses indicate the sample size and error bars represent 95% bootstrap confidence intervals. The P values are presented in the panel.

61.1%], and biochar [$\overline{lnRR} = 13.3\%$, 95% CI = -23.0%, 66.8%], amendments did not show any significant effect on N_2O emissions from agricultural soils (Fig. 3). For animal manure, on average, coarse and fine textured soils increased N_2O emissions by 182.6% [95% CI = 151.4%, 217.7%] and 228.3% [95% CI = 185.1%, 278.4%], respectively. In contrast, medium textured soils significantly mitigated N_2O emissions after animal manure by 78.5% [95% CI = -79.4%, -77.4%] (Fig. 3a).

On the other hand, medium textured soils significantly enhanced [$\overline{lnRR} = 65.6\%$, 95% CI = 49.6%, 83.4%] and coarse textured soils significantly mitigated [$\overline{lnRR} = -7.0\%$, 95% CI = -13.9%, 0.3%] N_2O emissions after biochar application (Fig. 3b). Whereas fine [$\overline{lnRR} = -5.72\%$, 95% CI = -17.8%, 8.3%] textured soils had not shown any significant effect on N_2O emissions from agricultural soils (Fig. 3b).

3.2.2. Soil pH

Fig. 4a(i), b(i) presents the overall effect sizes of soil pH on N_2O emissions after animal manure and biochar application. Overall ($n = 224$), soil pH significantly increased N_2O emissions after animal manure by 76.1% [95% CI = 16.0%, 167.5%] (Fig. 4a(i)). On average, alkaline ($n = 100$), neutral ($n = 62$) and acidic ($n = 62$) soils significantly enhanced N_2O emissions under animal manure amendment by 152.1%

[95% CI = 135.3%, 170.4%], 49.15% [95% CI = 27.2%, 74.8%] and 43.4% [95% CI = 24.4%, 65.3%], respectively (Fig. 4a(i)).

On the other hand, for the biochar amendment, the overall ($n = 172$) effect size of soil pH for N_2O emissions was not significantly different than control (95% CI overlapped with zero) (Fig. 4b(i)). On average, alkaline ($n = 93$) soils significantly increased N_2O emission after biochar amendment [$\overline{lnRR} = 13.0\%$, 95% CI = 5.44%, 21.2%], whereas biochar application significantly mitigated N_2O emission from neutral ($n = 33$) soils by 12.1% [95% CI = -21.3%, -18.1%]. N_2O emission was not affected in acidic ($n = 46$) soils after biochar amendment (Fig. 4b(i)).

3.2.3. Soil C: N ratio

Soil C: N ratio showed a significant positive effect on N_2O emissions after animal manure and biochar application (Fig. 4a(ii), b(ii)). For animal manure, overall ($n = 144$), soil C: N ratio overlapped with zero and did not show any significant difference (Fig. 4a(ii)). However, > 10 ($n = 65$) soil C: N ratios showed positive effect and increased N_2O emissions by 121.4% [95% CI = 110.6%, 133.0%], while ≤ 10 soil C: N ratios did not exhibit any effect [$\overline{lnRR} = -6.4\%$, 95% CI = -15.5%, 3.6%] on N_2O emissions after animal manure (Fig. 4a(ii)).

On the other hand, overall ($n = 144$), soil C: N ratios significantly enhanced N_2O emission after biochar application by 20.5% [95% CI =

