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Eco-friendly yield-scaled global warming potential assists to determine the right rate of nitrogen in rice system: A systematic literature review☆

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ABSTRACT

Rice paddies are one of the largest greenhouse gases (GHGs) facilitators that are predominantly regulated by nitrogen (N) fertilization. Optimization of N uses based on the yield has been tried a long since, however, the improvement of the state-of-the-art technologies and the stiffness of global warming need to readjust N rate. Albeit, few individual studies started to, herein attempted as a systematic review to generalize the optimal N rate that minimizes global warming potential (GWP) concurrently provides sufficient yield in the rice system. To satisfy mounted food demand with inadequate land & less environmental impact, GHGs emissions are increasingly evaluated as yield-scaled basis. This systematic review (20 published studies consisting of 21 study sites and 190 observations) aimed to test the hypothesis that the lowest yield-scaled GWP would provide the minimum GWP of CH_4 and N_2O emissions from rice system at near optimal yields. Results revealed that there was a strong polynomial quadratic relationship between CH_4 emissions and N rate and strong positive correlation between N_2O emissions and N rate. Compared to control the low N dose emitted less (23%) CH_4 whereas high N dose emitted higher (63%) CH_4 emission. The highest N_2O emission observed at moderated N level. In total GWP, about 96% and 4%, GHG was emitted as CH_4 and N_2O, respectively. The mean GWP of CH_4 and N_2O emissions from rice was 5758 kg CO_2 eq ha^{-1}. The least yield-scaled GWP (0.7565 (kg CO_2 eq. ha^{-1})) was recorded at 190 kg N ha^{-1} that provided the near utmost yield. This dose could be a suitable dose in midseason drainage managed rice systems especially in tropical and subtropical climatic conditions. This yield-scaled GWP supports the concept of win–win for food security and environmental aspects through balancing between viable rice productivity and maintaining convincing greenhouse gases.

1. Introduction

Global demand for synthetic N fertilizer is projected to exceed 118 million tones N in 2020—a 20% increase since 2010 (FAO, 2020). The present tendency of N demand is beyond some of the most aggressive forecasts (Erisman et al., 2008). The N fertilizer uses are accelerating due to mounting population and demand for food, fiber, and biofuel (Zhang et al., 2015b). The N management becomes a crucial issue for achieving the target yields with appropriate quantities, because the lower and over-rate of fertilizer can reduce yields and yield quality (Ju and Gu, 2014). Furthermore, continuous and excessive use of N has altered global N cycle and responsible for various harmful environmental consequences including eutrophication (Qiao et al., 2012), land degradation (Guo et al., 2010), ozone layer depletion (Gruber and Galloway, 2008), and global warming (Tian et al., 2012). Minimizing negative consequences as well as maintaining sustainable production with N fertilizer utilizations has become a concerning matter at present-day (Galloway et al., 2008).

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In the rice system, N management has become a vigilant issue because one GHG – CH_4 (28 times radiative force of CO_2, IPCC, 2014) augmented about 40–75% due to N fertilization compared to zero fertilized lands (Lindau et al., 1991). N fertilizer enhances the rice shoot biomass that may assist CH_4 transportation to the atmosphere (Banger et al., 2012) and increases root biomass and enhances the carbon substrates in the rhizosphere that helps to prolific and flourish of methane producing archaea (Lu et al., 2000; Schimel, 2000). On the other hand it is stated that N fertilization had no or minor effect on CH_4 emission (Amos et al., 2005; Mosier et al., 2006) and even it specified that CH_4 emissions declined due to synthetic N fertilizer application (Xie et al., 2010; Yao et al., 2012). Meta-analyses conveyed CH_4 emissions might be N rate dependent in the rice system; at low N rates CH_4 emissions was higher whereas CH_4 emission was lower at high N rates (Linquist et al., 2012b; Banger et al., 2012). Anomalies observations were noticed in the rule synthetic N fertilizer to CH_4 emission in the rice system that needs to be clarified.

N has a profound effect on another potent GHG - N_2O (265 times radiative force of CO_2, IPCC, 2014) emission albeit much lower than that of CH_4 (Kreye et al., 2007; Zschornack et al., 2018). N_2O is produced as a by-product of nitrification & as an intermediary product of denitrification (Di et al., 2014; Pan et al., 2016). The abundance of microorganisms, which are responsible for nitrification and denitrification, was declined when N availability was decreased (Chen et al., 2014). High N rates usually enhances the N_2O emissions, nevertheless results differ due to management practices including N rates, field drainage management, and soil submergence cycles (Kreye et al., 2007; Becker et al., 2007; Zhao et al., 2011). Even numerous studies have failed to report the impact of N on this gas (Huang et al., 2005).

Rice system becomes the hotspot of GHGs emission and rice plants per se become a potent source. Rice is a semi-aquatic plant species and usually grows in flooded low-land conditions (Kögel-Knabner et al., 2010). Stagnant growing condition is a profound cause of CH_4 releases (Le Mer and Roger, 2001; Yan et al., 2009), however, a short time drainage or intermittent drainage also provides a substantial quantities of N_2O emission (Zou et al., 2009a) and even short-term flooded cycles over long periods of time or during transition periods between two floods also contribute the GHGs emission (Yao et al., 1999; Kögel Knabner et al., 2010; Kögel-Lüdemann et al., 2000; Zhao et al., 2011). Rice cropping system also contributes to GHGs emission, for instance, single cropping rice emits almost a half (i.e., 46.38%) of total agricultural GHGs emissions in China (2013). A deepened understanding of CH_4 and N_2O emissions from rice-soil-water management and cropping systems is a prerequisite for identifying GHGs mitigation opportunities.

