Heliyon 9 (2023) e22132

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Paddy rice yield and greenhouse gas emissions: Any trade-off due to co-application of biochar and nitrogen fertilizer? A systematic review

Maduabuchi P. Iboko [a,b,c,*], Elliott R. Dossou-Yovo [d], Sunday E. Obalum [e], Chidozie J. Oraegbunam [f], Siméon Diedhiou [a,b,c], Christian Brümmer [g], Niaba Témé [h]

[a] *Graduate Research Program, Climate Change and Agriculture, Université des Sciences, des Techniques et des Technologies de Bamako (USTTB), Mali*
[b] *Graduate Research Program, Climate Change and Agriculture, Institut Polytechnique Rural de Formation et de Recherche Appliquée, Katibougou, Mali*
[c] *School of Agriculture, University of Cape Coast, Cape Coast, Ghana*
[d] *Africa Rice Center (AfricaRice), Bouake, Cote D'Ivoire*
[e] *Department of Soil Science, University of Nigeria, Nsukka, 410001, Nigeria*
[f] *Global Station for Food, Land & Water Resources, Research Faculty of Agriculture, Hokkaido University, Kita 9 Nishi 9 Kita-Ku, Sapporo, Hokkaido, 060-8589, Japan*
[g] *Thünen Institute of Climate-Smart Agriculture, Bundesallee 50, 38116, Braunschweig, Germany*
[h] *Labo Biotechnologie, Institute D'Economie Rurale, Sotuba, Mali*

ARTICLE INFO

Keywords:
Greenhouse gas
Systematic review
Biochar
Rice yield
, N fertilizer

ABSTRACT

Combined application of biochar and nitrogen (N) fertilizer could offer opportunities to increase rice yield and reduce methane emissions from paddy fields. However, this strategy may increase nitrous oxide (N_2O) emissions, hence its interactive effects on GHG emissions, global warming potential (GWP) and GHG intensity (GHGI) remained poorly understood. We conducted a systematic review to i) evaluate the overall effects of combined application of biochar and N fertilizer rates on GHGs emissions, GWP, rice yield, and GHGI, ii) determine the quantities of biochar and N-fertilizer application that increase rice yield and reduce GHGs emissions and GHGI, and iii) examine the effects of biochar and different types of nitrogen fertilizers on rice yield, GHGs, GWP, and GHGI using data from 45 research articles and 183 paired observations. The extracted data were grouped based on biochar and N rates used by researchers as well as N fertiliser types. Accordingly, biochar rates were grouped into low (≤9 tons/ha), medium (>9 and ≤ 20 ton/ha) and high (>20 tons/ha), while N rates were grouped into three categories: low (≤140 kg N/ha), medium (>140 and ≤ 240 kg N/ha), and high (>240 kg N/ha). For fertiliser types, N rates were grouped as: low (≤150 kg N/ha), medium (>150 and ≤250 kg N/ha), and high (>250 kg N/ha) and N types into: urea, NPK, NPK plus urea (NPK_urea) and NPK plus $(NH_4)_2SO_4$ (NPK_ $(NH_4)_2SO_4$). Results showed that biochar and N fertiliser significantly affected GHGs emissions, GWP, GHGI and rice yield. Compared to control (i.e., sole N application), co-application of high biochar and medium N rates significantly decreased CH_4 emission (82 %) while low biochar with low N rates enhanced CH_4 emission (114 %). In contrast, high biochar combined with low N decreased N_2O emission by 91 % whereas medium biochar and high N rates resulted in 82 %

---

[*] Corresponding author. Graduate Research Program, Climate Change and Agriculture, Université des Sciences, des Techniques et des Technologies de Bamako (USTTB), Mali.

E-mail address: Iboko.m@edu.wascal.org (M.P. Iboko).

https://doi.org/10.1016/j.heliyon.2023.e22132
Received 18 April 2023; Received in revised form 27 October 2023; Accepted 5 November 2023

increase in N_2O emission relative to control. The highest GWP and GHGI were observed under co-application of medium biochar and low N rates. Highest rice yield was observed under low biochar rate and high N rate. Regardless of N fertiliser type and biochar rates, increasing N rates increased rice yield and N_2O emissions. The highest GWP and GHGI were recorded under sole NPK application. Combination of low biochar and medium N produced low GHGs emissions, high grain yield, and the lowest GHGI, and could be recommended to smallholder farmers to increase rice yield and reduce greenhouse gas emissions from paddy rice field. Further studies should be conducted to evaluate the effects of biochar properties on soil characteristics and greenhouse gas emissions.

1. Introduction

Globally, rice is a strategic crop for combatting hunger and food insecurity [1]. More than half of the global population depend on rice for meeting their food needs [2–4]. Consequently, rice has become one of the fastest growing crops in the world in terms of production area [5]. However, rice production depends on large nitrogen (N) fertilizer and water inputs for optimal yield. More than 24 % of the global N consumption is linked to rice production [6], with less than 40 % N use efficiency [7]. Particularly, in high yielding rice varieties, maximum grain yield is achieved by reliance on chemical fertilizer [1]. Their growths and developments are hinged on the presence of N [8–10], without N, yield is significantly reduced [11–13], thus leading to excessive N application which pollutes the environment [14,15], causes disruption in the N cycle, and lowers N use efficiency by plants [16]. It is estimated that between 50 and 70 % of the added N is lost to the environment [17] where they are transformed into different greenhouse gases (GHGs), air pollutants such as ammonia (NH_3) or N monoxide (NO), or are leached through nitrates (NO_3^-), thereby making rice an important contributor to the current anthropogenic global warming [18–20].

Paddy rice production is a major source of methane (CH_4) [21–23] and accounts for about 11 % of the global CH_4 emission [24].

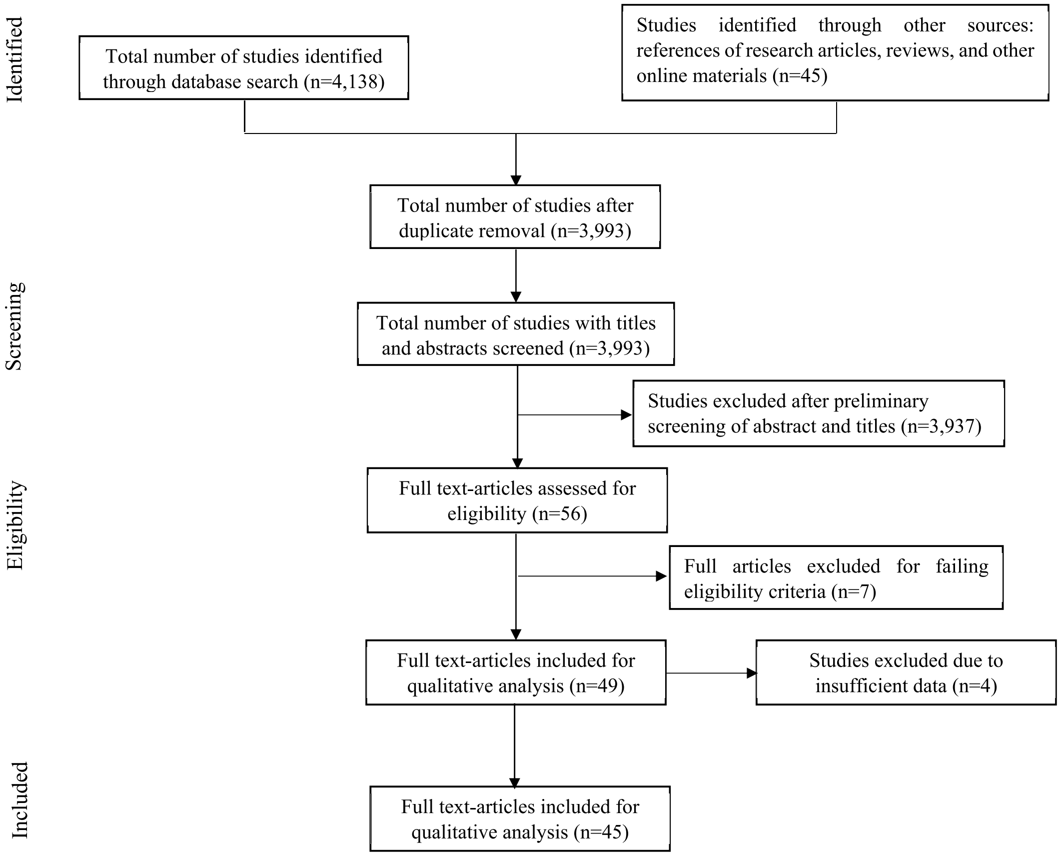

Fig.1: PRISMA diagram of article retrieval

Fig. 1. PRISMA diagram of article retrieval.

The high moisture [25] and N demand by rice [1,8,9,11,12] provide perfect conditions for the anaerobic production of CH_4 and nitrous oxide (N_2O) [20,26]. The flooded condition and N fertilization associated with rice production provide favourable environment and substantial ammonium (NH_4^+) and nitrate (NO_3^-) substrates for the microbial production of N_2O through nitrification and denitrification [25,27]; two processes that account for 39 % and 60 % of the global N_2O emission from the soil [28]. Aside from N_2O, the resulting lack of oxygen and other oxidant prevalent in paddy fields allows methanogenic archaea to decompose soil organic matter to release CH_4 [29–31]. From the foregoing, it is evident that alternative approaches to rice cultivation with concomitant advantages of raising crop yield and reducing emission footprint from paddy rice production are urgently needed. The situation is more compelling considering the growing demands for food especially rice by the teeming global population [32].

Different strategies have been deployed in reducing GHGs emissions from rice fields. The most popular are water management [33–36] and use of nitrification inhibitors like biochar [37]. However, results from researchers have shown mixed effects from the application of water management and biochar. For instance, changing irrigation regimes from continuous flooding to alternate wetting and drying results in either yield increase [38], or trade-off between CH_4 and N_2O [23,33,39]. While biochar application leads to either reduction of CH_4 emission and increase in carbon dioxide (CO_2) and N_2O emission or vice versa or other forms of unwanted effects such as yield decreases [40–45] or no effect [46]. Some studies showed that little effect of biochar application on rice yield was due to the inability of biochar to supply sufficient plant nutrients especially at low biochar rate, and other studies reported that high rate of biochar application leads to nutrient immobilization [44] and toxicity to plants due to the presence of toxic polycyclic aromatic hydrocarbons [40]. To overcome these challenges, the combined application of biochar and N fertilizer was advocated by several authors [47–50], and has shown good results in both rice yield [51] and GHGs reduction [52] albeit with some trade-offs for CH_4 and N_2O emissions, suggesting that optimal combination rate of these two amendments needs to be explored. Therefore, using the currently available data, this review i) assessed the overall effects of the combined application of biochar and N-fertilizer on GHGs emissions, global warming potential (GWP), rice yield, and yield-scaled GHG intensity (GHGI), ii) determined the quantity of biochar and N-fertilizer combinations that increases crop yield and reduces GHGs emissions and GHGI, and iii) determined the effect of different N types when combined with biochar, on rice yield, GHGs and GHGI.

2. Materials and method

2.1. Approach for data collection

A mixed method involving literature search, systematic and bibliographic review of literatures as well as assessment and analysis of published literature was adopted for retrieving articles for this review [53].

2.2. Systematic literature search

In principle, our literature collection approach as shown (Fig. 1) followed the guidelines for the preferred reporting items for systematic reviews and meta-analysis (PRISMA) [54]. The process involved an exhaustive systematic literature search of Web of Science, Science Direct and Google Scholar using the following keywords: “biochar and N-fertilization” OR “biochar and nitrogen fertilizer” OR “biochar and N fertilizer” OR “biochar and urea” OR “biochar and fertilizer” OR “biochar and inorganic amendment” OR “char and N-fertilization” OR “char and fertilizer” OR “char and urea” OR “char and inorganic fertilizer” OR “charcoal and inorganic fertilizer” OR “charcoal and nitrogen fertilizer” OR “charcoal and urea” OR “charcoal and N fertilizer” OR “charcoal and N-fertilization” OR “charcoal and fertilizer” AND “GHGs” OR “N2O” OR “nitrous oxide” OR “CO2” OR “carbon dioxide” OR “greenhouse gas emission” OR “methane” OR “CH4” AND “rice yield” in the title, keywords, abstract and in the papers body.

In addition to the systematic literature search, and to ensure that we captured all the relevant studies, bibliographies of the selected articles were also screened. The search returned a total of 4138 articles which were subjected to double entry check. After checking for double entry, a total of 3992 articles were retained for further screening of eligibility.

2.3. Eligibility criteria and screening

To avoid any form of bias and to restrict articles to only those relevant to our review, inclusion criteria were set. For a study to be included, it must have fulfilled the following criteria:

i. must be an original research article conducted on rice.
ii. must have applied both biochar and N fertilizer (either as treatment or soil amendment) with a fertilized or non-amended control.
iii. must have measured and reported any of the two main GHGs (N_2O and CH_4) as well as rice yield or provided other proxy data such as GHGI or GWP through which these variables can be extracted with relative accuracy.

Using the “abstract screener” function of metagear library in R, all the titles and abstracts of the retrieved articles were screened. Where the information contained in the titles and abstracts were insufficient for deciding on inclusion or exclusion, such articles were downloaded and the whole texts screened to determine their eligibility.

Furthermore, to ensure uniform comparisons, in a multi-season or year experiment, where biochar and N fertilizer were applied only in the first season or year, only the results obtained from the first season or year were considered. On the other hand, if an

Table 1
Summary of the retrieved articles used for this systematic review.