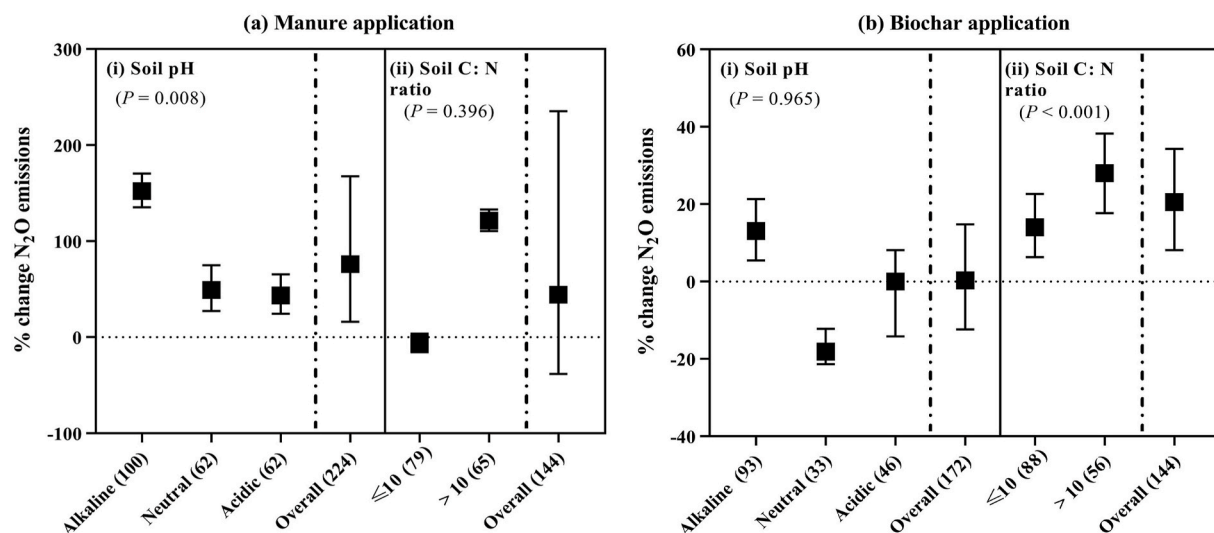


Fig. 4. Effect of organic amendments ((a) animal manure and (b) biochar) on N_2O emissions differed with soil pH and soil C: N ratio. Numbers in parentheses indicate the sample size and error bars represent 95% bootstrap confidence intervals. The P values are presented in the panel.

8.11%, 34.3%) (Fig. 4b(ii)). On average, ≤ 10 ($n = 88$) and >10 ($n = 56$) soil C: N ratios enhanced N_2O emissions from agricultural soils by 14.2% [95% CI = 6.2%, 22.6%] and 27.6% [95% CI = 17.7%, 38.2%], respectively after biochar amendment, respectively (Fig. 4b(ii)).

3.3. Effects of agricultural management practices on N_2O emissions

3.3.1. Crop type

For crop types, 193 and 110 observations (paired wise) were selected for animal manure and biochar amendments, respectively (Fig. 5). Overall, crop types had no shown any significant effect on N_2O emissions after animal manure and biochar amendments (Fig. 5). On average, fallow periods and grasslands considerably increased N_2O emissions by 369.2% [95% CI = 320.8%, 422.7%] and 328.0% [95% CI = 284.9%, 376.3%] after animal manure, respectively (Fig. 5a). In contrast, maize crops significantly mitigated N_2O emissions by 84.8% [95% CI = -85.8%, -83.7%] under animal manure (Fig. 5a).

On the other hand, after biochar application, vegetables significantly enhanced N_2O emissions [$\lnRR = 53.2\%$, 95% CI = 29.8%, 80.9%] from agricultural soils, whereas maize crops significantly mitigated N_2O emissions by 30.3% [95% CI = -36.8%, -23.2%] (Fig. 5b). However, no significant differences were observed under fallow seasons and rice crops after biochar amendment (Fig. 5b).

3.3.2. Animal manure and biochar application rate

Fig. 6 represents the effect sizes of animal manure ($n = 229$) and biochar ($n = 177$) application rates on N_2O emissions from agricultural soils. Overall, effect sizes of animal manure and biochar application rates had not shown any effect on N_2O emissions (Fig. 6).

For animal manure, on average, ≤ 120 kg N ha $^{-1}$ [$\lnRR = 77.1\%$, 95% CI = 59.0%, 97.3%] and >320 kg N ha $^{-1}$ [$\lnRR = 447.9\%$, 95% CI = 396.2%, 505.5%] application rates significantly enhanced N_2O emissions from agricultural soils (Fig. 6a). In contrast, 121–320 kg N ha $^{-1}$ animal manure rates significantly mitigated N_2O emissions by 72.3% [95% CI = -73.6%, -70.8%] (Fig. 6a).

Alternatively, ≤ 10 T ha $^{-1}$ and ≤ 20 T ha $^{-1}$ biochar application rates significantly increased N_2O emissions by 9.3% [95% CI = 0.8%, 18.6%] and 15.2% [95% CI = 4.6%, 26.8%], respectively (Fig. 6b), whereas biochar application rates with ≤ 30 T ha $^{-1}$ significantly mitigated N_2O emissions by 22.5% [95% CI = -31.8%, -12.0%] (Fig. 6b). On the other hand, > 30 T ha $^{-1}$ biochar application rates had no exhibited any effect on N_2O emissions from agricultural soils because 95% CI overlapped

with zero (Fig. 6b).

3.4. Animal manure and biochar C: N ratio

Of the total, 140 and 177 observations (paired wise) were chosen for animal manure and biochar C: N ratios, respectively (Fig. 7). The overall effect of animal manure C: N ratio increased N_2O emissions (Fig. 7a). On average, ≤ 10 and ≤ 30 animal manure C: N ratio significantly enhanced N_2O emissions by 184.3% and 57.2%, whereas animal manure C: N ratio with >30 had not exhibited any effect [$\lnRR = 16.6\%$, 95% CI = -10.5%, 52.3%] because 95% CI overlapped with zero (Fig. 7a).

