Journal of Environmental Management 310 (2022) 114755

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Potential methane emission reduction strategies from rice cultivation systems in Bangladesh: A critical synthesis with global meta-data

Milton Kumar Saha[a,1], Shamim Mia[b,1,*], AKM Abdul Ahad Biswas[a], Md Abdus Sattar[a], Md. Abdul Kader[c,d,e], Zhixiang Jiang[f]

[a] *Department of Disaster Risk Management, Patuakhali Science and Technology University, Dumki, Patuakhali, Bangladesh*
[b] *Department of Agronomy, Patuakhali Science and Technology University, Dumki, Patuakhali, Bangladesh*
[c] *Agriculture and Food Technology Discipline, School of Agriculture, Geography, Environment, Ocean and Natural Sciences, University of the South Pacific, Apia, 1343, Samoa*
[d] *Department of Soil Science, Bangladesh Agricultural University, Mymensingh, 2202, Bangladesh*
[e] *Agriculture Discipline, College of Science, Health, Engineering and Education, Murdoch University, Perth, WA, 6150, Australia*
[f] *College of Environmental Science and Engineering, Qingdao University, Qingdao, 266071, China*

ARTICLE INFO

Keywords:
CH_4 emission
Rice type
Rice-growing season
Management practices
Bangladesh

ABSTRACT

Methane (CH_4) is one of the dominant greenhouse gases (GHG) that is largely emitted from rice fields and thus, significantly contributes to global warming. Significant efforts have been made to find out suitable strategies to mitigate CH_4 emission from rice culture. However, the effectiveness of these management practices is often diverse with negative, no, or positive impacts making it difficult to adopt under a particular condition. The diversity of rice cultivation in terms of agro-climatic conditions and cultivation practices makes it difficult for providing specific recommendations. Here, we collected data from a total of 198 studies reporting 1052 observations. The management practices are categorized into five different management practices *i.e.*, water, organic and inorganic fertilizer management, crop establishment method, and agronomic practices while major categories were subdivided into different classes. To test statistically significant differences in the effectiveness between major management practices, an analysis of variance (ANOVA) was applied. The Gaussian and bootstrapping model were applied to find out the best estimate of the effectiveness of each practice. In addition, mechanisms controlling the CH_4 emission reductions were synthesized. Next, the adoption potentials of these practices were assessed based on the existing rice cultivation systems in Bangladesh. Our results showed that water and organic matter management were the most effective methods irrespective of the growing conditions. When these technologies are customized to Bangladesh, water management and crop establishment methods seem most feasible. Among the rice-growing seasons in Bangladesh, there is a larger scope to adopt these management practices in the *Boro* season (December to May), while these scopes are minimal in the other two seasons due to their rain-fed nature of cultivation. Altogether, our study provides fundamental insights on CH_4 reductions strategies from rice fields in Bangladesh.

1. Introduction

Methane (CH_4) is one of the most potent greenhouse gases (GHG) that significantly contribute to global warming. CH_4 concentration in the atmosphere has more than been doubled during the industrial era while its concentration reached at 1888.5 ppb in March 2021 (Global Monitoring Laboratory, 2021). The CH_4 is responsible for 21% of the total radiative forcing, placing it in the second highest contributor after CO_2 (Myhre et al., 2013). Although CH_4 has a relatively short atmospheric life-time (8–12 years), one molecule of CH_4 traps about 32 times more heat than a molecule of CO_2 (Badr et al., 1991). Moreover, it has significant roles in tropospheric and stratospheric chemistry since it can change the composition of ozone, water vapor, hydroxyl radical, and numerous other compounds (Wuebbles and Hayhoe, 2002).

Abbreviations: GHG, Greenhouse gas; FYM, Farmyard manure.

* Corresponding author. Department of Agronomy, Patuakhali Science and Technology University, Dumki, Patuakhali, 8602, Bangladesh.

E-mail address: smia_agr@pstu.ac.bd (S. Mia).