S/N	Country	Biochar feedstock	Soil type	Biochar pH	Biochar N (g/kg)	Biochar OC (g/kg)	Soil pH	Soil N (g/kg)	Soil OC (g/kg)	Reference
1	Bangladesh	Bagasse	Silt loam	9.5	6.5	597	6.2	–	23.2	[55]
2	China	poplar saw dust	–	–	–	–	6.42	1.72	16.98	[56]
3	China	Wheat straw	Hydragric anthrosol/Halic acrisol	9.51	13.3	–	6.38	1.56	22.8	[57]
				9.51	13.3	–	5.05	1.9	18.1	
4	China	Wheat straw	Stagnic anthrosols	10.5	11.29	513.17	5.6	–	20.26	[58]
5	China	wheat straw	littoral clay salt soil	9.4	5.6	467	8.5	0.9	11.5	[39]
6	China	wheat straw	Irragric Anthrosols	9.4	5.9	467	5.7	1.32	14.6	[50]
7	China	wheat straw	Anthrosol	10.3	10.7	490	7.35	2.1	20.3	[59]
8	China	Wheat	–	10.48	10.7	513.17	5.3	1.82	20.26	[60]
				10.48	10.7	513.17	5.64	1.45	14.62	
9	China	Maize straw	Histosols	9.8	20	624.2	6.8	1.87	15.39	[40]
				10.4	16.4	655.5				
10	South Korea	Sesame	–	10.1	10.9	710.7	4.95	0.58	2.02	[61]
11	South Korea	Bamboo	–	9.71	12.8	764	4.95	0.58	2.03	[48]
12	South Korea	Rice husk	–	–	5.7	454	5.4	–	12.79	[62]
13	Japan	poultry excreta	Alluvial	10	26.7	284.5	5.24	1.4	14.5	[63]
14	China	wheat straw	–	–	–	–	5.99	1.81	20.11	[46]
							6.21	1.79	18.76	
							4.89	1.59	17.7	
15	China	wheat straw	Hydragric Anthrosol	10.4	6	470	6	1.8	20.1	[64]
16	China	Bamboo	Loamy paddy	9.84	4.1	709	6.03	0.8	6.1	[65]
17	China	Maize straw	Sandy Loam		0.11	25.3		0.1	20.2	[66]
18	China	Rape straw	Orthic Entisol/Regosol	8.9		625.8	6.3	0.1	11.1	[41]
19	China	Pig manure compost/Maize straw/peanut husk/municipal waste	Entic Hydragric Anthrosol	6.84	16.8	508	5.82	3.08	33	[67]
				9.74	11.08	520.7				
				9.16	10.2	341				
				7.88	10.5	295.3				
20	Thailand	Mangrove	Vertisol	7.8	2.8	585	7	0.6	17.72	[68]
21	China	Rice straw	–	9.1	8.1	670.7	6.7	1.2	11	[69]
22	Thailand	Eucalypt wood	Loamy soil	7.98	5.4	614.3	5	0.8	7.1	[43]
23	Thailand	Mangrove tree	Clay loam	5.8	2.9	282.3	7.5	0.6	0.53	[52]
24	China	Rice husk	Orthic Anthrosols	9.1	6.2	465.4	7.8	0.42	4.8	[70]
25	China	Rice husk	Gleyi-Stagnic Anthrosol	10.9	0.81	238	7	2.83	26.6	[71]
26	China	rice straw/waste wood	Silt loam	–	–	–	6.5	1.93	18.16	[72]
27	China	Wheat straw	hydroagric Stagnic Anthrosol	10.4	5.9	467	6.5	1.8	24	[73]
28	Thailand	Mangrove	Alfisols	7.94	2.4	659	6.17	0.45	4.3	[74]
29	Cambodia	Rice straw	Sandy	–	15.1	503.4	4.79	0.53	5.25	[38]
30	Vietnam	Rice straw	–	10.1	1.9	209	5.7	1.63	12.55	[75]
31	China	Wheat straw	Latosolic soil	8.1	3.29	605	7	1.87	31.2	[76]
32	Japan	Rice husk	Haplic andosol	8.4	4.01	427	5.8	4.2	58.7	[77]
33	Japan	Rice husk	Haplic andosol	7.07	3.15	361.7	6.63	2.7	32.3	[78]
34	China	Rice straw/Bamboo	–	10.2	10.7	478	5.2	3.2	20.6	[79]
				9.81	5.9	815				
35	China	Rice straw	Stagnic anthrosol	9.8	5.8	500	5.31	1.98	18.4	[49]
36	China	Wheat straw	Stagnic Anthrosol	10.4	5.9	467	6.5	1.8	23.5	[80]
37	China	Rice straw	–	10.58	10.8	472.1	5.39	2.8	49.3	[81]
38	China	Rice straw	Stagnic Anthrosol	10.4	5.9	467	6.5	1.8	23.5	[82]
39	China	Rice straw	Anthrosols	9.16	13.3	620	6	1.79	16.6	[51]
40	China	Rice straw	Hydragric anthrosol	10.1	7.5	426	7.4	1.03	21.9	[83]
41	China	wheat straw	–	8.91	14.15	–	6.38	1.56	22.8	[84]
				9.63	4.72	–				
				4.64	12.26	–				
				3.74	4.5	–				
42	Vietnam	Rice straw	Alluvial	–	12.1	353.2	6.21	10.3	12.6	[44]
43	Malaysia	Rice straw	Dystric Fluvisol	10.08	–	–	5.9	6	240.9	[85]
44	China	wheat straw	Stagnic Anthrosol	9.1	5.8	418.3	5.1	2.1	18.9	[86]
45	China	Wheat straw	Stannic Anthrosol	9.3	5.8	418.3	5.1	1.62	17.5	[87]

Alternate Wetting and Drying = AWD, Continuous Flooding = CF, Intermittent Irrigation = IT, mgt = Management.

experiment lasted for more than a year or season with the same rate of biochar and N fertilizer application as the preceding seasons or years, and results reported on yearly or seasonal basis, the average of such results was calculated and used. However, if varying biochar and N fertilizer rates were applied in the succeeding years or seasons, each of the seasons or years was treated as a separate experiment. Similarly, where a study lasted for more than one year and the researcher failed to indicate whether biochar (treatment) was applied in the succeeding years, only the results of the first season trial was extracted and used. Also, in multi-water management or location studies, each water management or location constituted an independent experiment.

At the end of the screening, a total of 45 articles passed the eligibility criteria (Table 1). For each of these studies, the reported means of CH_4, N_2O, rice yield, GWP, and GHGI were extracted either directly from tables or graphs using WebPlotDigitizer 4.5. Also, biochar and N fertilizer application rates, as well information on N fertilizer sources were extracted.

2.4. Data standardization and grouping

To ensure uniform comparison, all the extracted data were standardized to the same metric units across all the studies for the same variables. Consequently, CH_4, N_2O, rice yield, biochar and N rates were converted to kg-C/ha, kg-N/ha, ton/ha, ton/ha, and kg N/ha, respectively. Similarly, GWP of CH_4 and N_2O were calculated and standardized for studies that reported both CH_4 and N_2O. A global warming potential of 27 and 273 for CH_4 and N_2O, respectively, relative to the CO_2 warming potential over a 100-year timescale [88] were used for the standardization. The resulting GWPs (Mg CO_2 equivalent) were used to calculate GHGI (Mg/ton). Additionally, when pH was reported in KCl, it was converted to $pH_{[H2O]}$ with the formula $pH_{[H2O1:5]} = -1.95 + \log_{10}(pH_{[KCl\ 1:2.5]})^{*}\ 11.58$ [89].

After data harmonization and standardization, the data were categorized into groups based on the rates of biochar, and the rates of N co-applied by different researchers. Similarly, based on N rates and N fertilizer types applied, another categorization was also made to assess the role of N fertilizer types and rates on the variables of interest as stated in the objectives of the review. But to determine the number of groups and to ensure even representation or spread of data in each group that will enable statistical comparison, all the extracted data on biochar, N rates, and N fertilizer types and rates of N fertiliser types were displayed on histograms. Thereafter, the frequencies of the rates of N, biochar, and N types applied were used to categorize biochar, and N rates data into three groups each while the treatment without biochar but N only irrespective of N fertilizer type was used as control (CN). The choice of N fertilizer as the control instead of no amendment or biochar only treatment is because we wanted to mimic the most wide-spread nutrient management practice by farmers. Also [90], have demonstrated through a meta-analysis that regardless of whether in comparison to no amendment control or fertilized control that biochar application alone is inefficient in increasing crop yield. Hence, for this review, we adopted a fertilized treatment with no biochar as our control. The biochar rate groups (derived from biochar and N fertilizer co-application treatments) included: low biochar (biochar application rate of ≤9 tons/ha; LB), medium biochar (biochar application rate between 9 and ≤20 ton/ha; MB), high biochar (biochar application rate of >20 tons/ha; HB), while N fertilizer rates (derived from biochar and N fertilizer co-application treatments) were grouped as: low N fertilizer (N fertilizer application rate of ≤140 kg N/ha; LN), medium N fertilizer (N fertilizer rate between 140 and ≤240 kg N/ha; MN), high N fertilizer (N fertilizer application rate of >240 kg N/ha; HN). The combination of biochar and N fertilizer groups resulted in a total of nine treatment groups (LBLN, LBMN, LBHN, MBLN, MBMN, MBHN, HBLN, HBMN, HBHN), and a total of ten groups when the CN is included. CN consisted of 62, HBHN 14, HBLN 10, HBMN 14, LBHN 10, LBLN 19, LBMN 10, MBHN 18, MBLN 8, and MBMN 18 data points.

Another group was also formed based on N fertilizer types, and N fertilizer rates combined with biochar. As stated above, the extracted data of yield and GHGs emissions from N fertiliser types and rates of N fertiliser types were displayed on histogram in order to ensure uniform distribution of data in each group, and thereafter categorized into groups. A total of three classes of N fertilizer rates were obtained: ≤150 kg N/ha as low rate, >150 and ≤ 250 kg N/ha as medium rate and >250 kg N/ha as high rate. Similarly, for N fertilizer types and the variables, N_2O, GWP, and GHGI, a total of three groups were formed (urea, NPK, NPK_urea) because under NPK_NH4SO4 [i.e., NPK_$(NH_4)_2SO_4$], N_2O was not reported and as such it was not possible to calculate GWP and GHGI. But for the variables; rice yield, and CH_4, a total of four groups were realized (urea, NPK, NPK_urea, NPK_NH4SO4[i.e., NPK_$(NH_4)_2SO_4$]). For each of the groups, urea was used as the control.

In the studies that make up urea, and NPK groups, only one of these N fertilizer types was used by the researchers while in NPK_urea, and NPK_NH4SO4 [i.e., NPK_$(NH_4)_2SO_4$] groups, researchers applied NPK and urea, and NPK and $(NH_4)_2SO_4$ respectively at different stages of the experiment. Overall, urea group consisted of 82 datasets, NPK_urea 16, NPK_NH4SO4 [i.e., NPK_$(NH_4)_2SO_4$] 5, and NPK 16. Please note that, under this classification, biochar rate was not considered. We therefore suggest that future research should consider biochar rates under N fertilizer types.

2.5. Data analysis

Data analyses for this review were performed using R statistical software. All the groups obtained after data standardization and grouping were subjected to one way analysis of variance and means separated by TukeyHSD test ($p < 0.05$). Results were presented in bar plots with different letters indicating statistical significance. The essence of the statistical tests was to understand the effects of biochar and N fertilizer application rates, N fertiliser types, and rates of N fertiliser types on rice yield, N_2O, CH_4, GWP and GHGI, and to determine the optimal rates of biochar and N to increase rice yield and reduce GHG emissions.

Additionally, rice yield, CH_4 and N_2O emissions were also regressed on the most widely reported soil and biochar properties (soil organic carbon, soil total N, soil pH, biochar organic carbon, biochar total N and biochar pH) using pairwise regression approach. The failure of many of the researchers to report climate data made it impossible to assess the impact of climate on the variables of interest. The Akaike Information Criterion (AIC) was used to determine the best model for the prediction of our dependent variables (rice yield, CH_4 and N_2O emissions) [91,92]. The model with the lowest AIC value was retained.

3. Results

In terms of geographical spread, the studies used for this review were conducted in eight countries (Supplementary Fig. S1). All the countries are in Asia. Most of the studies were carried out in China using urea as N fertilizer source and biochar derived from cereal waste (Table 1).

3.1. *Effect of nitrogen (N) fertilizer types and rates on methane (CH_4) and nitrous oxide (N_2O) emissions*

Greenhouse gas (GHG) evolution in rice field varied significantly among the different N fertilizer types and rates (Fig. 2). At low (≤150 kg N/ha), and high N rates (>250 kg N/ha), the application of NPK with biochar consistently produced the highest N_2O emission compared to other forms of N fertilizer. Specifically, NPK (364 %) and NPK_urea (318 %) caused more than double fold increase in N_2O emission under low N rate relative to urea. However, increasing N rate caused a deviation in the pattern of N_2O emission under NPK fertilizer. At medium N rate ($150 < N \leq 250$ kg N/ha), the use of NPK as N source resulted in about 100 % decrease in N_2O emission while NPK-urea induced N_2O emission by about 56 % compared to urea. Similar to the pattern observed under low N rate, the addition of NPK, or NPK_urea with biochar caused a rise in N_2O emission by 189 % and 51 %, respectively, compared to urea under high N rate (>250 kg N/ha). It appears that irrespective of N fertiliser types, N_2O emission increased as N rate increased except for NPK under medium N rate (Fig. 2A).

On the other hand, a contrasting pattern was observed for CH_4 emission under different N fertilizer types and rates. Under low N rate, combined application of biochar with either NPK or NPK_urea decreased CH_4 emission by 23 % and 70 %, respectively compared to the use of urea. However, these inhibitory effects waned at medium N rate ($150 < N \leq 250$ kg N/ha), resulting in 444 % (NPK) and 33 % (NPK_urea) increase in CH_4 emission relative to urea. Furthermore, at high N rate (>250 kg N/ha), NPK_urea promoted CH_4 emission more than any other N source, followed by NPK_NH4SO4 [i.e., $(NH_4)_2SO_4$]. Both N sources (NPK_urea and NPK_NH4SO4 [i.e., $(NH_4)_2SO_4$]) increased CH_4 emission by 63 % and 48 %, respectively, compared to urea. Contrastingly, under the same N rate (high N rate), NPK application sharply decreased CH_4 emission (31 %) relative to urea. More so, urea application also indicated a decreasing

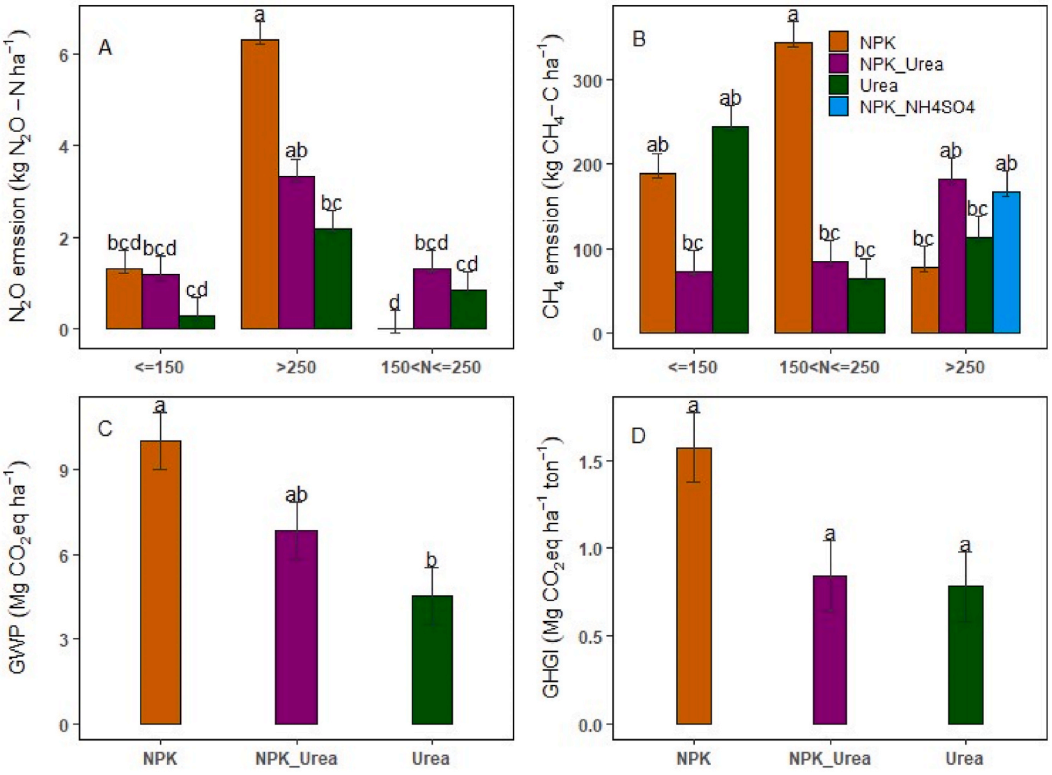

Fig. 2. Effect of biochar application with nitrogen fertilizer types and rates on N_2O (A) and CH_4 (B) emissions, GWP (C) and GHGI (D). Bars with different letters are statistically different from each other ($p < 0.05$). The error bars represent the standard deviation of the mean.

pattern in CH_4 emission as N rate increased (Fig. 2B). At low rate, urea strongly stimulated CH_4 emission but the stimulatory effect was less evident at higher N rates particularly at medium N rate (150 ≤ N250 kgN/ha). Medium rate of urea application significantly inhibited CH_4 emission. Except for NPK_urea which clearly showed an increasing pattern in CH_4 emission as N rate increased, no defined pattern of relation could be established between N fertilizer types and N rates. Different N fertilizer types appear to have different optimal rate for decreasing CH_4 emission. For instance, NPK at high rate (>250 kg N/ha) inhibited CH_4 emission, while NPK_urea and urea, were both more efficient in decreasing CH_4 emission at medium rates ($150 < N \leq 250$ kg N/ha). No pattern of effect on CH_4 emission could be established for NPK_NH4SO4 [i.e., $(NH_4)_2SO_4$] since it was only applied at high rate.