The impact of GHGs is quantitatively assessed by computing global warming potential (GWP) that accounts by all sources (e.g., carbon and non-carbon) of CO_2 equivalents (Robertson et al., 2000; Mosier et al., 2006). A new metric has been advocated to assimilate climate change issues with global food demand using a 'yield-scaled GWP' or 'greenhouse gas intensity (GHGI)' approach (Mosier et al., 2006; Van Groenigen et al., 2010). The GHGI is mainly estimated by the balance of CH_4 and N_2O emissions, and crop yields (Robertson et al., 2000; Mosier et al., 2005, 2006), which is articulated as GWP per unit crop yield (Mosier et al., 2006). These approaches represent imperative tools to focus the dual goals of enhancement of food production as well as reduction of environmental risks.

Few scientists (e.g., Liang et al., 2013; Zhong et al., 2016; Jiang et al., 2019; Kim et al., 2017; Kim et al., 2019) keeping the yield-scaled GWP as centerpiece tried to assess the tangible N dose for providing effective yield with less GWP. These individual studies might provide biased findings because short-term climatic inconsistency can have a largest influence on the total GHGs emissions (Dobbie et al., 1999). Compiling enormous findings – a systematic review is deemed obligatory to generalize these diffident findings and to clarify the depth of knowledge of exclusively N rules on GHGs. Given the global importance focusing on solely N impact on GWP and yield-scaled GWP or GHGI in rice systems, this systematic literature review paper designed to explore the following objectives (1) to determine the effects of urea form N fertilizer rates on the GHGs emissions in early-rice cropping system; (2) to ascertain optimal N fertilizer rates for attaining low GHG emissions and high grain yields in early-rice production system. In addition, we would hypothesize that yield-scaled GWP of rice is minimized at N rates which optimize yields.

2. Methodology

2.1. Literature search

An exhaustive literature survey of the peer-reviewed articles published from 2004 to July 2020 was carried out using Web of Science℠ (Thomson Reuters, Philadelphia, PA, USA), PubMed®(-National Center for Biotechnology Information, MD USA), SciFinder® (CAS, Columbus, OH, USA), and Google Scholar (Google Inc., Mountain View, CA,USA) following search terms: ["nitrogen addition" OR "nitrogen application" OR "nitrogen fertilization"] AND ["rice" OR "paddy"] AND ["CH4" OR "CH4 emission" OR "CH4 uptake" AND ["N2O" OR "N2O emission"] AND ["global warming potential"] OR ["net global warming potential"].

2.2. Systematic review process

As displayed in Fig. S1 (Supplementary), literature searching as well as articles retrieving were completed through preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines. PRISMA is an evidence-based least set of items for compiling in systematic reviews (Moher et al., 2010). A total of 1065 related papers were identified through this process (Fig. S1). After the title screen only 178 documents remained at preliminary stage. A total of 111 documents were discarded after a careful assessment. Then, only 67 records were nominated for suitability checking, from which 47 papers were removed. At last, a total of 20 empirical studies were identified for detailed analysis. The final data set consisted of 20 (21 sites, 190 observations) (Table 1).

2.3. Screening and selection criteria

To elude any selection bias, we pull out papers in our research that fulfilled the following criteria: (i) emissions of both CH_4 and N_2O were examined under field conditions during the full growing season; (ii) field experiments completed in situ and no other management practices (e.g. straw or any organic matter incorporation) and no special types of soils (e.g., saline, sodic, and peatland) were included; (iii) grain yields were reported; and (iv) N forms – only urea were used.

Additionally, location (altitude & longitude) and climatic conditions were collected directly from the records. Growing seasonal temperature (GST) and growing seasonal precipitation (GSP) were obtained from NOAA's National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/) and Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/). All the raw data were either achieved from tables or extracted from graphs through WebPlotDigitizer v4.3 - Web based (https://apps.automeris.io/wpd/). We also contacted authors if they were

Table 1
A summary of 20 publications having 21 sites and 190 observations which are considered for this systematic review.