For biochar, overall, the biochar C: N ratios did not show any significant effect (Fig. 7b), whereas on average, the biochar C: N ratios having ≤ 100 and ≤ 200 considerably increased N_2O emissions by 13.4% [95% CI = 7.3%, 19.7%] and 24.9% [95% CI = 9.8%, 45.4%], respectively. Alternatively, > 200 biochar C: N ratio significantly mitigated N_2O emissions by 25.7% [95% CI = -41.5%, -44.0%] from agricultural soils (Fig. 7b).

3.5. N_2O emission factors

Fig. 8 shows the overall N_2O EFs for animal manure and biochar application. Overall, the average animal manure induced N_2O EFs was 0.46% ($n = 210$) (Fig. 8A), whereas average biochar induced N_2O EFs was less than zero ($n = 184$) (Fig. 8B). Under soil pH, the mean EFs for acidic ($n = 92$), neutral (56) and alkaline ($n = 54$) soils were 0.40%, 0.27% and 0.65%, respectively after animal manure (Fig. 8A(a)). Medium textured ($n = 134$) soils (0.60%) showed highest mean animal manure induced N_2O EFs than coarse (0.23%) ($n = 38$) and fine (0.16%) ($n = 17$) textural classes (Fig. 8A(b)). Under crop type, maize (0.48%) ($n = 73$) and grasslands (0.56%) ($n = 41$) had highest mean N_2O EFs after animal manure than other crops (Fig. 8A(c)). On the other hand, the mean N_2O EFs following biochar amendment in soil pH were less than zero (Fig. 8B(a)), in contrast, fallow ($n = 15$), vegetables ($n = 18$) and fine textured soils ($n = 14$) showed positive mean N_2O EFs (Fig. 8B (b, c)). The minimum mean N_2O EFs was measured in maize crop (-0.02%) ($n = 30$) (Fig. 8B(c)).

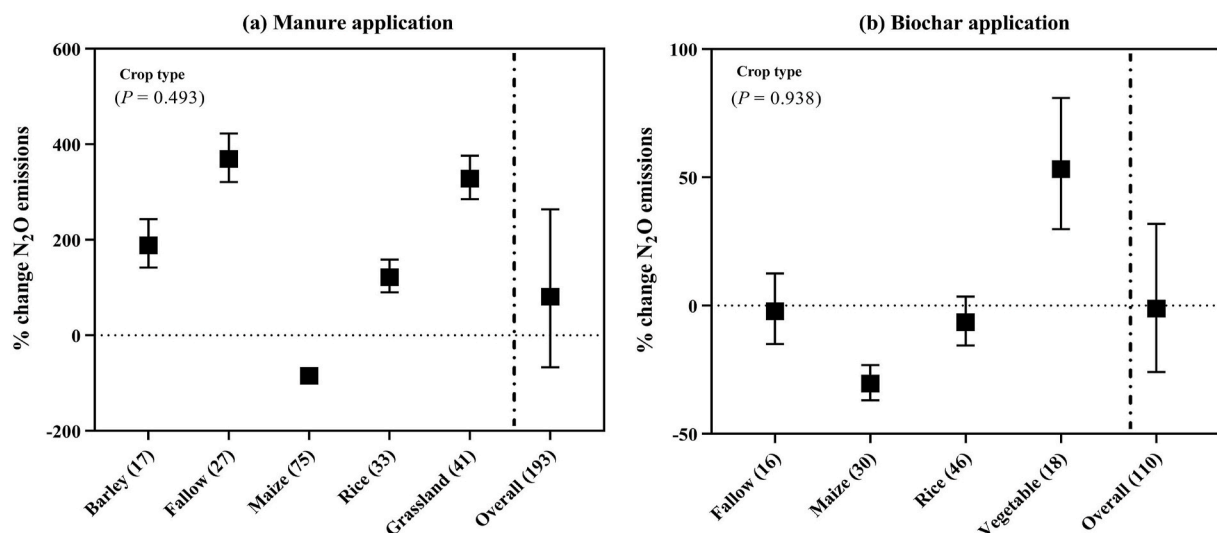


Fig. 5. Response of N_2O emissions to organic amendments ((a) animal manure and (b) biochar) influenced by crop type. Numbers in parentheses indicate the sample size and error bars represent 95% bootstrap confidence intervals. The P values are presented in the panel.