Global warming potential (GWP) varied significantly among the various N fertilizer types. NPK application increased GWP (122 %) compared to urea while the effect of NPK_urea on GWP relative to urea was moderately lower (51 %) (Fig. 2C). The high N_2O and CH_4 emissions associated with NPK application are responsible for its high GWP value. On the other hand, the greenhouse gas intensity (GHGI) from the various N sources varied non-significantly across the N fertilizer types (Fig. 2D). The use of NPK as N source resulted in highest GHGI compared to other N fertilizer types as was the case in GWP driven majorly by high GHG emissions.

3.2. Rice yield under different N fertilizer types and rates applied with biochar

Different N fertilizer types and rates combined with biochar significantly influenced paddy rice yield (Fig. 3). Overall, the calculated rice yield varied approximately from 5 ton/ha to 7 ton/ha under low N rate, 7 ton/ha to 11 ton/ha under medium N rate and 9 ton/ha to 15 ton/ha under high N rate across N fertilizer types regardless of biochar combination rates. For all the N fertilizer types, increase in N rate resulted in increase in rice yield. However, the magnitude of the increase varied according to N fertilizer types. Considering individual N fertilizer types applied with biochar, NPK_urea as N source was least responsive to increasing N rate while NPK was most responsive. Increasing N rate from (≤150 kg N/ha) to between >150 and < 250 kg N/ha almost did not result in any change in rice yield for NPK_urea as N source. However, increasing N rate from $150 < N < 250$ kg N/ha to >250 kg N/ha caused the highest increase in rice yield especially under NPK as N source. In addition, the application of the mixture of NPK and $(NH_4)_2SO_4$ with biochar similarly enhanced rice yield relative to the application of biochar with either urea or a mixture of NPK and urea. Under combined application of biochar and low N rate (≤150), NPK as N source decreased rice yield by 27 % and 24 % relative to urea and NPK_Urea respectively. But under medium N rate, combination of biochar with NPK enhanced rice yield by 26 % relative to urea while NPK_urea as N source applied with biochar caused a yield decrease of 20 % in comparison with urea applied with biochar. Furthermore, the use of high rate of $(NH4)_2SO_4$ (>250 kg N/ha) with biochar induced a 41 % increase in rice yield compared to applying high urea (>250 kg N/ha) with biochar. Similar increase in rice grain yield (61 %) under high NPK rate (>250 kg N/ha) applied with biochar relative to combined application of high urea rate (>250 kg N/ha) with biochar was also observed. However, high rate of NPK_urea (>250 kg N/ha) applied with biochar decreased rice grain yield (8 % decrease) compared to high urea rate applied with biochar (Fig. 3).

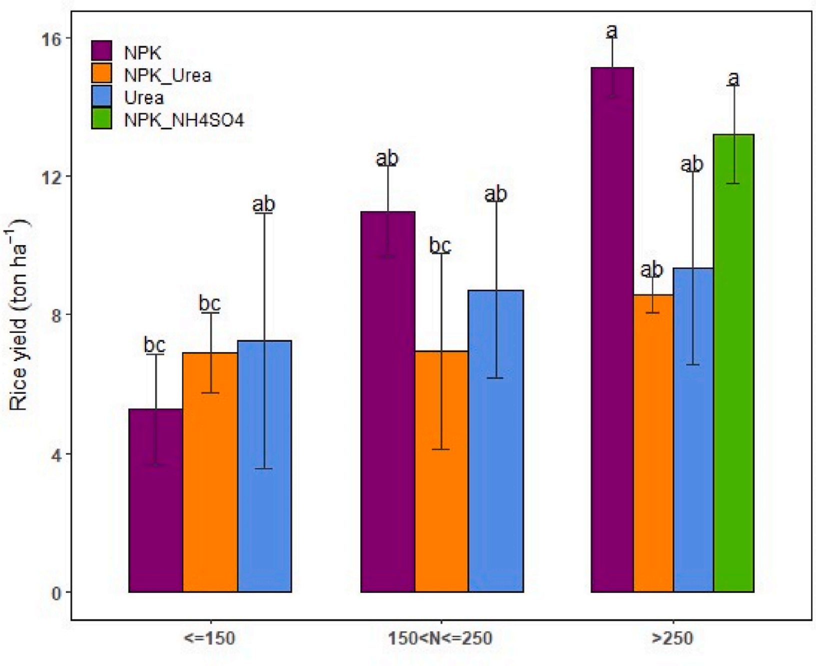

Fig. 3. Rice yield under different nitrogen fertilizer types and rates applied with biochar. Bars with different letters are statistically different from each other ($p < 0.05$). The error bars represent the standard deviation of the mean.

3.3. CH_4 and N_2O responses to rates of biochar and N fertilizer combination

The quantity of biochar combined with a given quantity of N fertilizer played a significant role in CH_4 emission (Fig. 4). Regardless of N fertiliser types, combination of low biochar (LB) and low N (LN) stimulated largest CH_4 emission (274 kg-C/ha) while the lowest mean CH_4 emission (24 kg-C/ha) was observed under high biochar (HB) and medium N (MN) group. Increasing biochar rate under low N rate resulted in significant decrease in CH_4 emission (Fig. 4). Similar effect was also observed when increasing biochar rate under medium N rates. But under high N rates, increase in biochar resulted in no definite pattern in CH_4 emission. Although, CH_4 emission decreased and increased at high biochar rate under moderate and high N rates, respectively. Contrarily, a linear decrease in CH_4 emission was observed under low biochar rate with increasing N rates. This pattern was retained as biochar rate was increased to medium and N rates gradually increased. Under high biochar rate with increasing N rates, no pattern could be established, but high N rate with high N increased CH_4 emission (Fig. 4). Also, no linear relationship between rates of biochar and N on CH_4 emissions was observed. Instead, a decrease in CH_4 emission was observed under medium biochar (MB) and MN rates while LBLN, as well as HB and high N (HN) combinations enhanced CH_4 emission. Nevertheless, the increase in CH_4 emission under HBHN was still smaller compared to LBLN.

According to Fig. 4, LBLN, MBLN, HBHN, and LBMN rates all enhanced CH_4 emission compared to the control (CN). Respectively, under these biochar and N combination rates, CH_4 emission increased by 114 %, 50 %, 38 % and 8 % compared to control N (CN). On the other hand, decreases in CH_4 emissions were found under HBMN (82 %), HBLN (53 %), MBHN (35 %), LBHN (6 %), and MBMN (5 %) compared to CN (Fig. 4). The result indicated that rates of biochar and N affect CH_4 emissions.

Fig. 5 shows the mean cumulative N_2O emission as affected by different rates of biochar and N fertilizer combinations. From the figure, rates of biochar and N strongly controlled the mean cumulative N_2O emission from rice field. Cumulative N_2O emission ranged from 0.14 kg-N/ha observed under HBLN rates to 2.74 kg-N/ha found under MBHN rate. The result (Fig. 5) showed that increasing N rate under low biochar application enhanced N_2O emission. Similar progressive N_2O enhancement can also be observed under medium and high biochar rates as N rate increased, indicating that at constant biochar rate, progressive increase in N rate results in gradual increase in N_2O emissions. On the other hand, gradually increasing biochar rates under low N level resulted in decrease in N_2O emission (Fig. 5), indicating the effectiveness of biochar in decreasing N_2O emissions at low N application rate (≤140 kg N/ha). Nevertheless, as N rate was increased to medium and biochar rates progressively increased, only high biochar rate was effective in decreasing N_2O emission. Under high N rate, no definite trend could be established as biochar rate was gradually increased, however, the mitigatory influence of biochar at high rate on N_2O emission was retained.

Irrespective of biochar rate, high N rate significantly promoted N_2O emission while high biochar reduced N_2O emission ($p < 0.05$).

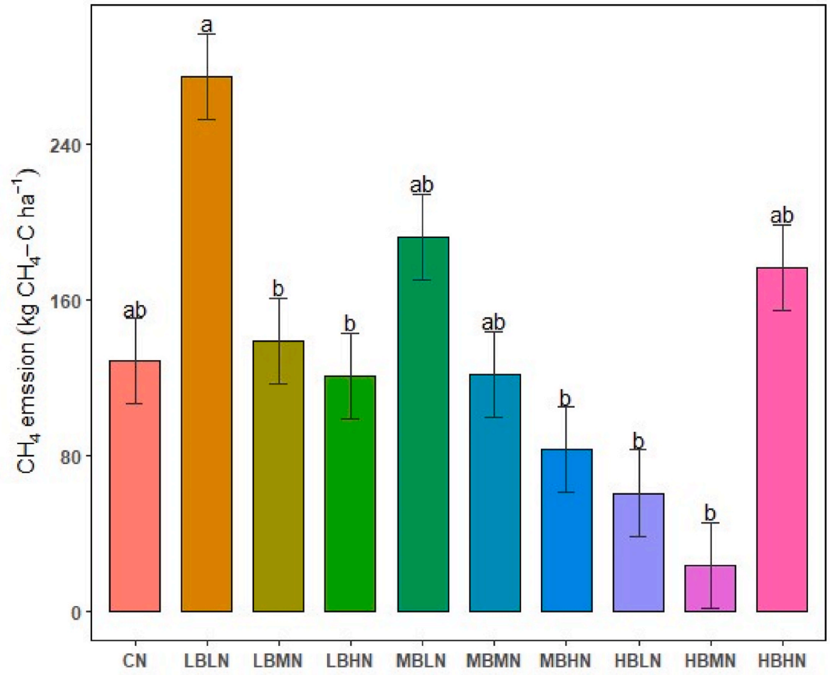

Fig. 4. CH_4 emissions under different levels of nitrogen fertilizer (N) applied with different biochar rates (B). CN (sole N; average, 195 kg N/ha), LBLN ($B \leq 9$ t/ha + $N \leq 140$ kg N/ha), LBMN ($B \leq 9$ t/ha+$140 < N \leq 240$ kg N/ha), LBHN ($B \leq 9$ t/ha + $N > 240$ kg N/ha), MBLN ($9 < B \leq 20$ t/ha + $N \leq 140$ kg N/ha), MBMN ($9 < B \leq 20$ t/ha+$140 < N \leq 240$ kg N/ha), MBHN ($9 < B \leq 20$ t/ha + $N > 240$ kg N/ha), HBLN ($B > 20$ t/ha + $N >$ 240 kg N/ha). Bars with different letters are statistically different from each other ($p < 0.05$). Error bars represent the standard deviation of the means.

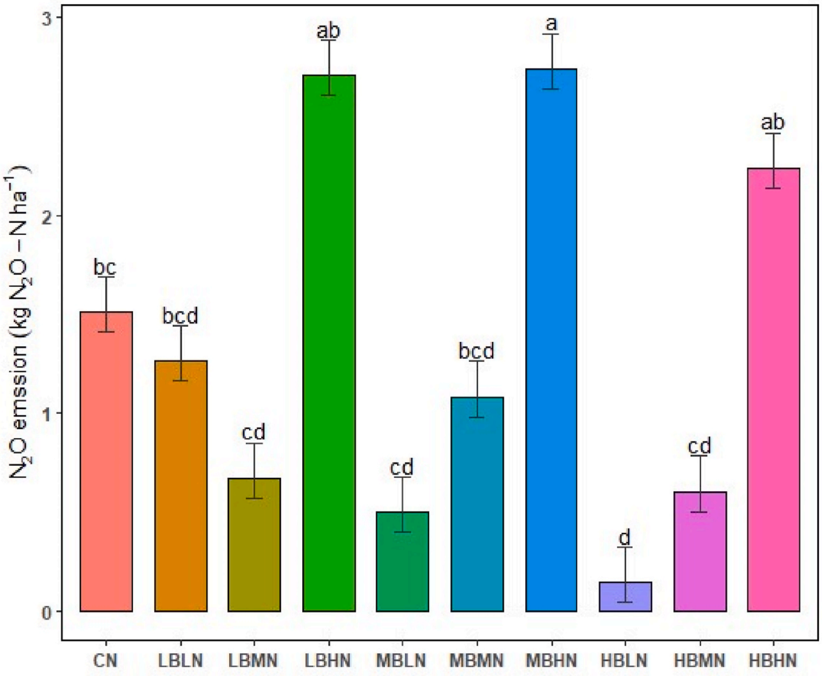

Fig. 5. Effects of biochar (B) and nitrogen fertilizer (N) rates on N_2O emission. CN (sole N; average, 195 kg N/ha), LBLN (B ≤ 9 t/ha + N ≤ 140 kg N/ha), LBMN (B ≤ 9 t/ha+140 < N ≤ 240 kg N/ha), LBHN (B ≤ 9 t/ha + N > 240 kg N/ha), MBLN (9 < B ≤ 20 t/ha + N ≤ 140 kg N/ha), MBMN (9 < B ≤ 20 t/ha+140 < N ≤ 240 kg N/ha), MBHN (9 < B ≤ 20 t/ha + N > 240 kg N/ha), HBLN (B > 20 t/ha + N > 240 kg N/ha). Bars with different letters are statistically different from each other ($p < 0.05$). Error bars represent the standard deviation of the mean.

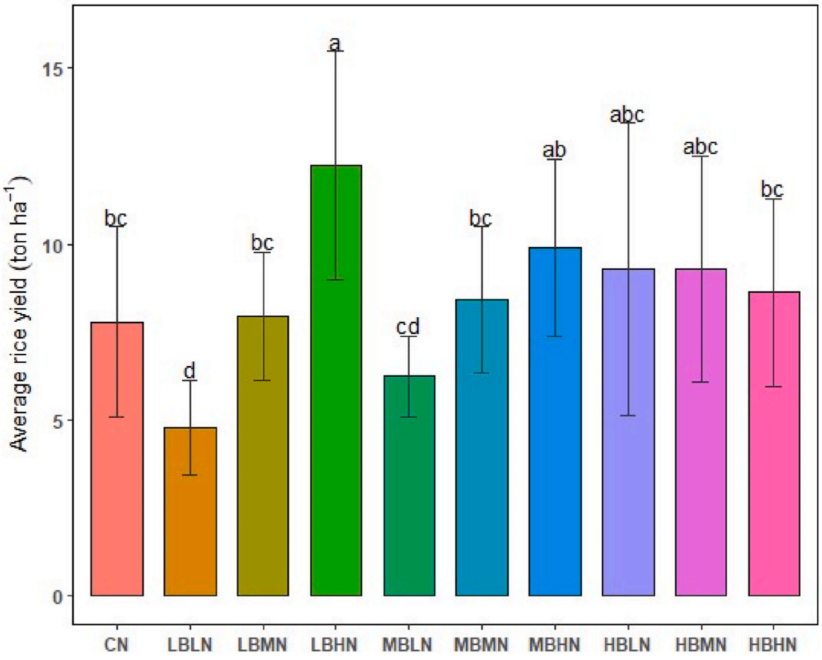

Fig. 6. Rice yield response to biochar (B) and nitrogen (N) fertilization rates. CN (sole N; average, 195 kg N/ha), LBLN (B ≤ 9 t/ha + N ≤ 140 kg N/ha), LBMN (B ≤ 9 t/ha+140 < N ≤ 240 kg N/ha), LBHN (B ≤ 9 t/ha + N > 240 kg N/ha), MBLN (9 < B ≤ 20 t/ha + N ≤ 140 kg N/ha), MBMN (9 < B ≤ 20 t/ha+140 < N ≤ 240 kg N/ha), MBHN (9 < B ≤ 20 t/ha + N > 240 kg N/ha), HBLN (B > 20 t/ha + N > 240 kg N/ha). Bars with different letters are statistically different from each other ($p < 0.05$). The error bars represent the standard deviation of the mean.