Article No.	Coordinates	Ecozone	Crop rotation	Drainage system [a]	GSMT (^{0}C)	GSMP (mm)	Climate	Reference
1	32°35′5‴N, 119°42′0″E	Jiangsu, China	Rice -wheat (*Triticum aestivum* L.)	Traditional management	24.5	140.7	subtropical monsoon	Yao et al. (2012)
2	20°25′N, 85°55′E	Odisha, India	Rice—rice	Traditional management	27.1	24.6	sub-humid tropical	Mohanty et al. (2017)
3	28°07′N, 112°18′E	Hunan, China	Rice-rice	Traditional management	23.5	143.9	humid mid subtropical monsoon	Chen et al. (2016)
4 Site 1	30.26°N, 120.12°E	Qingzhiwu, Zhejiang, China	Not mentioned	Traditional management	23.8	129.1	subtropical monsoon	Zhong et al. (2016)
4 Site 2	30.13°N, 120.16°E	Xiaoshan, Zhejiang, China	Not mentioned	Traditional management	23.0	153.5	subtropical monsoon	Zhong et al. (2016)
5	31°32′93″N, 120°41′88″E	Jiangsu, China	Rice-wheat	Traditional management	24.1	182.8	subtropical humid monsoon	Zhang et al. (2015a)
6	31°16′N, 105°28′E	Sichuan, China	Rice-wheat	Traditional management	24.1	150.6	subtropical monsoon	Zhou et al. (2017a)
7	14°09′45″N, 121°15′35″E	Los Baños, Philippines	Rice-rice	Traditional management	27.7	155.9	sub-tropical	Weller et al. (2015)
8	31°32′93″N, 120°41′88″E	Jiangsu, China	Rice-wheat	Traditional management	24.9	152.0	subtropical humid monsoon	Ma et al. (2013)
9	31°16′N, 105°28′E	Sichuan, China	Rice—wheat or rice—rapeseed (*Brassica napus*)	Traditional management	24.9	156.8	subtropical	Zhou et al. (2015)
10	28°09′N, 113°37′E	Hunan, China	Rice-rice-fallow	Traditional management	24.3	133.6	subtropical humid monsoon	Liu et al. (2015a)
11	31°32′N, 120°55′E	Jiangsu, China	Rice-wheat	Traditional management	24.8	142.0	subtropical monsoon	Yang et al. (2015)
12	120°16′N, 30°13′E	Zhejiang, China	Single rice	Traditional management	22.5	145.9	subtropical monsoon	Jiang et al. (2019)
13	32°35′5″N, 119°42′0″E	Jiangsu, China	Rice-wheat	Traditional management	23.9	86.7	northern subtropical monsoon	Yao et al. (2013)
14	29°510′ N, 115°330′ E	Hubei, China	Rice- rapeseed	Traditional management	23.4	149.5	mid-subtropical humid monsoon	Zhang et al. (2016b)
15	30°21′ N, 112°09′ E	Hubei, China	Rice-rice-fallow	Traditional management	22.8	121.6	subtropical monsoon	Wang et al. (2016)
16	120°40′ E, 30°50′ N	Zhejiang, China	Rice- rapeseed	Traditional management	25.5	134.9	subtropical monsoon	Liang et al. (2013)
17	31°32′93″N, 120°41′88″ E	Jiangsu, China	Rice-wheat	Traditional management	22.5	159.4	subtropical humid monsoon climate	Zhang et al. (2016a)
18	35° 06′ 33″ N, 128° 07′ 06″ E	Gyeongsangnam-do, South Korea	Mono rice	Traditional management	20.4	216.7	typical monsoon and temperate zone	Kim et al. (2019)
19	28°40′ N, 77°12′ E	New Delhi, India	Rice-wheat	Irrigated on alternate days	29.4	88.5	subtropical and semi-arid	Bhatia et al. (2012)
20	31°61′ N, 121°62′ E	Shanghai, China	Rice-broad bean (*Vicia faba* L.)	Traditional management	22.5	143.8	subtropical, wet and humid	Zhang et al. (2014)

[a] Traditional management = irrigation water was maintained at 2—7 cm during the cultivation period except one or two midseason drainage and final drainage before harvest; GSMT = Growing season mean temperature; GSMP = Growing season mean precipitation.

eager to provide raw data within our database; two datasets (e.g., Weller et al., 2015 and Kim et al., 2019) were included.

When soil factors were described with multiple soil depths, we included the data measured at 0—20 cm depths. All experiments maintained the traditional water management (local practices) i.e., the irrigation water was maintained constantly at 2—7 cm during the entire cultivation period except one or two midseason/intermittent drainage and final drainage before harvest, only one study that reported alternate days irrigation (Bhatia et al., 2012). Studies that presented individual data points recorded over multiple years were kept as such, and studies that presented averaged value were included as their number of years (only two studies; Yang et al., 2015 and Jiang et al., 2019). A study conducted in two different coordinates and in two different years; to maintain the homogeneity that experiment considered two separate experiments (Zhong et al., 2016). In rotation experiments either with rice or other crops we extracted only early-rice experimental data. Generally other rice cropping systems consume different levels of N fertilizer and thus stimulus different level of GHGs and GWPs.

2.4. Data calculation

Values for N application rate (kg N ha^{-1}), yield (Mg ha^{-1}), and emission of CH_4 (kg ha^{-1}) and N_2O (kg ha^{-1}) were extracted from individual records with unit conversions accomplished where necessary. For each observation, total GWP was estimated as kg CO_2 equivalents (CO_2 eq) over a 100-year time horizon using radiative forcing potential of 265 for N_2O and 28 for CH_4 relative to CO_2 (IPCC, 2014). Yield-scaled GWP or GHGI (kg CO_2 eq. kg^{-1} grain) = GWP (kg CO_2 eq. ha^{-1})/rice grain yield (kg ha^{-1}) following Kim et al. (2019). In addition to, we distinguished N rate classes as control, low, moderate, and high with 0 (no nitrogen), 1—120, 121—250, and 251—375 kg N ha^{-1}, respectively, and their frequency were recorded as 46, 22, 75, and 47, respectively (e.g., Zhang et al., 2014).

2.5. Data analysis

All relationship graphs were evaluated using both linear and non-linear regression methods. All figures were constructed by curve fitting through SigmaPlot 10.0 (Systat Software, Inc. USA).