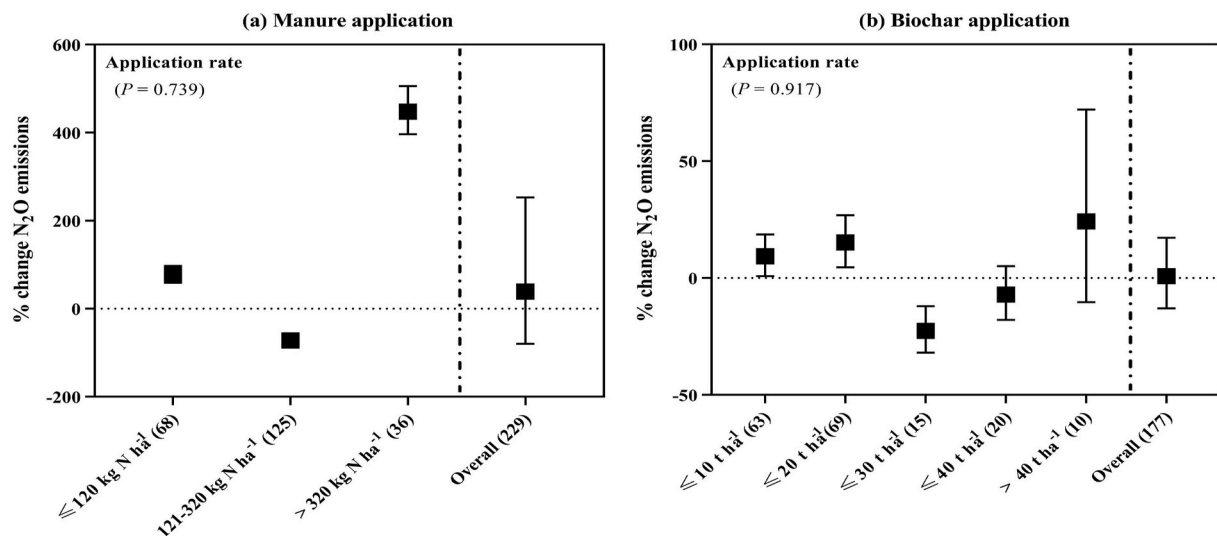


Fig. 6. Impact of application rates of (a) animal manure (kg N ha^{-1}) and (b) biochar (t ha^{-1}) on N_2O emissions. Numbers in parentheses indicate the sample size and error bars represent 95% bootstrap confidence intervals. The P values are presented in the panel.

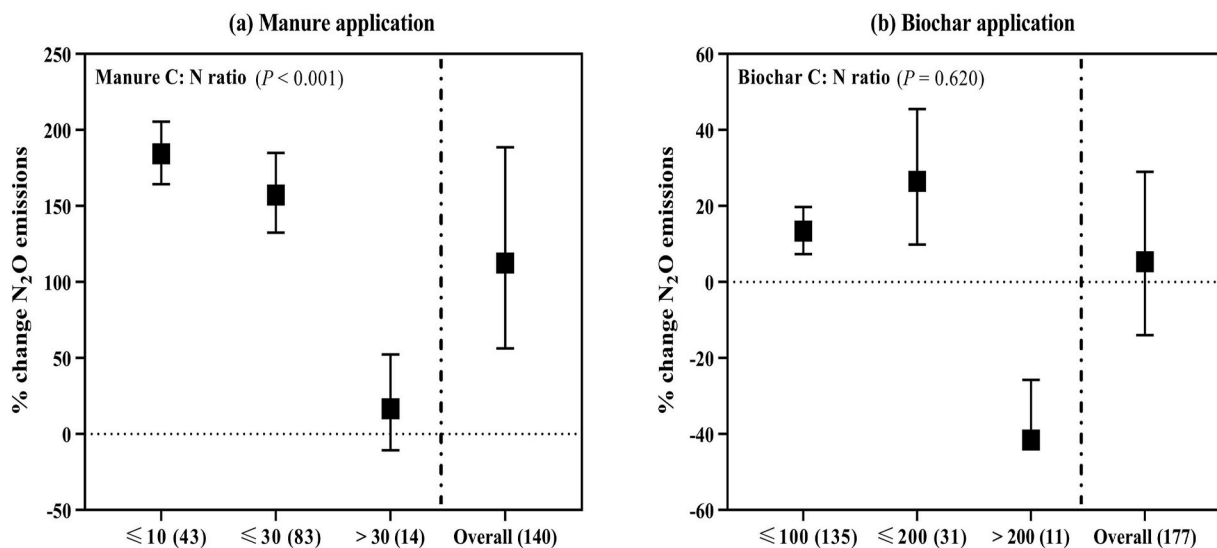


Fig. 7. Emissions of N_2O after (a) animal manure and (b) biochar amendments from croplands affected by animal manure C: N ratio and biochar C: N ratio. Numbers in parentheses indicate the sample size and error bars represent 95% bootstrap confidence intervals. The P values are presented in the panel.