The efficiency of high biochar in decreasing N_2O emission increased as N rate decreased (Fig. 5). Relative to control, LBLN inhibited N_2O emission by 16 %, LBMN by 55 %, MBLN by 67 %, and MBMN by 28 %. The highest decrease in N_2O emission (91 %) compared to control was recorded when high biochar was applied with low N (HBLN). On the other hand, LBHN, MBHN, HBHN all enhanced N_2O emission by 81 %, 82 % and 49 % respectively compared to the CN.

3.4. Effect of biochar and N fertilizer rates on rice yield, GWP and GHGI

Rice yield responded significantly to varying rates of biochar and N fertilizer combinations (Fig. 6). Higher N rate was most effective in increasing rice yield especially under low biochar rate. Maximum rice yield was observed under combined application of LBHN, while low biochar combined with low N fertilizer (LBLN) resulted in the lowest rice yield. Under low and medium N rates, increasing biochar rate promoted rice yield. However, at high N rate, progressive increase in biochar rates resulted in decrease in rice yield. Conversely, increasing N availability by increasing N rate in the presence of low biochar rate induced a progressive increase in rice yield. The positive effect of increase in N on rice yield continued even at medium biochar rate but faded under high biochar rate. Therefore, in order to avoid nutrient immobilization associated with biochar use, biochar should be applied at rates lower than 20 ton/ha.

Regardless of N fertilizer type and biochar rate, high N ensured high rice yield (Fig. 6). Consequently, relative to CN, LBHN promoted rice yield by 45 %. Whereas retaining high N rate but gradually increasing biochar rates enhanced yield by 30 % and 11 % under MBHN and HBHN respectively, compared to LBHN. This result indicated that increasing biochar rates under high N condition

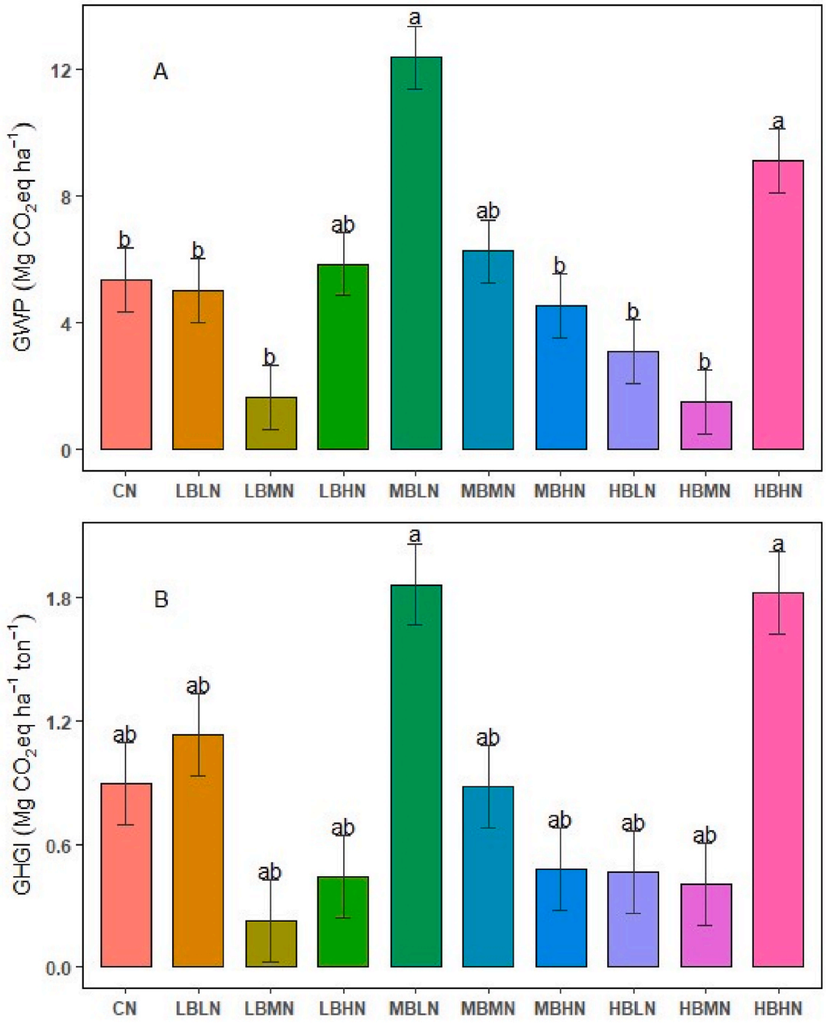

Fig. 7. Effect of combined biochar (B) and nitrogen fertilizer (N) rates on GWP (A) and GHGI (B). CN (sole N; average, 195 kg N/ha), LBLN ($B \leq 9$ t/ha + $N \leq 140$ kg N/ha), LBMN ($B \leq 9$ t/ha+$140 < N \leq 240$ kg N/ha), LBHN ($B \leq 9$ t/ha + $N > 240$ kg N/ha), MBLN ($9 < B \leq 20$ t/ha + $N \leq 140$ kg N/ha), MBMN ($9 < B \leq 20$ t/ha+$140 < N \leq 240$ kg N/ha), MBHN ($9 < B \leq 20$ t/ha + $N > 240$ kg N/ha), HBLN ($B > 20$ t/ha + $N > 240$ kg N/ha). Bars with different letters are statistically different from each other ($p < 0.05$). The error bars represent the standard deviation of the mean.

does not favour rice yield.

The calculated GWP and GHGI (indicator for GWP per rice yield) for different biochar and N fertilizer rates are shown in Fig. 7. Biochar and N rate significantly affected GWP (Fig. 7A) and GHGI (Fig. 7B). GWP and GHGI were generally similar for most of the treatments, however, highest and lowest GWP were recorded under MBLN rate, and HBMN rate, respectively. The general trend reveals that low N is the major contributor to GWP especially under low biochar rate while the combination of HBHN was also critical in enhancing GWP. GHGI followed similar pattern as GWP. The variations in GHGI were significant with medium rate of biochar combined with low rate of N (MBLN), and high rate of biochar combined with high rate of N (HBHN) generating the highest GHGI. The most promising biochar and N fertilizer combination for reducing GHGI is the combination of low biochar and medium N rates (LBMN) since it led to the lowest GHGI value (0.22 Mg CO_2 eq-ha^{-1} ton^{-1}). Moreover, Fig. 7A showed that low N also plays a key role in enhancing GHGI, probably due to its inability to enhance rice yield. It is important to state that we have not considered the effect of water management in arriving at the overall effect of N fertilizer types as well as different rates of biochar and N fertilizer combinations on GHGs emissions and rice yield. Water regimes and climatic conditions can severely interfere with rice yield and GHGs emissions. As such caution must be taken in interpreting and applying the results and recommendations of our finding.

3.5. Effect of some selected soil and biochar properties on rice yield, CH_4 and N_2O emissions

The most widely reported initial soil and biochar properties were selected to assist in determining some of the biochar and soil properties that regulate rice yield, CH_4 and N_2O emissions. It is important to note that failure of most of the researchers to report the soil properties at the end of their studies prevented the assessment of the after-effect of biochar and N fertilizer application on soil properties, GHGs emissions and rice yield. Hence the initial soil properties and biochar were used to assess the relationship of the effects of biochar and N application on the variables of interests. Thus, pairwise regression and Akaike Information Criterion (AIC) approach was used to determine the most important soil and biochar properties that control CH_4 and N_2O emissions as well as rice yield based on the initial soil and biochar properties. Although the p values of some of these properties were less than the set alpha level ($p < 0.05$) (Table 2), they were however retained as their inclusion optimised the model. The influences of these soil properties are presented in Table 2. According to the results (Table 2), rice yield were mainly regulated by initial soil total N, pH, biochar total N, and total soil organic carbon. Increase in soil total N and soil pH promoted rice yield, while initial soil organic carbon and biochar total N were less dominant in their influence on rice yield. On the other hand, the amount of CH_4 emitted from rice field was a function of initial soil pH, N content of applied biochar, biochar pH, soil organic carbon content, carbon content of biochar and soil total N with a regression coefficient (R^2) of 30 %. From the model (Table 2), high initial soil pH and total organic carbon, and applying biochar of high N content will enhance CH_4 emission, whereas high biochar pH, soil total N, and the application of biochar with high carbon content will all result in decrease in CH_4 emission. Similarly, N_2O emission was also driven by initial soil and biochar pH, soil total N and soil organic carbon, with a weak positive correlation ($R^2 = 29$ %). The model suggests that positive relationship exists between N_2O emission, soil organic carbon and biochar total N while increase in initial soil total N and biochar pH could result in decrease in N_2O emission.

Table 2
Response of rice yield, CH_4 and N_2O on some selected initial soil and biochar properties using a multilinear regression model.

Variables	Estimates	95 % confidence interval		p-value
		Lower limit	Upper limit	
Rice yield				**3.6e-06**
Intercept	−0.33	−4.20	3.52	0.86
Soil pH	1.00	0.43	1.56	0.00
Soil_TN	0.85	−0.32	2.04	0.15
Soil_OC	0.03	−0.05	0.11	0.46
B_TN	0.08	−0.01	0.18	0.07
CH_4 emission				**2.9e-06**
Intercept	278.15	64.34	491.97	0.01
Soil pH	13.54	−6.62	33.71	0.19
Soil_TN	−52.48	−92.29	12.68	0.01
Soil_OC	4.42	1.78	7.07	0.001
pH biochar	−26.22	−39.60	12.85	0.00
B_TN	6.69	2.93	10.46	0.00
B_OC	−0.12	−0.26	0.01	0.08
N_2O emission				**3.6e-06**
Intercept	3.97	1.68	6.26	0.00
B_TN	0.06	0.01	0.10	0.02
Soil_TN	−1.72	−2.43	−1.02	4.8e-06
Soil_OC	0.08	0.02	0.13	0.01
pH biochar	−0.19	−0.41	−0.03	0.10

pH_soil = soil pH, B_TN = biochar total nitrogen (g/kg), pH_biochar = biochar pH, soil_OC = soil organic carbon (g/kg), B_OC = biochar organic carbon (g/kg), and soil_TN = soil total nitrogen.

4. Discussion

4.1. Influence of initial soil and biochar properties on rice yield, methane (CH_4), nitrous oxide (N_2O) emission, global warming potential (GWP) and greenhouse gas intensity (GHGI) under combined biochar and nitrogen (N) fertilizer application

Soil physicochemical properties are important indicators of the general soil health and productivity and are strongly affected by managements. These factors affect both crop yield and greenhouse gases (GHGs) emissions and include soil pH, aggregate stability, and soil organic matter [93]. Table 2 indicated that the initial state of soil as well as biochar properties have varying impacts on GHGs emissions and rice yield. Specifically, our regression analysis indicated a positive relationship ($R^2 = 22$ %) between rice yield and initial soil pH, soil total N, soil organic carbon (C), and biochar total N, and that soil pH and biochar N content are the key properties that regulate rice yield. Soil pH controls the solubility and bioavailability of many chemicals in the soil and as such regulates environmental pollution and nutrients intake by plants [94]. Low soil pH can cause toxicity to the microbial population in the soil [60] and thus affect nutrient cycling within the soil eco-system. Low pH can also result in nutrient immobilization and availability of some heavy metals such as manganese and boron which are prevalent in rice fields and toxic to plant [95]. The application of biochar either singly or with N raises soil pH and improves nutrient availability in the soil. Moreover, some studies have attributed the improved crop yield observed under biochar and N especially in the tropics to the fertilization effect of biochar and N on the soil [96,97].

From Tables 2 and it is obvious that biochar and N application can significantly impact emission of CH_4 and N_2O, GWP and GHGI. According to [98], soil can be both source and sink of CO_2, CH_4 and N_2O gases depending on its management. Documented evidences suggest that management practices such as biochar addition improves soil functions [99–101]. Although biochar influence depends on biochar and soil properties [75,77]. Increased GWP due to increase in biochar pH and decrease in soil pH under co-application of biochar and N has been reported [96]. Biochar through its synergistic effect on added N enhances cation availability [69] and alters soil nutrient dynamics and biological activities [102]. Particularly, under anaerobic condition as obtained in rice field, presence of labile carbon in biochar can serve as source of substrates for the activities of methanogens and hence promote the production of CH_4 [55,73] and N_2O [39,103]. [49] attributed the decrease in CH_4 emission following biochar application to biochar induced increase in soil pH which led to increase in the population of methanotrophs. Methanogenic bacteria which break down organic matter to produce GHGs are known to be neutrophilic and as such are negatively impacted by large increase in soil pH [60]. Similarly, the change in pH from the liming effect of biochar facilitates the transfer of electrons to denitrifying bacteria and induces N_2O emissions [50]. Also, the decomposition of biochar by these organisms adds carbon [51,104] and a net negative charge to the soil [105]. Increase in negative charge affect soil's capacity to act as an electron acceptor and thus impact emission of both CH_4 [72] and N_2O [50] and potentially GWP. Moreover, the combined application of biochar with N has been noted to enhance soil content of both dissolved organic and inorganic carbon necessary for biological activities within the soil [102] which can impact gas production.

4.2. Biochar and N fertilizer rates regulate CH_4 and N_2O emissions, rice yield, GWP and GHGI

Nutrient management is a key strategy that influence gas evolution from soil and crop yield. Fig. 4 revealed that low biochar rates induced high CH_4 emission while high biochar rate decreased CH_4 emission. Decrease in CH_4 emission following biochar application has been reported [86]. Biochar interferes with soil aeration [62], carbon cycle [60], soil porosity [62] as well as soil pH [47]. The magnitude of such interference is linearly related to biochar application rate [72] and depends on soil properties [47]. [69] found that the addition of biochar at 29.6 ton/ha with N fertiliser increased soil C and C/N ratio, and soil porosity compared to treatment without biochar [69]. Similarly, a meta-analysis showed that biochar application resulted in 11.5–11.9 % increase in soil pH compared to untreated plots [103] and about 50 % increase in soil porosity with or without N fertilizer [40]. Such changes favour the growth and activities of methanotrophs [49] and CH_4 oxidation.