Interactions and family-wise graphs were prepared through analysis of variance and Tukey test using analytical software SPSS 23 (IBM SPP, USA) statistical software. Boxplot was prepared through R software (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. CH_4 and N_2O emission under different N application rates

The Nitrogen (N) fertilizer form of urea had a high significant ($P < 0.001$) impact on CH_4 emission and observed a polynomial quadratic ($\hat{y} = 0.004\ x^2 - 0.885\ x + 187.01$) relationship, where $\hat{y}$ and x indicate CH_4 emission (kg ha^{-1}) and N rate (kg ha^{-1}), respectively (Fig. 1a). The lowest CH_4 emission (ca. 138 kg ha^{-1}) was noticed at 110 kg ha^{-1} N rate and thereafter the CH_4 emission constantly increased with increasing the loading of N fertilizer in the fields. Probably, the N influenced the methanogens activity in the tested fields. At a low N rate CH_4 emission decreased (23%) whereas at a high N rate that was increased by 63% compared to control (no N) rate (Fig. 2a). N rate had a statistically positive significant ($p < 0.05$) impact on N_2O emission (Fig. 1b), with increasing N rate the N_2O emission constantly increased. Nevertheless, at a moderate N fertilizer level produced the greatest level of N_2O and the highest N rate emitted lower N_2O than that of moderate N rate (Fig. 2b). Compared to control at low N rate N_2O emission was the lowest (10% less) and at moderate N rate N_2O emission was the highest (289% high). Statistical reliability of the estimate for low N rate is also better than that for moderate and/or high N rates in both CH_4 and N_2O. Perhaps, high N rates hamper the activity of nitrifiers and denitrifiers. A highly positive significant ($p < 0.001$) relationship between CH_4 and N_2O emission was also observed (Fig. S2).

3.2. N loadings on rice yield

A strong positive significant ($P < 0.001$) relationship was observed between synthetic N rate and grain yield (Fig. 3a). The probable positive increment with increasing N fertilizer mostly responsible for integrated soil-crop system management (ISSM), which has mostly been practiced in China (e.g., Zhang et al., 2016a). The family-wise comparison from ANOVA analysis revealed that compared to control the yield was significantly increased at low, moderate, and the maximum yield was recorded at high N rate (Fig. 3b). Compared to low N rate the grain yield did not significantly increase at moderate N rate, albeit the high N rate showed significantly increased grain yield. However, compared to moderate N rate the high N rate did not have a profound impact on early-rice grain yield (Fig. 3b).

3.3. N fertilization impact on GWP and yield-scaled GWP

The measured GWP emissions patterns and the calculated yield-scaled GWP (GHGI) of different N fertilizer levels were shown in Fig. 4(a) and (b), respectively. A statistically strong significant ($P < 0.001$) relationship was observed between N rate and GWP that provided a polynomial quadratic trend. The least GWP (4123 $kgCO_2$ eq. ha^{-1}) was recorded at 104 kg ha^{-1} N. The lowest GWP recorded at low N rate (Fig. S3 a). Beyond of that dose the GWP rate also increased constantly with increasing N loadings (Fig. S3 a). Similar sorts of significant ($P < 0.001$) specific trend also observed between the relationship of urea form N fertilizer and yield-scaled GWP or GHGI. The lowest GHGI (0.7565 $kgCO_2$ eq. ha^{-1}) was observed at 190 kg ha^{-1} N rate, below and above of that dose, the GHGI rate increased in subject to that rate (Fig. 4b). The GHGI indicates the relationship between per unit grain yield and per unit GWP; therefore, the lowest GHGI indicates the lowest GWP with related N rate which gives the near maximum yield. Therefore, 190 kg ha^{-1} N rate would be the suitable value for maintaining the lowest GWP value and concurrently providing nearly the best rice yield.

4. Discussion

Vigorously synthetic N fertilization been practiced since last couple of decades and will be accelerated due to expansion of cultivable land and/or to multiply crop yield or to multiply cropping number in the existing land to feed the mounted populace in coming decades (Cai et al., 2007; Zhang et al., 2015b). The consequences of N uses with organic amendments or manipulative types (e.g., slow release formation) reviewed elsewhere (Linquist et al., 2013; Dai et al., 2017). The impacts of solely N from urea on GHGs has not been well elucidated yet. Albeit some individual studied have been attempted to explore the exclusive N impact on GHGs, an uneven outcome perceived (e.g., Liu et al., 2015a, b; Sass et al., 2002; Minamikawa and Sakai, 2005; Krüger and Frenzel, 2003; Li et al., 2006; Huang et al., 2005). To generalize these diffident findings and to clarify the depth of knowledge of exclusively N rules on GHGs, a review with vigilant findings is deemed obligatory.

4.1. Nitrogen fertilization regulating CH_4 emissions

Methane production and consumption — biological processes — are affected by N directly or indirectly (Schimel, 2000). Nitrogen loadings influence on either increased (Liu et al., 2015a, b) or decreased (Sass et al., 2002; Minamikawa and Sakai, 2005; Krüger and Frenzel 2003; Zou et al., 2009b; Xie et al., 2010) or no impacts on CH_4 emission (Hou, 2000; Linquist 2012a) in rice system. Even a