4. Discussions

4.1. The overall response of animal manure and biochar on N_2O emissions

Organic amendments such as animal manure and biochar to croplands not only increased SOC contents, soil fertility, and crop yield but also significantly influenced N_2O emissions. The results of this study show that the overall effect of animal manure and biochar increased and decreased N_2O emissions from agricultural soils, respectively (Fig. 2). A recent meta-analysis studies conducted by Zhou et al. (2017) and Shakoor et al. (2021b) and reported that N_2O emissions enhanced after animal manure amendments to croplands. On the other hand, Cayuela et al. (2014) and He et al. (2017) studied and reported that biochar amendment significantly mitigated N_2O emissions by 30% and 54% from agricultural soils, respectively.

Generally, animal manure comprises a significant amount of nitrogen, phosphorus, and other nutrients that the plant needs to grow (Cavalli et al., 2017). However, manure application significantly

contributes up to 45% of global N_2O emissions from the agricultural soils (Hou et al., 2016; Shakoor et al., 2020a). Microbial denitrification and nitrification processes considered the main processes for regulating the N_2O from agricultural soils (Rodríguez, 2019; Shakoor et al., 2016), which are dependent on the availability of C and N substrate (Groffman and Tiedje, 1991; Zhou et al., 2017). Application of animal manure as an organic amendment increased C and N substrates for microbial N_2O consumption and production that significantly affect and increase the N_2O emissions from soils (Ball et al., 2014; Thangarajan et al., 2013). For example, continuous application of animal manure (18-years) increased SOC (19%), available N (13%), and total N (14%) contents (Lv et al., 2011), which significantly increased N_2O emissions from croplands (Bolan et al., 2004). Furthermore, animal manure can easily decompose by soil microbial community as compared to other organic amendments and converted into SOC contents, which may also be improved nitrification and denitrification processes and, consequently increased N_2O emissions (Hayakawa et al., 2009).

On the other hand, the application of biochar to agricultural soils has the ability to mitigate GHGs emissions through soil C sequestrations

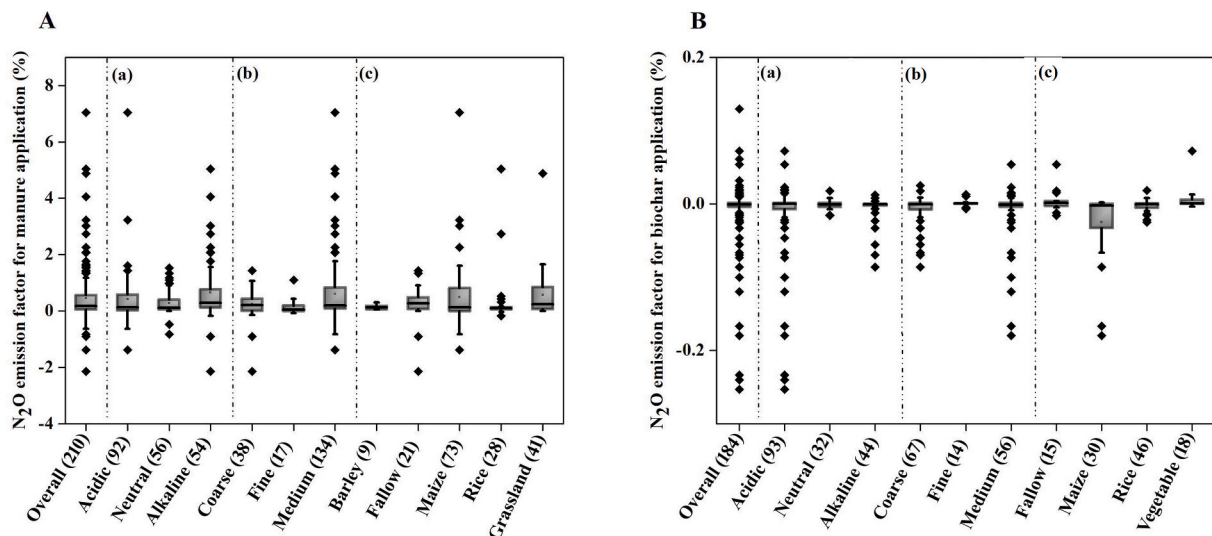


Fig. 8. Boxplots of N₂O emission factors (EF, %) for (A) animal manure and (B) biochar amendments regarding (a) soil pH, (b) soil textural classes, and (c) crop type. Black boxes show outliers, while median values were presented with solid black lines in each box.