As demonstrated by [60], biochar application caused a significant reduction in CH_4 emission which was attributed to increase in the population of methanotrophs in response to biochar-induced increase in soil pH. Methanotrophs have higher sensitivity to rising soil pH than methanogens [50]. Ideally, methanogenic activities are maximum within the pH range of 6.0–7.5 [49,60,68,106]; a pH value obtainable under low biochar application. This partly explains the high CH_4 observed in this study at low biochar rate. Moreover, CH_4 production in paddy field only starts when iron (III) oxide (Fe^{3+}) is reduced to iron (II) oxide (Fe^{2+}) which occurs around pH neutral point [107] and is favoured by low biochar rate. Reduction of Fe^{3+} to Fe^{2+} decouples organic matter from Fe^{3+} which stimulates methanogenic activities and increases CH_4 emission [72]. Also, low biochar application with N promote CH_4 emissions by enhancing N utilization and plant growth [40] and soil redox potential [97] which is crucial in regulating CH_4 emissions [55,62]. It therefore implies that in the absence of enough biochar, microbial oxidation of CH_4 could be hampered as was the case in our analysis. Nevertheless, some studies have also indicated that the application of biochar can result in decrease in CH_4 emission. But decreases in CH_4 emissions are more frequently reported at high biochar rates [49,69,87]. Besides shifting soil pH to strongly alkaline ($pH > 10$), at medium to high rates, biochar through its large surface area adsorbs indigenous carbon and restricts their availability to microbial decomposition [43,49]. Medium to high biochar application in paddy fields also promotes oxygen availability within the root zones and oxidation of CH_4 [52,62] as well as increases the microbial abundance of particulate monooxygenase gene (*pmoA*) known to enhance oxidation of CH_4 [56] and hence leads to decrease in CH_4 emission.

On the other hand, low N application enhanced CH_4 emission (Fig. 4). [108] reported that low N rate (<100 kg N/ha) stimulates the emission of CH_4 while high N rates (>200 kg N/ha) results in CH_4 inhibition. N at 70 kg N/ha applied with biochar induced 10 % higher CH_4 emission relative to biochar only treatment [22]. Low N rate (≤ 150) enhances CH_4 emissions by limiting N supply to methanotrophs. Nitrogen is an essential nutrient for methanotrophs and therefore N limitation may inhibit CH_4 oxidation in soils, and increase CH_4 emissions [22,109,110]. Furthermore, low N rate also tends to moderate the soil pH within the neutral point which enhances the activities of methanogens and production of CH_4 [49,67]. Although, CH_4 emission is controlled by the interaction of different factors, the role of low N in moderating soil pH within the neutral range may have contributed significantly to the observed increase in CH_4 emission under the combination of biochar with low N.

In contrast, high N rate inhibits CH_4 emission [111] by decreasing soil pH with a resultant toxicity effect on methanogen population [60]. Different studies have reported [54,60,112] N induced toxicity to methanogenic activities at high N rate as the leading cause of CH_4 inhibition in fertilized paddy fields. High N application also leads to the production of lower root biomass and activities within the rhizospheres which decreases carbon substrates necessary for CH_4 production [113]. Increasing N application especially at panicle initiation stage enhanced the production of organic acid within the rhizosphere which decreased CH_4 emission [113]. However [41,97, 114], have reported enhancing effect of high N on CH_4 emissions especially when N is applied with biochar. The likely explanation for this is the inhibition of CH_4 oxidation by NH_4^+ [111]. At high NH_4^+, methanotrophs use oxygen as an electron acceptor, and NH_4^+ for energy derivation instead of CH_4 which leads to increase in CH_4 emissions [111]. N application at over 500 kg N/ha in combination with biochar inhibits the growth of methanotrophs and enhances CH_4 emission [41]. Also, the interactive effect of biochar and N fertiliser can also alter the diversity of soil microbes which can affect CH_4 pattern [115].

Apart from the increases observed under low biochar and low (LBLN) rates as well as high biochar and high N (HBHN) rate, large part of the groups agreed with previous researchers who reported increased CH_4 uptakes after biochar applications with N [79,81, 116]. It is therefore evidently clear that proper management is crucial to the mitigation of GHGs emissions from soils under combined biochar and N fertiliser.

Contrary to CH_4 emission pattern, N_2O emission increased with N rate irrespective of biochar rate (Fig. 5). The presence of high N substrate under high N rate stimulated N_2O emission. In soils, substrate availability is the main factor that determines whether N_2O emission will be enhanced or suppressed. Therefore, the application of fertilizer promoted N_2O emission [20,64] by providing substrates for microbial nitrification and denitrification [48]. However, the addition of biochar especially at high rate, disrupted the pattern of N_2O emission under low N application. Some of the reasons are the changes in soil aeration and oxygen availability [62], porosity [40] and C/N ratio following biochar application [117]. Application of biochar changes the soil C/N and causes a net N immobilization which hinders N_2O production [97]. C/N ratio >35 is linked with N immobilization [118,119]. Specifically, application of N rate>15 kg N/ha in combination with biochar leads to inhibition of N_2O emission, and rate of inhibition increases with N rates until about 500 kg N/ha after which additional N enhances N_2O emission [120]. Large biochar surface area also causes adsorption [22,52,56,121,122] of NH_4^+ which leads to reduced substrate availability for the production of N_2O [123]. About 67 % reduction in N_2O was reported by Ref. [122] following the addition of biochar to a vegetable soil which can be linked to the complete reduction of N_2O to N_2 during denitrification by the presence of easily decomposable carbon from biochar [63]. Reduction in N_2O following biochar application has also been attributed to biochar-induced changes in soil pH which favours the growth of N_2O reductase that are inhibited under acidic condition [63,64,124]. Also, biochar related processes such as improvement in soil moisture content inhibits nitrification process and alters N_2O production [22,23].

From Fig. 6, combined application of biochar and N significantly increased rice yield especially at low biochar and high N (LBHN) rate. High yield under LBHN may be related to the availability of N for rice utilization. N application is closely associated with increased grain yield [54,125,126]. Depending on biochar rate, biochar inclusion with N reduces N loss from soil and hence increases crop yield [120]. Various researchers have similarly reported crop yield increases after biochar application [90,122,127]. Biochar through its effects on soil chemical, biological and physical properties can elicit improved crop performances. The main pathway is by directly supplying nutrients [106] such as Ca, K, P, Mg, S, and Si to plants [104,128], improving nutrient adsorption for plants uptake [40,56,106], and increase in soil biological diversity [64]. However, high biochar rates, causes N immobilization through negative priming [125]. According to Ref. [90] application of biochar at more than 10 ton/ha can potentially lead to decrease in plant biomass probably due to nutrient immobilization. Further negative impact of biochar is observed if rate reaches 100 g kg^{-1} of soil [129]. Biochar-induced N immobilization and the consequent reduction in bioavailability of essential nutrients through their sorption on biochar has been reported [130] as the leading cause of yield reduction under biochar and is related to pyrolysis temperature [40].

Highest GWP was found under medium biochar and low N (MBLN) while lowest GWP was observed under low biochar and medium (LBMN) rate irrespective of N source. Yield and GHG emissions regulate GWP and GHGI [131] as can be seen with low biochar and low N (LBLN) as well as MBLN combinations (Fig. 6). Similarly, despite increasing yield, the high emission associated with high biochar and high N (HBHN) resulted in high GHGI.

4.3. *Responses of CH_4 and N_2O emission, rice yield, GWP and GHGI to N fertiliser types and rates of N fertiliser types*

Nitrogen is the most limiting nutrient for crop production [126,132]. To overcome this challenge, N fertilizer is used [40,57] particularly in rice fields. These fertilizers are derived from different N sources (e.g., NPK, urea, ammonium sulphate, ammonium nitrate etc.) and behave differently in the soil [133]. As such, they have varying impacts on crop yield and GHGs emissions. As indicated in Fig. 3, different N fertilizer types influenced rice yield differently under the same N rates. Altering the rates of N applied with biochar also produced varying effects on N_2O and CH_4 emissions under different N fertilizer types. Urea and NPK increased N_2O emission mostly at medium N rate probably due to increased N substrate availability (Fig. 2A). While increase in micro-organism diversity may have been responsible for the enhanced CH_4 emission observed under both NPK and urea at low and medium N rates. Nitrogen rates generally produced inconsistent pattern on both CH_4 and N_2O emissions under different N fertiliser types. Only NPK_urea showed a consistent increase in CH_4 emission as N rate increased. The varied responses of both CH_4 and N_2O to N rates and types is a clear indication that N fertiliser types impact gas emissions from paddy fields differently [132]. However, the nature of this impact and the mechanism involved are still uncertain [11,54]. Varying sensitivity to the products of the hydrolyzation of N fertilizer sources by soil micro-organisms might be responsible for the variation in the observed N_2O and CH_4 emission as N rate changed. For instance, by-products of sulphate and nitrate-based N fertilizer are toxic which may affect nitrification-denitrification process by micro-organisms [132] and eventually N_2O production and emission. These N fertilizers also appear more effective in reducing N-induced CH_4 emission through competition for electrons under anaerobic condition [54,132]. Contrarily, ammonium-based N fertilizer enhances CH_4 emission through the inhibition of CH_4 oxidation by NH_4^+ [123]. The process involves blocking the systems of methanotrophic enzymes, which causes the inhibition of CH_4 oxidation. Other mechanisms such as the stimulation of CH_4 within the rhizosphere by urea and other N types have also been reported [56]. Increased growth and root respirations, within the rhizosphere depletes the oxygen needed for CH_4 oxidation [72] and thus increases CH_4 emission. It also appears that while $(NH_4)_2SO_4$ inhibits CH_4 emission, it promotes N_2O production [134] compared to other N fertilizer types [135]. Similarly, the use of urea also promotes N_2O emission [136]. N_2O is produced from nitrification-denitrification process which depends on weather conditions, therefore, varying N_2O production from N types are site and weather dependent [137]. It is important to note that, other elements like phosphorus and potassium were applied to all the experiments, although not as treatments. The varied time and rates of application of these elements may have also influenced the dynamics of CH_4 and N_2O emissions.

Aside GHGs emissions, N rates and N fertiliser types also significantly influenced rice yield (Fig. 3). For all the N fertiliser types, increasing N rate resulted in higher yield. This is due to increased availability of N for plant utilization. NPK and $(NH_4)_2SO_4$ produced the highest rice yield. The variation in rice yield under the same N rate but not N fertiliser types is an indication that N types affect rice yield.

Combining N fertilizers especially NH_4^+ and NO_3^- based fertilizers have been reported to promote crop yields [133]. However, their effects differ depending on the environment. Compared to NO_3^- fertilizers, NH_4^+ based fertilizer gives better yield under anaerobic conditions [138]. Hydrolysis of NH_4^+ [e.g. $(NH_4)_2SO_4$] and NO_3^- based fertilizers results in the production of NH_4^+ and NO_3^- respectively. Whereas NO_3^- are easily leached out, NH_4^+ tends to be fixed in the soil [138] for plants uptake. Our result (Fig. 3) shows that the co-application of biochar with NPK resulted in highest rice grain yield followed by combined biochar and $(NH_4)_2SO_4$ mixed with NPK [90]. has observed that N fertilizer type applied with biochar significantly influences the effect of the co-application to crop yield. High yield from NPK may be linked to increased availability of other nutrients such as phosphorus and potassium contained in the fertilizer. On the other hand, the improved rice yield observed under $(NH_4)_2SO_4$ fertilizer maybe linked to the toxicity of SO_4^{2-} to soil micro-organisms which may have reduced the microbial transformation of NH_4^+ and thus made more nutrients available to the plants. Additionally, the sulphur content of $(NH_4)_2SO_4$ may have also served as an additional source of nutrients for plants' uptake. Our finding agrees with the result of [133] who reported an improved maize yield under $(NH_4)_2SO_4$ fertilizer than urea. Similarly, results from [139] showed a 22 % increase in rice yield under $(NH_4)_2SO_4$ fertilizer compared to urea. While low sugarcane yield from urea amended plots have also been reported by [140] which suggests that urea is less efficient in increasing crop yield possibility due to high loss of N though ammonia volatilization [141,142] and N_2O emissions [135].

Highest GWP was recorded under NPK application due to its low mitigatory role on CH_4 and N_2O emissions (Fig. 2C). Despite its high rice yield, the high N_2O and CH_4 emitted under NPK ensured that GHGI under NPK N type remained the highest. The combined application of organic materials such as biochar and inorganic fertilizer triggers the evolution of CH_4 and N_2O emission which can cause more than 80 % increase in GWP [143]. It is therefore important that caution should be taken in the choice of N fertilizer type to be applied with biochar. Our results suggest that high rate of urea applied with biochar can enhance rice yield and mitigate GHG emissions from rice field.

5. Conclusion

In conclusion, combined application of biochar and N fertilizer is beneficial to both crop yield and GHGs mitigation. However, the benefits depend on both biochar and N rates as well as N source and rate. Low biochar and high N (LBHN) stimulated high N_2O emission, although it increased rice yield and decreased CH_4 emission. Application of low biochar and medium N rates (LBMN) reduced GWP and GHGI while achieving high rice yield.

At high N rate, sole NPK application with biochar, or combined application of NPK and $(NH_4)_2SO_4$ with biochar were most efficient in increasing rice yield. But due to lack of data, we could not assess the effect of $(NH_4)_2SO_4$ applied with biochar on N_2O emission, as such, the result should be taken with caution. On the other hand, medium rate of NPK applied with biochar, significantly reduced N_2O but promoted CH_4 emissions. However, the application of medium rate of NPK and biochar appeared most profitable for both rice yield and environmental protection since its stimulatory effect on CH_4 is compensated for by increased rice yield and decreased N_2O. Biochar pH, biochar total N, biochar carbon, soil pH, soil carbon, and soil total N were the most important biochar and initial soil properties regulating rice yield, N_2O, and CH_4 emissions under the biochar and N fertilizer application.

6. Recommendations

1. From our review, we found that most researches have been focussed on the effects of nitrogen (N) fertilizer rates on rice yield and greenhouse gases (GHGs) emissions. However, considering the variation in hydrolysation process of various N fertilizer types and the peculiarity of paddy fields, we recommend that future researches on biochar and N application should focus more on the role of N fertilizer types on GHGs emissions.
2. Also, given the strong influence of environmental factors on GHGs emissions and the scope of our current study, we recommend that future review should integrate environmental factors in analysing the factors driving GHGs emission from rice field under

biochar and N fertilizer application. The integration of environmental factors will help to better isolate under what environmental conditions the recommended biochar and N rate is most suitable.

3. There is also an urgent need for more GHGs studies in Africa as the literature clearly shows dearth of research on the subject area in the region.
4. Since the current study reviewed only CH_4 emission from NPK and $(NH_4)_2SO_4$ application with biochar, and given the contradictory pattern of CH_4 and N_2O emissions, our finding should be taken with caution and future research should focus on the simultaneous emission of CH_4 and N_2O from this management practice to make a more informed recommendation.

Data availability

Data will be made available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Maduabuchi P. Iboko: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elliott R. Dossou-Yovo:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Sunday E. Obalum:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Chidozie J. Oraegbunam:** Writing – review & editing, Resources, Data curation. **Siméon Diedhiou:** Writing – review & editing, Formal analysis, Data curation. **Christian Brümmer:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Niaba Témé:** Writing – review & editing, Supervision, Data curation, Conceptualization.

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.