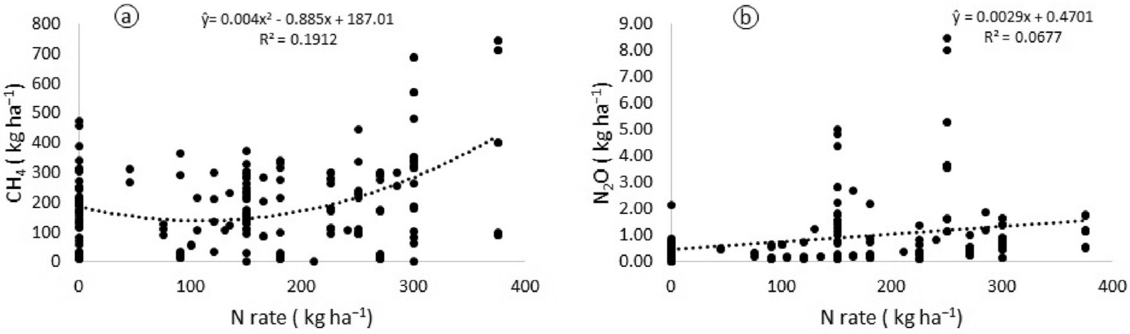

Fig. 1. Relationship between nitrogen (N) rate and CH_4 emission (a) and N rate and N_2O emission (b).

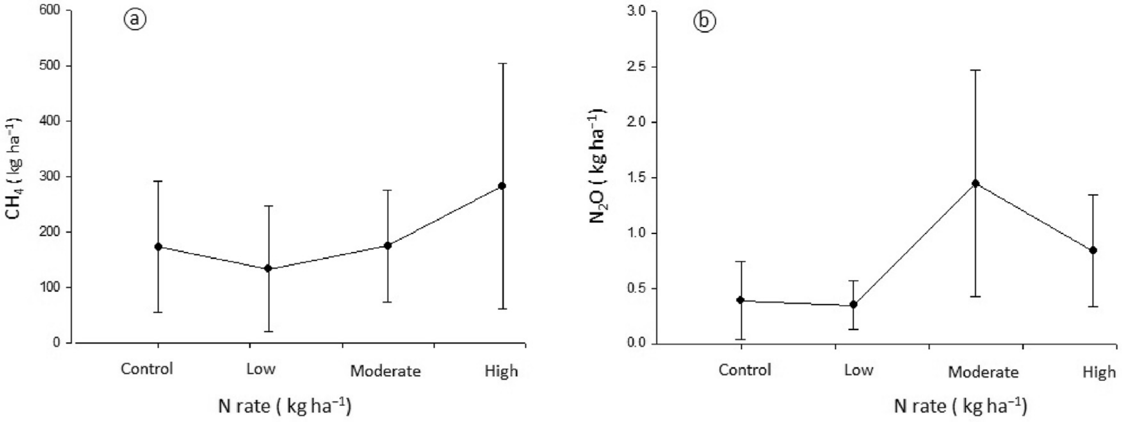

Fig. 2. The control (0; no fertilizer), low (1–120 kg N ha^{-1}), moderate (121–250 kg N ha^{-1}), and high (251–375 kg N ha^{-1}) value was average of 46, 22, 75, 47 observations, respectively.

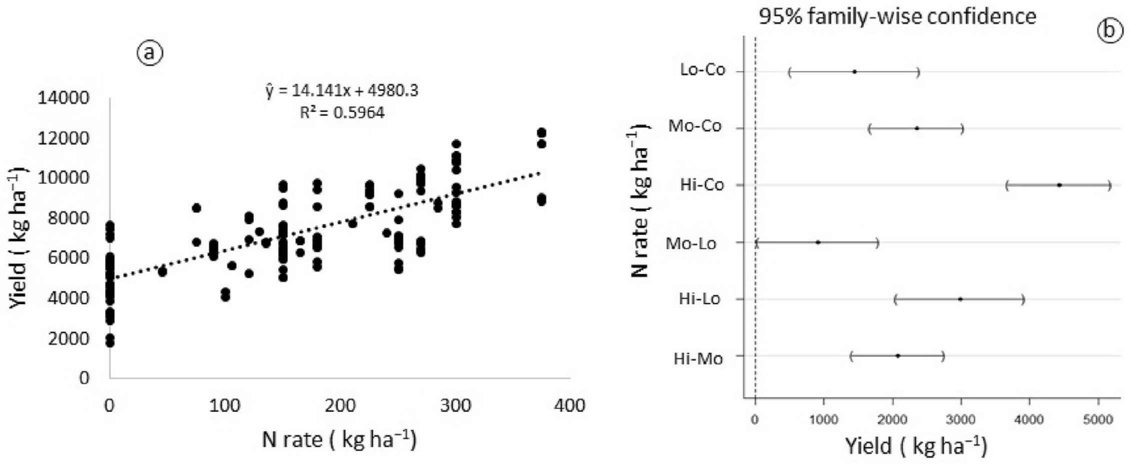

Fig. 3. Relationship between nitrogen (N) rate and grain yield (a) and family-wise nitrogen rate level i.e., the comparative N rate effect on early-rice grain yield (b).