(Cayuela et al., 2014; He et al., 2017; Woolf et al., 2010). Rondon et al. (2005) was the first researcher who reported that N₂O emission decreased after biochar application in a greenhouse experiment. In grassland and soybean, they found 80% and 50% reduction in N₂O emission after the biochar amendment, respectively. From agricultural soils, there are many factors that are affecting N₂O emissions such as denitrification as well as nitrification processes, and these processes are directly influenced by biochar amendments (Lévesque et al., 2018; Nelissen et al., 2014). Cayuela et al. (2014) studied and found that N₂O emission reduced after the biochar amendment and this response might be due to changes in the nitrifiers as well as denitrifiers activities that directly produce N₂O emissions. Moreover, the application of biochar to agricultural soils increases soil porosity and aeration due to the adsorption of nitrate and ammonium by biochar (Bai et al., 2015; He et al., 2017). The increased soil aeration may stop the denitrification process due to easily available of the oxygen (He et al., 2017) and ultimately reduced N₂O emissions from agricultural soils. Furthermore, the biochar amendment restricts the inorganic N availability to nitrifiers as well as denitrifiers through immobilization and eventually suppresses N₂O emission (Case et al., 2014, 2015).

4.2. Effects of soil physiochemical properties on N₂O emissions

Soil physicochemical properties significantly regulate GHGs emissions particularly N₂O after organic amendments (Butterbach-Bahl et al., 2013). According to this meta-analysis, coarse and fine textured soils showed a positive correlation with N₂O emissions after manure application (Fig. 3a). A recent meta-analysis study conducted by Chen et al. (2013) and found that coarse textured soils increased N₂O emissions. Velthof & Mosquera (2011) conducted a research study and reported that fine textured soils also significantly enhanced N₂O emissions after animal manure application.

4.2.1. Soil texture

Soil texture plays an important role in regulating the N₂O emissions by moderating the oxygen availability due to size and pore distributions (Corre et al., 1999). Nitrification is considered the dominant process that regulates the N₂O emissions in coarse textured soils (Zhou et al., 2014). Furthermore, the application of animal manure significantly provides C substrate to denitrifiers that can easily increase N₂O emissions from agricultural soils (Shakoor et al. et al., 2020a). Fine textured soils have small pores due to aggregation (Kunickis et al., 2010) that can easily

hold water contents. In fine textured soil, the application of animal manure significantly increased SOM contents that directly increases the water holding capacity (Jäger et al., 2011). Higher water contents also produce anaerobic conditions, which favors the denitrification process and eventually emitted N₂O emissions after manure (Ruser et al., 2006). Nevertheless, more research studies have to be done under medium textured soils for further scientific investigation that how application of animal manure mitigated N₂O emissions.

Soil texture is also considered the main component in biochar efficiency and N₂O production. According to this study, medium textured soils positively correlated with N₂O emissions after the biochar amendment, while a slightly reduction effect was observed under coarse textured soils (Fig. 3b). Basalirwa et al. (2020) studied and reported that N₂O emissions increased in medium textured soils after the biochar amendment. Cayuela et al. (2014) studied and reported that the application of biochar in coarse soils did not show any positive effect. In medium textured soil, biochar significantly favors the denitrification process due to high clay contents. Generally, clay soils have the largest pore space, therefore the greatest water holding capacity resulting in the maximum conversion of N₂ (dinitrogen) to N₂O emissions (Cayuela et al., 2013; Yuan et al., 2011). Due to the lack of enough research studies, it is difficult to predict how textural classes affect biochar efficiency to mitigate N₂O emissions. Therefore, there are several factors, such as water-filled pore spaces, percentage of clay contents, irrigation type and rainfall pattern have to discuss more critically in future research studies to understand the response of soil texture to N₂O emissions after biochar amendment.

4.2.2. Application of organic amendments

Application of animal manure significantly enhances soil pH, porosity, and aggregations (Whalen et al., 2000), which can control different abiotic as well as biotic processes influencing N₂O production (Butterbach-Bahl et al., 2013; Zhou et al., 2017). In this study, soil pH significantly increased N₂O emissions after animal manure application from agricultural soils (Fig. 4a(i)). Shakoor et al. (2021b) and Ren et al. (2017) performed meta-analysis studies and reported that alkaline and acidic soils significantly increased N₂O emissions after animal manure application. Generally, autotrophic nitrifier prefers neutral to slightly alkaline conditions for oxidization process, and subsequently, the nitrification process is normally high in alkaline soils than acidic soils (Chen et al., 2013). However, another researcher studied and reported that the application of animal manure can also promote N₂O production

by denitrifiers in acidic soils and ultimately increase N_2O emissions from agricultural soils (Stevens et al., 1998). It is notable that there might be possible uncertainties in the response of N_2O to animal manure under different soil pH levels. According to Butterbach-Bahl et al. (2013), there is still a lack of scientific knowledge on how different soil pH levels control N_2O emission. Moreover, the application of animal manure neutralizes the acidity of soil and increases soil pH (Thangarajan et al., 2013) that can also raise the complexity of how animal manure affects N_2O emissions under different pH levels.