Acknowledgment

We are grateful to the authors whose research papers were used to conduct this review. We also would like to thank Kallista Chan and Edeh Ifeoma for their insights during data extraction.

This work was supported by the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e22132.

References

[1] S. Fahad, M. Adnan, M. Noor, M. Arif, M. Alam, I.A. Khan, H. Ullah, F. Wahid, I.A. Mian, Y. Jamal, A. Basir, S. Hassan, S. Saud, Amanullah, M. Riaz, C. Wu, M. A. Khan, D. Wang, Major constraints for global rice production, in: Adv. Rice Res. Abiotic Stress Toler., Elsevier, 2019, pp. 1–22, https://doi.org/10.1016/B978-0-12-814332-2.00001-0.

[2] A.K. Mishra, V.O. Pede, A. Arouna, R. Labarta, R. Andrade, P.C. Veettil, H. Bhandari, A.G. Laborte, J. Balie, B. Bouman, I. Rice, L. Ban, Helping feed the world with rice innovations : CGIAR research adoption and socioeconomic impact on farmers, Global Food Secur. 33 (2022), 100628, https://doi.org/10.1016/j.gfs.2022.100628.

[3] N. Bandumula, Rice production in asia: key to global food security, Proc. Natl. Acad. Sci. India B Biol. Sci. 88 (2018) 1323–1328, https://doi.org/10.1007/s40011-017-0867-7.

[4] S. Fukai, L.J. Wade, Rice, Crop Physiol. Case Hist. Major Crop, Elsevier, 2021, pp. 44–97, https://doi.org/10.1016/B978-0-12-819194-1.00002-5.

[5] A.N.M.R. Bin Rahman, J. Zhang, Trends in rice research: 2030 and beyond, Food Energy Secur. 12 (2023), https://doi.org/10.1002/fes3.390.

[6] R. Prasad, Y.S. Shivay, D. Kumar, Current status, challenges, and opportunities in rice production, in: B.S. Chauhan, K. Jabran, G. Mahajan (Eds.), Rice Prod. Worldw., Springer International Publishing, Cham, 2017, pp. 1–32, https://doi.org/10.1007/978-3-319-47516-5_1.

[7] X. Yu, C. Keitel, Y. Zhang, A.N. Wangeci, F.A. Dijkstra, Global meta-analysis of nitrogen fertilizer use efficiency in rice, wheat and maize, Agric. Ecosyst. Environ. 338 (2022), 108089, https://doi.org/10.1016/j.agee.2022.108089.

[8] P. Fu, J. Wang, T. Zhang, J. Huang, S. Peng, High nitrogen input causes poor grain filling of spikelets at the panicle base of super hybrid rice, Field Crops Res. 244 (2019), 107635, https://doi.org/10.1016/j.fcr.2019.107635.

[9] J. Jiang, H. Fan, B. Pang, J. Zhang, Z. Li, S. Jiang, J. Wu, Assessment of reactive nitrogen mitigation potential of different nitrogen treatments under direct-seeded rice and wheat cropping system, Environ. Sci. Pollut. Res. 25 (2018) 20241–20254, https://doi.org/10.1007/s11356-018-2104-1.

[10] Y. Pu, B. Zhu, Z. Dong, Y. Liu, C. Wang, C. Ye, Soil N 2 O and NO x emissions are directly linked with N-cycling enzymatic activities, Appl. Soil Ecol. 139 (2019) 15–24, https://doi.org/10.1016/j.apsoil.2019.03.007.

[11] E.E. Kara, H.G. Ozdilek, The effect of nitrogenous fertilizers on methane oxidation in soil, Ekoloji 19 (2010) 1–9.

[12] D. Afreh, J. Zhang, D. Guan, K. Liu, Z. Song, C. Zheng, A. Deng, X. Feng, X. Zhang, Y. Wu, Q. Huang, W. Zhang, Long-term fertilization on nitrogen use efficiency and greenhouse gas emissions in a double maize cropping system in subtropical China, Soil Tillage Res. 180 (2018) 259–267, https://doi.org/10.1016/j.still.2018.03.016.

[13] Z. Cai, Y. Shan, H. Xu, Effects of nitrogen fertilization on CH4 emissions from rice fields, Soil Sci. Plant Nutr. 53 (2007) 353–361, https://doi.org/10.1111/j.1747-0765.2007.00153.x.

[14] P.O. Igboji, Using traditional and simulation methods for C and N cycling studies with additional periods of human civilisation: replicating the procedures at regional levels advocate, in: Carbon Nitrogen Cycl. Soil, Springer Singapore, Singapore, 2020, pp. 117–184, https://doi.org/10.1007/978-981-13-7264-3_5.

[15] A. A, K.R. R, J. Mathew, Fate of the conventional fertilizers in environment, in: .R.K. S T, F.B. Lewu, Tatiana Volova (Eds.), Control. Release Fertil. Sustain. Agric., Elsevier, London, 2021, pp. 25–39, https://doi.org/10.1016/B978-0-12-819555-0.00002-9.

[16] M.A. Noor, M.M. Nawaz, M. ul Hassan, A. Sher, T. Shah, M.M. Abrar, U. Ashraf, S. Fiaz, M.A. Basahi, W. Ahmed, W. Ma, Small farmers and sustainable N and P management: implications and potential under changing climate, in: Carbon Nitrogen Cycl. Soil, Springer Singapore, Singapore, 2020, pp. 185–219, https://doi.org/10.1007/978-981-13-7264-3_6.

[17] U.A. Naher, M.N. Ahmed, M.I.U. Sarkar, J.C. Biswas, Q.A. Panhwar, Fertilizer management strategies for sustainable rice production, in: Org. Farming, Elsevier, 2019, pp. 251–267, https://doi.org/10.1016/B978-0-12-813272-2.00009-4.

[18] K. Kritee, D. Nair, D. Zavala-araiza, J. Proville, J. Rudek, T.K. Adhya, High Nitrous Oxide Fluxes from Rice Indicate the Need to Manage Water for Both Long- and Short-Term Climate Impacts, vol. 115, 2018, https://doi.org/10.1073/pnas.1809276115.

[19] Y.K. Gaihre, U. Singh, S.M.M. Islam, A. Huda, M.R. Islam, J. Sanabria, M.A. Satter, M.R. Islam, J.C. Biswas, M. Jahiruddin, M.S. Jahan, Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields, Nutrient Cycl. Agroecosyst. 110 (2018) 277–291, https://doi.org/10.1007/s10705-017-9897-z.

[20] S.M.M. Islam, Y.K. Gaihre, J.C. Biswas, U. Singh, M.N. Ahmed, J. Sanabria, M.A. Saleque, Nitrous oxide and nitric oxide emissions from lowland rice cultivation with urea deep placement and alternate wetting and drying irrigation, Sci. Rep. 8 (2018), 17623, https://doi.org/10.1038/s41598-018-35939-7.

[21] S. Jeffery, F.G.A.A. Verheijen, C. Kammann, D. Abalos, Biochar effects on methane emissions from soils: a meta-analysis, Soil Biol. Biochem. 101 (2016) 251–258, https://doi.org/10.1016/j.soilbio.2016.07.021.

[22] M. Shaukat, K. Samoy-Pascual, E.D.v.L. Maas, A. Ahmad, Simultaneous effects of biochar and nitrogen fertilization on nitrous oxide and methane emissions from paddy rice, J. Environ. Manag. 248 (2019), 109242, https://doi.org/10.1016/j.jenvman.2019.07.013.

[23] X. Liu, T. Zhou, Y. Liu, X. Zhang, L. Li, G. Pan, Effect of mid-season drainage on CH4 and N2O emission and grain yield in rice ecosystem: a meta-analysis, Agric. Water Manag. 213 (2019) 1028–1035, https://doi.org/10.1016/j.agwat.2018.12.025.

[24] Intergovernmental Panel on Climate Change (IPCC), Agriculture, Forestry and Other Land Use (AFOLU), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, https://doi.org/10.1017/cbo9781107415416.017.

[25] I. Kögel-Knabner, W. Amelung, Z. Cao, S. Fiedler, P. Frenzel, R. Jahn, K. Kalbitz, A. Kölbl, M. Schloter, Biogeochemistry of paddy soils, Geoderma 157 (2010) 1–14, https://doi.org/10.1016/j.geoderma.2010.03.009.

[26] M. Aslam Ali, K. Inubushi, P. Joo Kim, S. Amin, Management of paddy soil towards low greenhouse gas emissions and sustainable rice production in the changing climatic conditions, in: Soil Contam. Altern. Sustain. Dev., IntechOpen, 2019, https://doi.org/10.5772/intechopen.83548.

[27] M.M. Campanha, A.D. de Oliveira, I.E. Marriel, M.M. Gontijo Neto, J.V. Malaquias, E.C. Landau, M.R. de Albuquerque Filho, F.P. Ribeiro, A.M. de Carvalho, Effect of soil tillage and N fertilization on N2O mitigation in maize in the Brazilian Cerrado, Sci. Total Environ. 692 (2019) 1165–1174, https://doi.org/10.1016/j.scitotenv.2019.07.315.

[28] E. Harris, L. Yu, Y.-P. Wang, J. Mohn, S. Henne, E. Bai, M. Barthel, M. Bauters, P. Boeckx, C. Dorich, M. Farrell, P.B. Krummel, Z.M. Loh, M. Reichstein, J. Six, M. Steinbacher, N.S. Wells, M. Bahn, P. Rayner, Warming and redistribution of nitrogen inputs drive an increase in terrestrial nitrous oxide emission factor, Nat. Commun. 13 (2022) 4310, https://doi.org/10.1038/s41467-022-32001-z.

[29] R. Conrad, Microbial ecology of methanogens and methanotrophs, Adv. Agron. 96 (2007) 1–63, https://doi.org/10.1016/S0065-2113(07)96005-8.

[30] E. Hasan, Proposing mitigation strategies for reducing the impact of rice cultivation on climate change in Egypt, Water Sci 27 (2014) 69–77, https://doi.org/10.1016/j.wsj.2013.12.007.

[31] United States Environmental Protection Agency, Global Greenhouse Gas Emission Projections & Mitigation, 2019. https://www.epa.gov/sites/production/files/2020-05/documents/epa_non-co2_greenhouse_gases_rpt-epa430r19010.pdf.

[32] United Nations Department of Economic and Social Affairs, World Population Prospects, 2019.

[33] Z.Y. Feng, T. Qin, X.Z. Du, F. Sheng, C.F. Li, Effects of irrigation regime and rice variety on greenhouse gas emissions and grain yields from paddy fields in central China, Agric. Water Manag. 250 (2021), 106830, https://doi.org/10.1016/j.agwat.2021.106830.

[34] M. Ishfaq, M. Farooq, U. Zulfiqar, S. Hussain, N. Akbar, A. Nawaz, S.A. Anjum, Alternate wetting and drying: a water-saving and ecofriendly rice production system, Agric. Water Manag. 241 (2020), https://doi.org/10.1016/j.agwat.2020.106363.

[35] B. Liao, X. Wu, Y. Yu, S. Luo, R. Hu, G. Lu, Effects of mild alternate wetting and drying irrigation and mid-season drainage on CH4 and N2O emissions in rice cultivation, Sci. Total Environ. 698 (2020), 134212, https://doi.org/10.1016/j.scitotenv.2019.134212.

[36] S.M.M. Islam, Y.K. Gaihre, M.R. Islam, M. Akter, A. Al Mahmud, U. Singh, B.O. Sander, Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh, Sci. Total Environ. 734 (2020), https://doi.org/10.1016/j.scitotenv.2020.139382.

[37] S. Wang, J. Shan, Y. Xia, Q. Tang, L. Xia, J. Lin, X. Yan, Different effects of biochar and a nitrification inhibitor application on paddy soil denitrification: a field experiment over two consecutive rice-growing seasons, Sci. Total Environ. (2017) 347–356, https://doi.org/10.1016/j.scitotenv.2017.03.159, 593–594.

[38] P. Ly, Q. Duong Vu, L.S. Jensen, A. Pandey, A. de Neergaard, Effects of rice straw, biochar and mineral fertiliser on methane (CH4) and nitrous oxide (N2O) emissions from rice (Oryza sativa L.) grown in a rain-fed lowland rice soil of Cambodia: a pot experiment, Paddy Water Environ. 13 (2015) 465–475, https://doi.org/10.1007/s10333-014-0464-9.

[39] L. Sun, J. Deng, C. Fan, J. Li, Y. Liu, Combined effects of nitrogen fertilizer and biochar on greenhouse gas emissions and net ecosystem economic budget from a coastal saline rice field in southeastern China, Environ. Sci. Pollut. Res. 27 (2020) 17013–17022, https://doi.org/10.1007/s11356-020-08204-6.

[40] J. Gao, Y. Zhao, W. Zhang, Y. Sui, D. Jin, W. Xin, J. Yi, D. He, Biochar prepared at different pyrolysis temperatures affects urea-nitrogen immobilization and N 2 O emissions in paddy fields, PeerJ 7 (2019), e7027, https://doi.org/10.7717/peerj.7027.

[41] L. Qi, P. Pokharel, S.X. Chang, P. Zhou, H. Niu, X. He, Z. Wang, M. Gao, Biochar application increased methane emission, soil carbon storage and net ecosystem carbon budget in a 2-year vegetable–rice rotation, Agric. Ecosyst. Environ. 292 (2020), 106831, https://doi.org/10.1016/j.agee.2020.106831.

[42] J. Shin, D. Park, S. Hong, C. Jeong, H. Kim, W. Chung, Influence of activated biochar pellet fertilizer application on greenhouse gas emissions and carbon sequestration in rice (Oryza sativa L.) production, Environ. Pollut. 285 (2021), 117457, https://doi.org/10.1016/j.envpol.2021.117457.

[43] N. Thammasom, P. Vityakon, P. Lawongsa, P. Saenjan, Biochar and rice straw have different effects on soil productivity, greenhouse gas emission and carbon sequestration in Northeast Thailand paddy soil, Agric. Nat. Resour. 50 (2016) 192–198, https://doi.org/10.1016/j.anres.2016.01.003.

[44] T.N. Thu, L.B.T. Phuong, T.M. Van, S.N. Hong, Effect of water regimes and organic matter strategies on mitigating green house gas emission from rice cultivation and Co-benefits in agriculture in vietnam, Int. J. Environ. Sci. Dev. 7 (2016) 85–90, https://doi.org/10.7763/IJESD.2016.V7.746.

[45] N. Wang, Z. Chang, X. Xue, J. Yu, X. Shi, L.Q. Ma, H. Li, Biochar decreases nitrogen oxide and enhances methane emissions via altering microbial community composition of anaerobic paddy soil, Sci. Total Environ. 581–582 (2017) 689–696, https://doi.org/10.1016/j.scitotenv.2016.12.181.

[46] X. Liu, J. Qu, L. Li, A. Zhang, Z. Jufeng, J. Zheng, G. Pan, Can biochar amendment be an ecological engineering technology to depress N2O emission in rice paddies?—a cross site field experiment from South China, Ecol. Eng. 42 (2012) 168–173, https://doi.org/10.1016/j.ecoleng.2012.01.016.

[47] M. Aamer, M.U. Hassan, M. Shaaban, F. Rasul, T. Haiying, M. Qiaoying, M. Batool, A. Rasheed, Z. Chuan, S. Qitao, H. Guoqin, Rice straw biochar mitigates N2O emissions under alternate wetting and drying conditions in paddy soil, J. Saudi Chem. Soc. 25 (2021), 101172, https://doi.org/10.1016/j.jscs.2020.11.005.