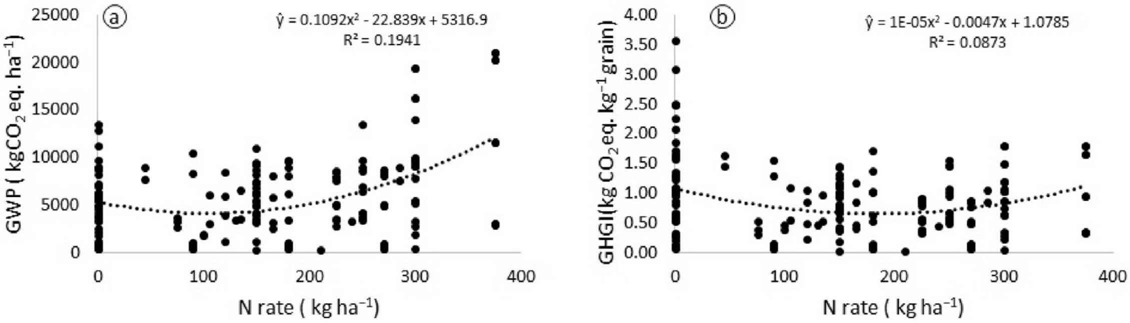

Fig. 4. Relationship between nitrogen (N) rate and GWP (a) and N rate and GHGI (b).

narrative review Cai et al. (2007) conveyed that it is not possible to make any concrete decision about N rules on CH_4 emission. In this systematic review — having fairly homogenous experimental studies — provided a bit concrete trend that CH_4 emission appeared a quadratic increment with increasing synthetic N fertilizer rate in the rice systems. A meta review by Linquist et al. (2012b) stated that at low N rate CH_4 emission increased whilst CH_4 emission decreased with incremental N loadings, which was utterly a contrary of present findings (Fig. 2a). The differences could be mainly (a) heterogeneous data sources, (b) NH_4SO_4 fertilization. When ammonium based fertilizer is applied in the field it is easily hydrolyzed into ammonium and sulfate. Sulfate performs as an alternate electron acceptor in anaerobic conditions that reduces CH_4 production through competition for electrons. Besides, H_2S product of SO_4^{2-} reduction may be toxic to methanogenic archaea and thus CH_4 production is decreased (Minami, 1994). Cai et al.

(2007) reported that less CH_4 emission detected from rice fields that applied ammonium sulfate than that of urea applied, (c) authors considered that above 100 kg N ha^{-1} yield would decline (though they did not consider the yield), thereby, CH_4 emission also would decline. Again it was contradicting the present study that high nitrogen (>300 kg N ha^{-1}) rate provided the higher yield (Fig. 3a) (Ma et al., 2013; Zhang et al., 2015a, 2016a). Therefore, the present outcome is far more robust than any other earlier study.

Production, oxidation, and transportation are involved in CH_4 emission and controlled by N loadings (Bodelier and Laanbroek, 2004) because N helps in increasing of shoot biomass (e.g., aerenchyma tissue), which assists rice plants transmit CH_4 emission vigorously from the anaerobic soil to the atmosphere (Le Mer and Roger, 2001). Schimel (2000) suggested that N fertilizers increased the root growth and enhanced carbon supply for methanogenic archaea. Therefore, it is reasonable to conclude that N fertilizers enhance CH_4 production through increasing rice biomass (Bodelier and Laanbroek, 2004). The present study strengthened the inference that CH_4 was profoundly ($p = 0.001$) increased with increasing N rate, which has been accord with several previous studies (Dan et al., 2001; Banger et al., 2012; Liu et al., 2015b). However, it was also observed in the present study that compared to control at low N rate CH_4 emission was clearly declined and then it turned to increased. This sort of trend might have been responsible not only for synthetic fertilizer but also for relevant other factors e.g., soil physical, chemical, biological factors are involve in it. Nevertheless, Yao et al. (2012) mentioned a contrary findings that CH_4 emission decreased due to increasing fertilizer and explained that CH_4 oxidizing bacteria — methanotrophs' activity increased at higher N level and thereby CH_4 consumption increased at higher N rate. Bodelier et al. (2000) reported that the function and activity of methanotrophic bacteria increased with adding ammonium-based fertilizer in the rhizosphere. Albeit, Zou et al. (2005) substantiated that the rule of synthetic fertilizer on CH_4 flux from paddy fields is unpredictable and need to be understood meticulously.

In addition, underflooding state, rice roots excrete C sources that support to proliferate CH_4 forming archaea i.e., Methanogens as well as rice plants favoring CH_4 transmission into the atmosphere (Dannenberg and Conrad, 1999). Rice plants stimulate CH_4 production in the field under flooding conditions (Inubushi et al., 2003; Xu et al., 2004) that trend supported by the present study (Fig. S4a); CH_4 emission increased with increasing growing season moisture whereas at low moisture that one was low. At low moisture or midseason drainage reduces CH_4 emission which has been fortified by a recent meta-analysis (Liu et al., 2019).

4.2. Nitrogen fertilization regulating N_2O emissions

N_2O emission significantly increased with increasing N loadings in the present study that was in line with several studies in rice paddies (Zou et al., 2005; Ma et al., 2007; Zhao et al., 2011). Chen et al. (2016) reported that the peaks of N_2O emission appear immediate after N application. In rice field, when urea applies it hydrolyses and provides the sufficient substrate of NO_3^- and NH_4^+ in the nitrification and denitrification process; moreover, N also stimulates crop roots function and thus increase root secretions, which enhances the multiplication of microorganisms and their activity, eventually N_2O emissions enhanced (Ma et al., 2009). Furthermore, aerobic conditions favor the N_2O emissions (Liu et al., 2010). Intermittent drainage or short drainage with chemical fertilized rice fields favor a greater level of N_2O (Kim et al., 2014). Most N_2O emissions from rice systems occur during drainage events with the increase of urea fertilization (Li et al., 2006; Yao et al., 2010). Some studies, on the contrary, showed that large quantities of N fertilization in paddy fields may be responsible for the slow growth of N_2O emissions. The greatest N_2O emission was observed in the moderate nitrogen level and then the N_2O emission decreased in the present study (Fig. 2b). The excess level of fertilizer might have decreased the microbial activities as it is reported that high rate of inorganic N significantly decreased the abundance and activity of soil bacteria (Ramirez et al., 2010; Zhou et al., 2017b). Huang et al. (2005) also indicated that no significant improvement of N_2O emission with the escalation of urea content. A 6-year paddy study showed that seasonal N_2O emission diverse considerably between years and nitrogen rates & sources (Liang et al., 2013). Therefore, to arrive at a vigilant inference need to rely on data of long time experiment or big data compilation findings.