After the biochar amendment, N_2O emissions significantly increased under alkaline soils, whereas a considerably mitigated effect was observed in neutral soils (Fig. 4b(i)). He et al. (2017) studied and reported that biochar significantly mitigated N_2O emissions from agricultural soil under different soil pH levels. Activities of soil microbes substantially contribute to the total global N_2O emissions and microbial activities are most sensitive to different soil pH levels. For example, N_2O reductase activity (N_2OR) increases in alkaline soil than acidic soils (Liu et al., 2014), which eventually promotes N_2O emissions. Furthermore, according to the early findings of Sahrawat and Keeney (1986), the optimal soil pH for denitrifier activities is > 7 , which can significantly help in N_2O emissions.

4.2.3. Soil C: N ratio

Soil C: N ratio significantly affected N_2O emissions after animal manure and biochar amendments. According to this meta-analysis study results, > 10 soil C: N ratio significantly increased N_2O emissions after both organic amendments (Fig. 4a(ii), b (ii)).

De Rosa et al. (2018) and Vallejo et al. (2006) studied and found that higher soil C: N ratio significantly enhanced N_2O emissions after different animal manures. On the other hand, Lin et al. (2015) and Zhang et al. (2016a,b) studied and observed the maximum N_2O emission from high soil C: N ratio (> 10). Mechler et al. (2018) also found similar results after the biochar amendment. Application of animal manure significantly increases soil C: N ratio by increases SOC contents in the soil profile (Maillard and Angers, 2014), and increasing SOC contents may influence soil N_2O production (Guenet et al., 2020). Application of animal manure and compost (under high soil C: N ratio) increased the denitrification process, which ultimately increased the availability of soil N contents, which favors the N_2O emissions (Charles et al., 2017). On the other hand, biochar application may also enhances soil C: N ratio, also improves microbial activities, and increases GHGs emissions (Muñoz et al., 2019). Most of the research studies that were comprised in this meta-analysis study did not account the changes of soil C: N ratio with animal manure and biochar amendments, so might be due to this, we found variation in the results.

4.3. Effects of agricultural management practices on N_2O emissions

Crop species are also considered the main source for N_2O emissions after different organic amendments (Ali et al., 2013; Huang et al., 2018). According to this study, grasslands and fallow periods considerably increased N_2O emissions, in contrast, maize crops significantly mitigated N_2O emissions after the application of animal manure (Fig. 5a). A recent meta-analysis conducted by Shakoore et al. (2021b) and found that grasslands significantly produced N_2O emission after animal manure amendment. Another researcher studied and reported that almost 28% of the total global N_2O was produced from grasslands (Rafique et al., 2011). Nitrification, denitrification, nitrifier-denitrification, and respiration are the main microbial processes that significantly affect N_2O emissions (Case et al., 2015; Xu et al., 2017). Application of animal manure to grasslands affects the biochemical conditions of soil and ultimately enhances microbial activities that directly influence nitrification and denitrification rates and increases N_2O production (Schirrmann et al., 2020). Alternatively, maize crop significantly mitigated N_2O from agricultural soils after animal manure. It might be due to the low application rate of manure and/or other soil and environmental factors.

This Knowledge gaps on mitigation of N_2O emissions can be addressed in future research studies.

On the other hand, vegetables showed a significant positive correlation with N_2O emissions after the biochar amendment. In contrast, maize crops significantly mitigated N_2O emissions (Fig. 5b). Jia et al. (2012) reported that the biochar amendment increased N_2O emissions from vegetable crops. Whereas, Li et al. (2017) performed a long-term experiment and found that the application of biochar (during the first year) increased N_2O emissions from the vegetable field. A small amount of biochar might serve as an extra C source for heterotrophic nitrifiers and increased N_2O emissions from vegetable crops (Lehmann et al., 2011; Li et al., 2015).

N_2O emissions are directly proportional to the rate of organic amendments to the agricultural lands. A high amount of animal manure ($> 320 \text{ kg N ha}^{-1}$) significantly increased N_2O emission, whereas $\leq 20 \text{ t ha}^{-1}$ biochar application rates significantly enhanced N_2O emissions from agricultural soils (Fig. 6). Shakoore et al. (2021b) studied and found that a higher amount of animal manure had a positive correlation with N_2O emissions. The high rate of animal manure determines the availability of N for nitrification as well as denitrification processes. The N_2O emissions released by the nitrification process were linearly correlated to the amounts of N (Khalil et al., 2004). According to our results, 30 t ha^{-1} was the best biochar application rate where the significant reduction was observed. According to Song et al. (2016) meta-analysis study, the higher biochar application rates significantly mitigated N_2O emissions. Normally, a high amount of biochar might restrict the availability of N, the main driver of N_2O emissions, and ultimately decreased N_2O emissions (Cayuela et al., 2013). Generally, the surface of the biochar can easily absorb nitrate contents and therefore reduce N_2O emissions (Cayuela et al., 2013; Clough et al., 2013). However, there is more scientific research need to do to find the best biochar application rate with minimum N_2O emissions and crop yield.