[48] S.-W. Kang, Y.H. Cheong, J.-J. Yun, J.-H. Park, J.-H. Park, D.-C. Seo, J.-S. Cho, Effect of biochar application on nitrogen use efficiency for sustainable and productive agriculture under different field crops, J. Plant Nutr. 44 (2021) 2849–2862, https://doi.org/10.1080/01904167.2021.1921200.

[49] J. Shen, H. Tang, J. Liu, C. Wang, Y. Li, T. Ge, D.L. Jones, J. Wu, Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems, Agric. Ecosyst. Environ. 188 (2014) 264–274, https://doi.org/10.1016/j.agee.2014.03.002.

[50] Z. Wu, X. Zhang, Y. Dong, B. Li, Z. Xiong, Biochar amendment reduced greenhouse gas intensities in the rice-wheat rotation system: six-year field observation and meta-analysis, Agric. For. Meteorol. 278 (2019), 107625, https://doi.org/10.1016/j.agrformet.2019.107625.

[51] X. Zhao, J. Wang, S. Wang, G. Xing, Successive straw biochar application as a strategy to sequester carbon and improve fertility: a pot experiment with two rice/wheat rotations in paddy soil, Plant Soil 378 (2014) 279–294, https://doi.org/10.1007/s11104-014-2025-9.

[52] V. Vat, A. Chidthaisong, S. Towprayoon, Effect of biochar and its combined application with manure and fertilizer on nitrogen leaching, greenhouse gas (GHG) emissions, and grain yield under alternate wetting and drying (AWD) system, J. Agric. Crop Res. 8 (2020) 33–47, https://doi.org/10.33495/jacr_v8i2.19.168.

[53] E.M. Okon, B.M. Falana, S.O. Solaja, S.O. Yakubu, O.O. Alabi, B.T. Okikiola, Systematic review of climate change impact research in Nigeria: implication for sustainable development E.M, Heliyon 7 (2021), https://doi.org/10.1016/j.heliyon.2021.e07941.

[54] M.S. Islam Bhuiyan, A. Rahman, G.W. Kim, S. Das, P.J. Kim, Eco-friendly yield-scaled global warming potential assists to determine the right rate of nitrogen in rice system: a systematic literature review, Environ. Pollut. 271 (2021), 116386, https://doi.org/10.1016/j.envpol.2020.116386.

[55] M.A. Ali, M.A. Hoque, P.J. Kim, Mitigating global warming potentials of methane and nitrous oxide gases from rice paddies under different irrigation regimes, Ambio 42 (2013) 357–368, https://doi.org/10.1007/s13280-012-0349-3.

[56] D. Chen, Y. Zhou, C. Xu, X. Lu, Y. Liu, S. Yu, Y. Feng, Water-washed hydrochar in rice paddy soil reduces N2O and CH4 emissions: a whole growth period investigation, Environ. Pollut. 274 (2021), 116573, https://doi.org/10.1016/j.envpol.2021.116573.

[57] H. Sun, A. D, Y. Feng, M. Vithanage, S. Mandal, S.M. Shaheen, J. Rinklebe, W. Shi, H. Wang, Floating duckweed mitigated ammonia volatilization and increased grain yield and nitrogen use efficiency of rice in biochar amended paddy soils, Chemosphere 237 (2019), 124532, https://doi.org/10.1016/j.chemosphere.2019.124532.

[58] T. He, J. Yuan, J. Xiang, Y. Lin, J. Luo, S. Lindsey, X. Liao, D. Liu, W. Ding, Combined biochar and double inhibitor application offsets NH3 and N2O emissions and mitigates N leaching in paddy fields, Environ. Pollut. 292 (2022), 118344, https://doi.org/10.1016/j.envpol.2021.118344.

[59] Y. Ma, D.L. Liu, G. Schwenke, B. Yang, The global warming potential of straw-return can be reduced by application of straw-decomposing microbial inoculants and biochar in rice-wheat production systems, Environ. Pollut. 252 (2019) 835–845, https://doi.org/10.1016/j.envpol.2019.06.006.

[60] T. He, J. Yuan, J. Luo, S. Lindsey, J. Xiang, Y. Lin, D. Liu, Z. Chen, W. Ding, Combined application of biochar with urease and nitrification inhibitors have synergistic effects on mitigating CH4 emissions in rice field: a three-year study, Sci. Total Environ. 743 (2020), 140500, https://doi.org/10.1016/j.scitotenv.2020.140500.

[61] S.-W. Kang, J.-W. Park, D.-C. Seo, Y.S. Ok, K.-D. Park, I.-W. Choi, J.-S. Cho, Effect of biochar application on rice yield and greenhouse gas emission under different nutrient conditions from paddy soil, J. Environ. Eng. 142 (2016), 04016046, https://doi.org/10.1061/(ASCE)EE.1943-7870.0001083.

[62] J. Kim, G. Yoo, D. Kim, W. Ding, H. Kang, Combined application of biochar and slow-release fertilizer reduces methane emission but enhances rice yield by different mechanisms, Appl. Soil Ecol. 117–118 (2017) 57–62, https://doi.org/10.1016/j.apsoil.2017.05.006.

[63] S.M. Kimani, P.O. Bimantara, S. Hattori, K. Tawaraya, S. Sudo, X. Xu, W. Cheng, Co-application of poultry-litter biochar with Azolla has synergistic effects on CH4 and N2O emissions from rice paddy soils, Heliyon 6 (2020), e05042, https://doi.org/10.1016/j.heliyon.2020.e05042.

[64] X. Liu, J. Zhou, Z. Chi, J. Zheng, L. Li, X. Zhang, J. Zheng, K. Cheng, R. Bian, G. Pan, Biochar provided limited benefits for rice yield and greenhouse gas mitigation six years following an amendment in a fertile rice paddy, Catena 179 (2019) 20–28, https://doi.org/10.1016/j.catena.2019.03.033.

[65] H.H. Lu, , Y.Y.F.Y.F.Y. Wang, Y.X. Liu, , Y.Y.F.Y.F.Y. Wang, L.L. He, Z.K. Zhong, S.M. Yang, Effects of Water-Washed Biochar on Soil Properties, Greenhouse Gas Emissions, and Rice Yield, Clean-Soil Air Water, vol. 46, 2018, https://doi.org/10.1002/clen.201700143.

[66] Y. Ma, D. Gu, L. Liu, Z. Wang, H. Zhang, J. Yang, Changes in grain yield of rice and emission of greenhouse gases from paddy fields after application of organic fertilizers made from maize straw, Rice Sci. 21 (2014) 224–232, https://doi.org/10.1016/S1672-6308(13)60187-0.

[67] L. Qian, L. Chen, S. Joseph, G. Pan, L. Li, J.J. Zheng, X. Zhang, J.J. Zheng, X. Yu, J. Wang, Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China, Carbon Manag. 5 (2014) 145–154, https://doi.org/10.1080/17583004.2014.912866.

[68] P. Sriphirom, A. Chidthaisong, K. Yagi, S. Tripetchkul, N. Boonapatcharoen, S. Towprayoon, Effects of biochar on methane emission, grain yield, and soil in rice cultivation in Thailand, Carbon Manag. 12 (2021) 109–121, https://doi.org/10.1080/17583004.2021.1885257.

[69] Y. Sui, J. Gao, C. Liu, W. Zhang, Y. Lan, S. Li, J. Meng, Z. Xu, L. Tang, Interactive effects of straw-derived biochar and N fertilization on soil C storage and rice productivity in rice paddies of Northeast China, Sci. Total Environ. 544 (2016) 203–210, https://doi.org/10.1016/j.scitotenv.2015.11.079.

[70] J. Wang, X. Pan, Y. Liu, X. Zhang, Z. Xiong, Effects of biochar amendment in two soils on greenhouse gas emissions and crop production, Plant Soil 360 (2012) 287–298, https://doi.org/10.1007/s11104-012-1250-3.

[71] S. Wang, S. Ma, J. Shan, Y. Xia, J. Lin, X. Yan, A 2-year study on the effect of biochar on methane and nitrous oxide emissions in an intensive rice–wheat cropping system, Biochar 1 (2019) 177–186, https://doi.org/10.1007/s42773-019-00011-8.

[72] X. Yin, J. Peñuelas, J. Sardans, X. Xu, Y. Chen, Y. Fang, L. Wu, B.P. Singh, E. Tavakkoli, W. Wang, Effects of nitrogen-enriched biochar on rice growth and yield, iron dynamics, and soil carbon storage and emissions: a tool to improve sustainable rice cultivation, Environ. Pollut. 287 (2021), 117565, https://doi.org/10.1016/j.envpol.2021.117565.

[73] A. Zhang, L. Cui, G. Pan, L. Li, Q. Hussain, X. Zhang, J. Zheng, D. Crowley, Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China, Agric. Ecosyst. Environ. 139 (2010) 469–475, https://doi.org/10.1016/j.agee.2010.09.003.

[74] P. Sriphirom, A. Chidthaisong, K. Yagi, S. Tripetchkul, S. Towprayoon, Evaluation of biochar applications combined with alternate wetting and drying (AWD) water management in rice field as a methane mitigation option for farmers' adoption, Soil Sci. Plant Nutr. 66 (2020) 235–246, https://doi.org/10.1080/00380768.2019.1706431.

[75] A. Pandey, V.T. Mai, D. Quynh, T. Phuong, L. Bui, T. Lan, A. Mai, L. Stoumann, A. De Neergaard, D.Q. Vu, T.P.L. Bui, T.L.A. Mai, L.S. Jensen, A. de Neergaard, D. Quynh, T. Phuong, L. Bui, T. Lan, A. Mai, L. Stoumann, A. De Neergaard, Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam, Agric. Ecosyst. Environ. 196 (2014) 137–146, https://doi.org/10.1016/j.agee.2014.06.010.

[76] X. Qin, Y. Li, H. Wang, C. Liu, J. Li, Y. Wan, Q. Gao, F. Fan, Y. Liao, Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: a four-year case study in south China, Sci. Total Environ. (2016) 1390–1401, https://doi.org/10.1016/j.scitotenv.2016.06.222, 569–570.

[77] S. Koyama, T. Katagiri, K. Minamikawa, M. Kato, H. Hayashi, Effects of rice husk charcoal application on rice yield, methane emission, and soil carbon sequestration in andosol paddy soil, Japan Agric. Res. Q. JARQ. 50 (2016) 319–327, https://doi.org/10.6090/jarq.50.319.

[78] S. Koyama, F. Inazaki, K. Minamikawa, M. Kato, H. Hayashi, Increase in soil carbon sequestration using rice husk charcoal without stimulating CH4 and N2O emissions in an Andosol paddy field in Japan, Soil Sci. Plant Nutr. 61 (2015) 873–884.

[79] D. Dong, M. Yang, C. Wang, H. Wang, Y. Li, J. Luo, W. Wu, Responses of methane emissions and rice yield to applications of biochar and straw in a paddy field, J. Soils Sediments 13 (2013) 1450–1460, https://doi.org/10.1007/s11368-013-0732-0.

[80] A. Zhang, R. Bian, G. Pan, L. Cui, Q. Hussain, L. Li, J.J. Zheng, J.J. Zheng, X. Zhang, X. Han, X. Yu, Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles, Field Crops Res. 127 (2012) 153–160, https://doi.org/10.1016/j.fcr.2011.11.020.

[81] Q. Nan, C. wang, Q.Q. Yi, L. Zhang, F. Ping, J.E. Thies, W.X. Wu, Biochar amendment pyrolysed with rice straw increases rice production and mitigates methane emission over successive three years, Waste Manag. 118 (2020) 1–8, https://doi.org/10.1016/j.wasman.2020.08.013.

[82] A. Zhang, R. Bian, Q. Hussain, L. Li, G. Pan, J. Zheng, X. Zhang, J. Zheng, Change in net global warming potential of a rice–wheat cropping system with biochar soil amendment in a rice paddy from China, Agric. Ecosyst. Environ. 173 (2013) 37–45, https://doi.org/10.1016/j.agee.2013.04.001.

[83] S. Yang, Y. Xiao, X. Sun, J. Ding, Z. Jiang, J. Xu, Biochar improved rice yield and mitigated CH4 and N2O emissions from paddy field under controlled irrigation in the Taihu Lake Region of China, Atmos. Environ. 200 (2019) 69–77, https://doi.org/10.1016/j.atmosenv.2018.12.003.

[84] B. Zhou, Y. Feng, Y. Wang, L. Yang, L. Xue, B. Xing, Impact of hydrochar on rice paddy CH4 and N2O emissions: A comparative study with pyrochar, Chemosphere 204 (2018) 474–482. https://doi.org/10.1016/j.chemosphere.2018.04.056.