Midseason drainage increases N_2O emission (Liu et al., 2019), whereas at flooding N_2O production decreases (Brentrup et al., 2000) because it inhibits the microbial activity (Signor and Cerri, 2013). Furthermore, exporting of nitrate through runoff and leaching into groundwater is known to be an important control on dissolved N_2O concentrations (Sawamoto et al., 2005; Turner et al., 2015; Griffis et al., 2017). Decreasing N_2O emission with increasing soil moisture was observed in our study (Fig. S4b). Similarly, Ma et al. (2007) and Yao et al. (2010) reported that low or even negligible N_2O emissions from rice paddies after heavy rainfall may be result from reducing air-filled pore space and O_2 availability in the soil and increasing anaerobic condition, which favor N_2O transformed into N_2 through denitrification.

4.3. Nitrogen fertilization influences grain yield

Grain yields are directly associated with fertilizer management. Rice grain yield constantly increased with increasing the N rate in the present study. Albeit Weller et al. (2015) and Kim et al. (2019) reported that at 180 kg N ha^{-1} the grain yield significantly decreased than the recommended dose of the respective studies. However, in China, an effective nitrogen managed practice i.e., integrated soil-crop system management (ISSM) had been accomplished in which high level of N could regulate and thus the greater amount of grain yield was achieved (e.g., Ma et al., 2013; Zhang et al., 2015a; Zhang et al., 2016a). In the present study, among 21 experiments, 17 studies were recorded from China and substantial numbers had been followed ISSM practice, therefore a strong positive correlation between yield and N rate was observed (Fig. 3a). Earlier studies revealed that ISSM strategies can successfully increase the rice grain yield (Ma et al., 2013; Liu et al., 2015a). Compare to low N rate, high N rate provided significant yield, however, compare to moderate N rate, the high N rate did not provide profound grain yield, because when the rates of N exceed plant N demand it hampers the plants physiological functions (Kong et al., 2017); consequently declines the grain yield.

4.4. Nitrogen fertilization regulating GWP and yield-scaled GWP

Both GHGs i.e., CH_4 and N_2O emissions increased with increasing N rate. The magnitude of CH_4 and N_2O emissions expressed asCO_2-eq. specifies that the climatic impact of CH_4 emissions from paddies was distinctly higher than that of N_2O emissions; CH_4 contributed about 96% of total GWP in the present study (Supplementary Table 1). Zhou et al. (2018) reported CH_4 emissions were the key contributor of total GWP (e.g., 96% of total GWP). GWP is mainly altered by CH_4 as confirmed by former studies (e.g., Banger et al., 2012; Naser et al., 2020). Significant N_2O fluxes were identified in the present study during rice growing seasons perhaps due to high N inputs and flooding & drainage cycles in the fields (Zhou et al., 2015). We also have a very strong positive correlation ($p > 0.001$) between CH_4 and N_2O emission

(Supplementary Fig. S2), which indicates the complementary relationship between both gases. The mean GWP of CH_4 and N_2O emissions was 5758 kg CO_2-eq kg ha^{-1}during the rice-growing seasons (Supplementary Table 1). A study of 3 year midseason drainage rice system provided the mean GWP was 6564 kg CO_2-eq kg ha^{-1} (Zhou et al., 2015) while in other study the GWP mean value was 3757 kg CO_2-eq kg ha^{-1} (Linquist et al., 2012a). The divergent findings could reflect the contribution of CH_4 emission. The mean CH_4 emission in present study was 197 kg ha^{-1} that was lower than 246 kg ha^{-1} in Zhou et al. (2015) on the contrary the mean CH_4 value did not provide in Linquist et al. (2012a). We assume that the mean CH_4 emission of Linquist et al. (2012a) would be lower than Zhou et al. (2015) and the present study because Linquist et al. (2012a) did not find any relationship between CH_4 emission and N application. Since CH_4 emissions became the most vital component of GWP in typical rice paddies (Zou et al., 2005; Wang et al., 2012), several tested had been done aiming to reduce GWP through suppression of CH_4 emission including judicial chemical fertilizer application (Ju et al., 2009), irrigation management (Gao et al., 2015), and timing and rate of N management (Zhang et al., 2013). Nevertheless, we need to be conscious that agricultural management practices that change one type of GHG source/sink may also impact on other sources/sinks and thereby alter the total GWP (Mosier et al., 2006; Shang et al., 2011).