4.4. Animal manure and biochar C: N ratio

Animal manure and biochar C: N ratios also an important parameter that significantly influences the N_2O emissions. According to this study results, ≤ 10 animal manure C: N ratio increased N_2O emissions, while higher biochar C: N ratio (≤ 200) significantly mitigated N_2O emissions from agricultural soils (Fig. 7). Cayuela et al. (2014) and Shakoore et al. (2021b) also found similar findings. Normally, animal manure contains a considerable amount of organic C as well as N contents that can directly influence nitrification as well as denitrification processes (Meng et al., 2005). Moreover, low animal manure C: N ratio significantly enhanced N_2O , because animal manure provides a favorable environment for denitrifiers (Flessa and Beese, 1995; Meng et al., 2005). Biochar amendment with higher C: N ratios significantly decreased N_2O emissions due to microbial N immobilization (Cayuela et al., 2010; Baggs et al., 2010). Consequently, a very less amount of soil N is available for microbial processes for N_2O emissions.

4.5. N_2O emission factors

According to this meta-analysis study, the average animal manure induced N_2O EFs was 0.46%, which is less than the default IPCC EFs value (1%) (IPCC, 2006), however, the emission was ranged from -2.2% to 7.5% , whereas, average biochar induced N_2O EFs was less than zero (Fig. 8). Zhang et al. (2020), Velthof & Mosquera (2011) and Charles et al. (2017) studied and reported the similar N_2O EFs values after animal manure application. Basically, IPCC EFs value was firstly derived by Stehfest and Bouwman (2006) and the average EFs value was 0.9%. Later on, The IPCC (2006) rounded off this value to 1% due to uncertainties linked with this value as well as the inclusion. Differences in the N_2O EFs depend on the N application rate and organic amendment techniques, which can increase the quantification of N_2O emission and mitigation options. The N_2O emission from agricultural soils can be

reduced by decreasing the application rate of N.

5. Limitations and suggestions

In this study, most of the research studies that are included in this study reported no changes in the physiochemical properties of soil after organic amendments. Therefore, more research is required to better understand the relationship between the application of organic amendments and N₂O emissions.

The subsequent generation of research studies on organic amendments and N₂O emissions should systemically include complete animal manure and biochar physicochemical properties (i.e. pH, C: N ratio, bulk density, BET surface area, electrical conductivity (EC), particle size, potential toxicity, and adsorption capacity), origin and chemical properties of feedstock, pyrolysis conditions (i.e. temperature, reactor type and exposure time) and physicochemical properties of soil such as pH, bulk density, texture, EC, total N, total organic C, available phosphorus and potassium contents.

6. Conclusions

Generally, applications of organic amendments such as animal manure and biochar to agricultural soils significantly increase SOC contents. Though the potential role of SOC contents for N₂O mitigation dependent on the physicochemical properties of soil and both organic amendments as well as application rates. This meta-analysis study showed that animal manure increased N₂O emissions by 17.7%, whereas, 19.7% of N₂O emissions mitigated after the biochar amendment. Soil attributes had a strong effect on N₂O emission after both organic amendments. For example, animal manure amendment to coarse textured soils increased N₂O emissions by 182.6%. In contrast, coarse textured soils significantly decreased N₂O emissions (7.0%) after biochar application. On the other hand, overall, soil pH significantly enhanced N₂O emissions by 76.1% after the manure amendment. While, for the biochar amendment, the overall effect of soil pH for N₂O emissions did not show a significant difference as compared to control. Furthermore, > 10 soil C: N ratio showed a strong effect and increased N₂O emissions by 121.4% and 27.6% after animal and biochar amendments, respectively. Overall, no significant effects of animal manure and biochar amendments on N₂O emissions were observed under crop types. According to this meta-analysis study, medium doses such as 121–320 kg N ha⁻¹ and ≤ 30 T ha⁻¹ application rates of animal manure and biochar had strong mitigation effects on N₂O emissions. Overall effect of animal manure C: N ratio significantly increased N₂O emissions, whereas, the biochar C: N ratios did not show any significant effect on N₂O emissions. The results of this study shown that the average animal manure and biochar induced N₂O EFs were less than the default IPCC EFs value. Hence, this study provides a comprehensive comparison between animal manure and biochar amendments to mitigate the N₂O emissions from agricultural soils and can be used for policymaking, but no research is completed without saying “DO MORE”.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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