[85] L. Lai, M.R. Ismail, M.M. Yusof, R. Ismail, Rice straw biochar and different urea rates on rice yield and CH4 and CO2 gases emissions, Chil. J. Agric. Res. 81 (2021) 448–455, https://doi.org/10.4067/S0718-58392021000300448.
[86] J. Liu, J. Shen, Y. Li, Y. Su, T. Ge, D.L. Jones, J. Wu, Effects of biochar amendment on the net greenhouse gas emission and greenhouse gas intensity in a Chinese double rice cropping system, Eur. J. Soil Biol. 65 (2014) 30–39, https://doi.org/10.1016/j.ejsobi.2014.09.001.
[87] C. Wang, J. Liu, J. Shen, D. Chen, Y. Li, B. Jiang, J. Wu, Effects of biochar amendment on net greenhouse gas emissions and soil fertility in a double rice cropping system: a 4-year field experiment, Agric. Ecosyst. Environ. 262 (2018) 83–96, https://doi.org/10.1016/j.agee.2018.04.017.
[88] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2021 – the Physical Science Basis, Cambridge University Press, 2023, https://doi.org/10.1017/9781009157896.
[89] C. Kabała, E. Musztyfaga, B. Gałka, D. Łabuńska, P. Mańczyńska, Conversion of soil pH 1:2.5 KCl and 1:2.5 H2O to 1:5 H2O: conclusions for soil management, environmental monitoring, and international soil databases, Polish J. Environ. Stud. 25 (2016) 647–653, https://doi.org/10.15244/pjoes/61549.
[90] L. Ye, M. Camps-Arbestain, Q. Shen, J. Lehmann, B. Singh, M. Sabir, Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls, Soil Use Manag. 36 (2020) 2–18, https://doi.org/10.1111/sum.12546.
[91] M. Ingdal, R. Johnsen, D.A. Harrington, The Akaike information criterion in weighted regression of immittance data, Electrochim. Acta 317 (2019) 648–653, https://doi.org/10.1016/j.electacta.2019.06.030.
[92] S. Portet, A primer on model selection using the Akaike Information Criterion, Infect. Dis. Model. 5 (2020) 111–128, https://doi.org/10.1016/j.idm.2019.12.010.
[93] M. He, X. Xiong, L. Wang, D. Hou, N.S. Bolan, Y.S. Ok, J. Rinklebe, D.C.W. Tsang, A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils, J. Hazard Mater. 414 (2021), https://doi.org/10.1016/j.jhazmat.2021.125378.
[94] H. Asadi, M. Ghorbani, M. Rezaei-Rashti, S. Abrishamkesh, E. Amirahmadi, C. Chengrong, M. Gorji, Application of rice husk biochar for achieving sustainable agriculture and environment, Rice Sci. 28 (2021) 325–343, https://doi.org/10.1016/j.rsci.2021.05.004.
[95] F. Nadeem, M. Farooq, Application of micronutrients in rice-wheat cropping system of south asia, Rice Sci. 26 (2019) 356–371, https://doi.org/10.1016/j.rsci.2019.02.002.
[96] H. Xu, A. Cai, D. Wu, G. Liang, J. Xiao, M. Xu, G. Colinet, W. Zhang, 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 Tillage Res. 213 (2021), 105125, https://doi.org/10.1016/j.still.2021.105125.
[97] M.A. Ali, P.J. Kim, K. Inubushi, Mitigating yield-scaled greenhouse gas emissions through combined application of soil amendments: a comparative study between temperate and subtropical rice paddy soils, Sci. Total Environ. 529 (2015) 140–148, https://doi.org/10.1016/j.scitotenv.2015.04.090.
[98] T. Shah, S. Lateef, M.A. Noor, Carbon and nitrogen cycling in agroecosystems: an overview, in: Carbon Nitrogen Cycl. Soil, Springer Singapore, Singapore, 2020, pp. 1–15, https://doi.org/10.1007/978-981-13-7264-3_1.
[99] P. Campos, A.Z. Miller, H. Knicker, M.F. Costa-pereira, A. Merino, J.M. De la Rosa, J. María, D. Rosa, Chemical, physical and morphological properties of biochars produced from agricultural residues: implications for their use as soil amendment, Waste Manag. 105 (2020) 256–267, https://doi.org/10.1016/j.wasman.2020.02.013.
[100] D. Woolf, J.E. Amonette, F.A. Street-Perrott, J. Lehmann, S. Joseph, Sustainable biochar to mitigate global climate change, Nat. Commun. 1 (2010) 1–9, https://doi.org/10.1038/ncomms1053.
[101] M.C. Maguyon-Detras, M.V.P. Migo, N. Van Hung, M. Gummert, Thermochemical conversion of rice straw, in: Sustain. Rice Straw Manag., Springer International Publishing, Cham, 2020, pp. 43–64, https://doi.org/10.1007/978-3-030-32373-8_4.
[102] M. Mustapha, H. Zhang, L. Guo, Y. Chen, M. Heiling, B. Zhou, Y. Mao, European Journal of Soil Biology Biochar interaction with chemical fertilizer regulates soil organic carbon mineralization and the abundance of key C-cycling-related bacteria in rhizosphere soil, Eur. J. Soil Biol. 106 (2021), 103350, https://doi.org/10.1016/j.ejsobi.2021.103350.
[103] Y.M. Awad, J. Wang, A.D. Igalavithana, D.C.W. Tsang, K.-H. Kim, S.S. Lee, Y.S. Ok, Biochar effects on rice paddy: meta-analysis, in: Adv. Agron., first ed., Elsevier Inc., 2018, pp. 1–32, https://doi.org/10.1016/bs.agron.2017.11.005.
[104] Y. Zhang, J. Wang, Y. Feng, The effects of biochar addition on soil physicochemical properties: a review, Catena 202 (2021), 105284, https://doi.org/10.1016/j.catena.2021.105284.
[105] G.K.M.M. Rahman, M.M. Rahman, M.S. Alam, M.Z. Kamal, H.A. Mashuk, R. Datta, R.S. Meena, Biochar and organic amendments for sustainable soil carbon and soil health, in: Carbon Nitrogen Cycl. Soil, Springer Singapore, Singapore, 2020, pp. 45–85, https://doi.org/10.1007/978-981-13-7264-3_3.
[106] K.K. Boateng, G.Y. Obeng, E. Mensah, Eco-Friendly yield and greenhouse gas emissions as affected by fertilization type in a tropical smallholder rice system, Ghana, Sustainability 12 (2020), 10239, https://doi.org/10.3390/su122410239.
[107] R. Conrad, Mechanisms controlling methane emission from wetland rice fields, Biogeochem. Glob. Chang. (1993) 317–335, https://doi.org/10.1007/978-1-4615-2812-8_17.
[108] B.F. Sun, H. Zhao, Y.Z. Lü, F. Lu, X.K. Wang, The effects of nitrogen fertilizer application on methane and nitrous oxide emission/uptake in Chinese croplands, J. Integr. Agric. 15 (2016) 440–450, https://doi.org/10.1016/S2095-3119(15)61063-2.
[109] K. Banger, H. Tian, C. Lu, Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields? Glob. Chang. Biol. 18 (2012) 3259–3267, https://doi.org/10.1111/j.1365-2486.2012.02762.x.
[110] P.L. Bodelier, H.J. Laanbroek, Nitrogen as a regulatory factor of methane oxidation in soils and sediments, FEMS Microbiol. Ecol. 47 (2004) 265–277, https://doi.org/10.1016/S0168-6496(03)00304-0.
[111] M.A.A. Adviento-borbe, B. Linquist, Assessing fertilizer N placement on CH 4 and N 2 O emissions in irrigated rice systems, Geoderma 266 (2016) 40–45, https://doi.org/10.1016/j.geoderma.2015.11.034.
[112] M. Zhou, B. Zhu, X. Wang, Y. Wang, Long-term field measurements of annual methane and nitrous oxide emissions from a Chinese subtropical wheat-rice rotation system, Soil Biol. Biochem. 115 (2017) 21–34, https://doi.org/10.1016/j.soilbio.2017.08.005.
[113] Y. Chen, S. Li, Y. Zhang, T. Li, H. Ge, S. Xia, J. Gu, H. Zhang, B. Lü, X. Wu, Z. Wang, J. Yang, J. Zhang, L. Liu, Rice root morphological and physiological traits interaction with rhizosphere soil and its effect on methane emissions in paddy fields, Soil Biol. Biochem. 129 (2019) 191–200, https://doi.org/10.1016/j.soilbio.2018.11.015.
[114] S. Wang, S. Ma, J. Shan, Y. Xia, J. Lin, X. Yan, A 2-year study on the effect of biochar on methane and nitrous oxide emissions in an intensive rice–wheat cropping system, Biochar 1 (2019) 177–186, https://doi.org/10.1007/s42773-019-00011-8.
[115] W. Yang, C. Li, S. Wang, B. Zhou, Y. Mao, C. Rensing, S. Xing, Influence of biochar and biochar-based fertilizer on yield, quality of tea and microbial community in an acid tea orchard soil, Appl. Soil Ecol. 166 (2021), 104005, https://doi.org/10.1016/j.apsoil.2021.104005.
[116] Q. Nan, C. Wang, H. Wang, Q. Yi, W. Wu, Mitigating methane emission via annual biochar amendment pyrolyzed with rice straw from the same paddy field, Sci. Total Environ. 746 (2020), 141351, https://doi.org/10.1016/j.scitotenv.2020.141351.
[117] M.L. Cayuela, L. van Zwieten, B.P. Singh, S. Jeffery, A. Roig, M.A. Sánchez-Monedero, Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis, Agric. Ecosyst. Environ. 191 (2014) 5–16, https://doi.org/10.1016/j.agee.2013.10.009.
[118] K. Yin Chan, Z.H. Xu, K.Y. Chan, Z.H. Xu, K. Yin Chan, Z.H. Xu, K.Y. Chan, Z.H. Xu, Biochar: nutrient properties and their enhancement, in: Johannes Lehmann, Stephen Joseph (Eds.), Biochar Environ. Manag. Sci. Technol., Earthscan Books Ltd, Earthscan Books Ltd, 2009.
[119] F.N. Mukome, S.J. Parikh, Chemical, physical, and surface characterization of biochar, in: N. Ok, K. Y, S.M. Uchimiya, S.X. Chang, Bolan (Eds.), Biochar Prod. Charact. Appl., CRC Press, Boca Raton, FL, USA, 2016, pp. 67–96.
[120] L. Qi, Z. Ma, S.X. Chang, P. Zhou, R. Huang, Y. Wang, Z. Wang, M. Gao, Biochar decreases methanogenic archaea abundance and methane emissions in a flooded paddy soil, Sci. Total Environ. 752 (2021), 141958, https://doi.org/10.1016/j.scitotenv.2020.141958.
[121] C. Ji, S. Li, Y. Geng, Y. Miao, Y. Ding, S. Liu, J. Zou, Differential responses of soil N2O to biochar depend on the predominant microbial pathway, Appl. Soil Ecol. 145 (2020), 103348, https://doi.org/10.1016/j.apsoil.2019.08.010.

[122] B. Li, W. Huang, L. Elsgaard, B. Yang, Z. Li, H. Yang, Y. Lu, Optimal biochar amendment rate reduced the yield-scaled N2O emissions from Ultisols in an intensive vegetable field in South China, Sci. Total Environ. 723 (2020), 138161, https://doi.org/10.1016/j.scitotenv.2020.138161.

[123] Á.M. Barbosa de Sousa, R.R. Soares Santos, C. Gehring, Charcoal in Amazonian paddy soil—nutrient availability, rice growth and methane emissions, J. Plant Nutr. Soil Sci. 177 (2014) 39–47, https://doi.org/10.1002/jpln.201300088.

[124] L. Van Zwieten, C. Kammann, M.L. Cayuela, B.P. Singh, S. Joseph, S. Kimber, S. Donne, T. Clough, K.A. Spokas, L. Van Zwieten, C. Kammann, M.L. Cayuela, B.P. Singh, S. Joseph, S. Kimber, S. Donne, T. Clough, K.A. Spokas, Biochar effects on nitrous oxide and methane emissions from soil, in: Biochar Environ. Manag., Routledge, New York, 2015, pp. 521–552.

[125] T.T.N. Nguyen, C.-Y. Xu, I. Tahmasbian, R. Che, Z. Xu, X. Zhou, H.M. Wallace, S.H. Bai, Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis, Geoderma 288 (2017) 79–96, https://doi.org/10.1016/j.geoderma.2016.11.004.

[126] Y. Pu, B. Zhu, Z. Dong, Y. Liu, C. Wang, C. Ye, Soil N2O and NOx emissions are directly linked with N-cycling enzymatic activities, Appl. Soil Ecol. 139 (2019) 15–24, https://doi.org/10.1016/j.apsoil.2019.03.007.

[127] X. Liu, A. Zhang, C. Ji, S. Joseph, R. Bian, L. Li, G. Pan, J. Paz-Ferreiro, Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data, Plant Soil 373 (2013) 583–594, https://doi.org/10.1007/s11104-013-1806-x.

[128] T. Limwikran, I. Kheoruenromne, A. Suddhiprakarn, N. Prakongkep, R.J. Gilkes, Most plant nutrient elements are retained by biochar in soil, Soil Syst 3 (2019) 1–16, https://doi.org/10.3390/soilsystems3040075.

[129] N. Borchard, J. Siemens, B. Ladd, A. Möller, W. Amelung, Application of biochars to sandy and silty soil failed to increase maize yield under common agricultural practice, Soil Tillage Res. 144 (2014) 184–194, https://doi.org/10.1016/j.still.2014.07.016.

[130] T.J. Clough, L.M. Condron, C. Kammann, C. Müller, S.N. Dynamics, T.J. Clough, L.M. Condron, C. Kammann, C. Müller, A review of biochar and soil nitrogen dynamics, Agronomy 3 (2013) 275–293, https://doi.org/10.3390/agronomy3020275.

[131] A. Zhang, G. Cheng, Q. Hussain, M. Zhang, H. Feng, M. Dyck, B. Sun, Y. Zhao, H. Chen, J. Chen, X. Wang, Contrasting effects of straw and straw–derived biochar application on net global warming potential in the Loess Plateau of China, Field Crops Res. 205 (2017) 45–54, https://doi.org/10.1016/j.fcr.2017.02.006.

[132] Z. Cai, Y. Shan, H. Xu, Effects of nitrogen fertilization on CH 4 emissions from rice fields, Soil Sci. Plant Nutr. 53 (2007) 353–361, https://doi.org/10.1111/j.1747-0765.2007.00153.x.

[133] M.K. Abbasi, M.M. Tahir, N. Rahim, Effect of N fertilizer source and timing on yield and N use efficiency of rainfed maize (Zea mays L.) in Kashmir-Pakistan, Geoderma 195–196 (2013) 87–93, https://doi.org/10.1016/j.geoderma.2012.11.013.

[134] M.R. Martins, C.P. Jantalia, J.C. Polidoro, J.N. Batista, B.J.R. Alves, R.M. Boddey, S. Urquiaga, Nitrous oxide and ammonia emissions from N fertilization of maize crop under no-till in a Cerrado soil, Soil Tillage Res. 151 (2015) 75–81, https://doi.org/10.1016/j.still.2015.03.004.

[135] W.K. Atakora, P.K. Kwakye, D. Weymann, N. Brüggemann, Stimulus of nitrogen fertilizers and soil characteristics on maize yield and nitrous oxide emission from Ferric Luvisol in the Guinea Savanna agro-ecological zone of Ghana, Sci. African. 6 (2019), e00141, https://doi.org/10.1016/j.sciaf.2019.e00141.

[136] I.A.M. Degaspari, J.R. Soares, Z.F. Montezano, S.J. Del Grosso, A.C. Vitti, R. Rossetto, H. Cantarella, Nitrogen sources and application rates affect emissions of N2O and NH3 in sugarcane, Nutrient Cycl. Agroecosyst. 116 (2020) 329–344, https://doi.org/10.1007/s10705-019-10045-w.

[137] C.S. Snyder, T.W. Bruulsema, T.L. Jensen, P.E. Fixen, Review of greenhouse gas emissions from crop production systems and fertilizer management effects, Agric. Ecosyst. Environ. 133 (2009) 247–266, https://doi.org/10.1016/j.agee.2009.04.021.

[138] A. Wahhab, H.M. Bhatti, Effect of various sources of nitrogen on rice paddy yield 1, Agron. J. 49 (1957) 114–116, https://doi.org/10.2134/agronj1957.00021962004900030002x.

[139] N.K. Fageria, A.B. dos Santos, A.M. Coelho, Growth, yield and yield components of lowland rice as influenced by ammonium sulfate and urea fertilization, J. Plant Nutr. 34 (2011) 371–386, https://doi.org/10.1080/01904167.2011.536879.

[140] M.E.-M.H. Amin, Effect of different nitrogen sources on growth, yield and quality of fodder maize (Zea mays L.), J. Saudi Soc. Agric. Sci. 10 (2011) 17–23, https://doi.org/10.1016/j.jssas.2010.06.003.

[141] P. Rochette, J.D. MacDonald, D.A. Angers, M.H. Chantigny, M.-O. Gasser, N. Bertrand, Banding of urea increased ammonia volatilization in a dry acidic soil, J. Environ. Qual. 38 (2009) 1383–1390, https://doi.org/10.2134/jeq2008.0295.

[142] P. Rochette, D.A. Angers, M.H. Chantigny, J.D. MacDonald, N. Bissonnette, N. Bertrand, Ammonia volatilization following surface application of urea to tilled and no-till soils: a laboratory comparison, Soil Tillage Res. 103 (2009) 310–315, https://doi.org/10.1016/j.still.2008.10.028.

[143] Q. Shang, X. Yang, C. Gao, P. Wu, J. Liu, Y. Xu, Q. Shen, J. Zou, S. Guo, Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments, Glob. Chang. Biol. 17 (2011) 2196–2210, https://doi.org/10.1111/j.1365-2486.2010.02374.x.