Greenhouse gas emissions need to be valued as a function of crop yield (e.g., yield-scaled GWP) for achieving both goal of mitigating CH_4 and N_2O emissions whilst guaranteeing crop yields (Van Groenigen et al., 2010; Linquist et al., 2012a). A quadratic strong significant relationship was observed between yield-scaled GWP and N rate in this review while in a meta-review, the yield-scaled GWP was not affected by N rate in a rice system (Linquist et al., 2012a). These variations could be due to the heterogeneous data source (please see Table 2, p 197; Linquist et al., 2012a); different water management and too much variation in treatments, which had certainly been impacted on their results. The minimum yield-scaled GWP was recorded at 190 kg N ha^{-1} in the present study whereas Xia et al. (2016) and Kim et al. (2019) reported the least yield-scaled GWP at 210 kg and 04–112 kg N ha^{-1} of nitrogenous fertilizer, respectively. The differ findings of these individual studies could exist because of the applied fertilizer dose in the respective trials; 300 kg N ha^{-1} and 180 kg N ha^{-1} was the maximum N fertilizer dose in Xia et al. (2016) and (Kim et al., 2019), respectively.

Zhou et al. (2018) stated yield-scaled GWP was 2.61–3.90 kg CO_2-eq kg^{-1} grain from a 3 years rice study, and a 2 years study reported yield-scaled GWP with 1.10–1.28 kg CO_2-eq. kg^{-1} grain (Kim et al., 2019) these findings were matched with the range of present findings i.e., 0.03–3.57 kg CO_2-eq kg^{-1} grain (Supplementary Table 1). The usual GHGI, in Chinese rice paddies appeared at 0.24–1.25 kg CO_2 eq. kg^{-1} grain (Li et al., 2006; Qin et al., 2010; Zhang et al., 2016a). ISSM practice had been followed in China with maintained lower GWP and with higher grain yield (e.g., Ma et al., 2013; Zhang et al., 2015a; Zhang et al., 2016a), therefore, the GHGI become low in Chinese rice because of yield scaled GWP is calculated based on grain yield. A similar GHGI i.e., 0.28 kg CO_2-eq kg^{-1} was recorded in a global data (Linquist et al., 2012a). However, the higher and lower GHGI mainly depend on proper fertilizer dose with cultivation success (Zhang et al., 2016a) because low GWP with high Yield provides low GHGI and vice versa. Therefore, GHGI indicates the proper fertilizer management for target yield while maintaining eco-friendly lower GWP. Zhang et al. (2016a) advocated that having the similar GWP of two practices, when one provides more yield the GHGI of that practice is lower than that of the other. Burney et al. (2010) substantiated the similar findings the net effect of higher yields offsets GHGs emissions. These evidence prudently suggest that the dual goals (i) mitigation of GHG emissions and (ii) sustainable crop production, can be achieved with maintaining N fertilization properly.

5. Limitations and implications

This systematic review is an initial assessment based on currently available field data, therefore few heterogeneities exist due to the paucity of data and agricultural management practices. First, during the GWP calculation, CO_2 emissions were not included due to the limited findings. Increasing N rates can enhance C sequestration by increasing rice biomass, whereas overuse of N fertilizer enhances GHGs emission, including direct CH_4 and N_2O emissions from rice paddies and indirect GHGs emissions during N fertilizer production. Soil CO_2 emissions from rice fields are fairly trivial and even rice soil may act as a CO_2 sink (McMillan et al., 2007). N fertilization has also improved slightly soil C than that of unfertilized soil (Ladha et al., 2011). Therefore, considering the CO_2 in GWP estimation may provide more accurate estimation of required N for target yield, which has not been assessed here. Second, we included the irrigation practices (local applications) that have one or two midseason drainage whereas a considerable area either permanent flooding or dry season rice cultivation are practiced, which are not included here. Third, in the present study early-rice system is considered, though a vast area covered by double or triple rice cropping system (e.g., in Bangladesh (Sarker et al., 2012)), even, in several parts of the world, especially in the tropics, multiple crops are grown along with rice on the same piece of land (Linquist et al., 2012a), those are left in this study. Finally, to understand the holistic assessment of N fertilization, year round assessment i.e., life cycle assessment would be a choice.

6. Conclusion

Given the assumed rise in demand for rice, efforts should be focused on how to sustain environmentally feasible N inputs levels, while concurrently increasing absolute production. The lower yield-scaled GWP in early-rice systems indicates the lower emission of GHGs and achieve target yield with minimum N inputs. The lowest yield-scaled GWP with near maximum yield was achieved at 190 Kg Nha^{-1}. Affirming this dose as an environmentally feasible and economically sound further investigation should be warranted especially in subtropical or tropical climatic condition. Greenhouse gases emission enhanced with N loadings especially CH_4 emission that had a strong relation with N fertilizations. The data source might have played a vital role in the present trend; homogenous sources are more effective to arrive at concrete inference vis-à-vis big data sources. Meticulous comparisons of climate, water management, and soil properties with nitrogenous fertilizers need to be assessed to understand in which surroundings synthetic N fertilizers might stimulate, decline or not affect carbon footprint. Keeping the yield-scaled GWP as a centerpiece the strategies need to be set up for win-win outcome e.g., target yield and lower environmental degradation.

Credit author statement

Mohammad Saiful Islam Bhuiyan: Conceptualization, Methodology, Data curation, Software, Writing – original draft, Writing – review & editing. Azizur Rahman: Software, Formal statistical analysis. Gil Won Kim: Data curation, Software, analysis. Suvendu Das: Data curation, Writing – review & editing. Pil Joo Kim: Investigation, Project administration, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

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