[1] Milton Kumar Saha and Shamim Mia contributed equally.

https://doi.org/10.1016/j.jenvman.2022.114755
Received 5 November 2021; Received in revised form 2 February 2022; Accepted 16 February 2022

Rice is one of the most dominant crops in Asian countries and thus, rice culture is one of the dominant contributors to GHG emissions, especially through CH_4 emission. In rice farming with standing water (*i.e.*, under anaerobic conditions) favors CH_4 production while its aerenchyma system facilitates the transportation of the generated CH_4 to the atmosphere (Aulakh et al., 2001; Lu et al., 2000; Wassmann and Aulakh, 2000). Over the last century, the expansion of rice production has significantly been increased while it is predicted that the cultivation needs to be extended in the future to feed the increasing population (Ciais et al., 2013; Zhang et al., 2016). Therefore, rice farming has become a major source of anthropogenic CH_4 emission estimating at 11% of the total anthropogenic CH_4 emission (Oyediran et al., 1996; Smartt et al., 2016).

CH_4 is produced in the rice field through various processes. The most important process is the microbial breakdown of organic compounds under strictly anaerobic conditions, which is usually maintained in rice cultivation (Oremland, 1988). Under anaerobic conditions, methanogenic bacteria utilize carbon substrates including freshly added organic matter, and root exudates for their growth and development (Sandin, 2005). The incomplete mineralization of organic matter under anaerobic environment produces CH_4 through generating a number of intermediate products (*i.e.,* H_2/CO_2, formate, methanol, methylamines, and acetate) (Le Mer and Roger, 2001; Yao et al., 1999). However, a large fraction of the produced CH_4 (80%) in rice paddy is oxidized by methanotrophs (obligate aerobes) before escaping it to the atmosphere (Cai et al., 2016; Frenzel et al., 1992; Kumar et al., 2021). This oxidation takes place mostly at the aerobic–anaerobic interfaces of oxygenated at soil surface or oxygenated water layer and in the area around the oxygen-releasing roots of rice plants (Conrad, 2007). Therefore, CH_4 production can significantly be reduced if the rice farming conditions are optimized.

Methane emission reduction from rice fields has extensively been studied with multiple management practices including water, inorganic and organic fertilizer management, adoption of cultivars, etc (details can be found in the supporting information, SI). For instance, dry or intermediate irrigation in place of continuous flooded irrigation can significantly reduce CH_4 emission since aerobic conditions promote the growth of methane-oxidizing microbial communities (known as methanotrophs) in the soil (Wang et al., 1999). In addition, CH_4 production also depends on the status of soil organic matter and its quality (labile *vs.* recalcitrant) while the amount and form of organic matter replenishment can affect CH_4 emission (Xiong et al., 2007: Zou et al., 2005). Moreover, the relevant soil management practices (*i.e.,* tillage and fertilization) that control the mineralization of soil organic matter are also important for the production of CH_4 in rice fields (Allen et al., 2003; Bhattacharyya et al., 2013). Generally, the application of labile organic matter (*i.e.,* the fresh straw addition just after rice harvest) can generate a larger CH_4 emission than that of the application of a similar amount of well-decomposed organic matter (Watanabe and Kimura, 1998). In addition, nutrient supply, particularly the N, largely affects CH_4 emission with a positive impulse with N addition rates (0–100 kg ha^{-1}) (Sun et al., 2016) while application of N at higher rates (100–250 kg ha^{-1}) shown to reduce CH_4 emission due to a greater oxidation. This oxidation is suggested to occur by a relative suppression of methanogens through changes in the soil C:N ratio and by encouraging the predomination of denitrifying bacteria (Xie et al., 2010). However, the attributed mechanisms for these observed effects are diverse and there are still considerable debates on this issue (Guo et al., 2017; Linquist et al., 2012). Nevertheless, N application at higher rates (100–250 kg N ha^{-1}) can be considered as one of the important CH_4 reduction strategy.

Soil properties (*i.e.,* redox potential and pH) have critical roles in CH_4 formation. It has been determined that methanogenic bacteria in the soil can continue their function only when the redox potential is below a certain level of 200 mv (Minami, 1994; Wang et al., 1993). Since soils vary in buffering soil pH and Eh, therefore, soil type could also affect CH_4 production (Akter et al., 2018). Apart from the aforementioned aspects, soil environment (*i.e.,* temperature and CO_2 concentration) has also been suggested to be associated with CH_4 production (Akter et al., 2018; Bhattacharyya et al., 2013; Li et al., 2004).

Table 1

Categorization system of strategies of CH_4 emission reduction in rice cultivation.

Major management practices	Control group	Treatment group
Water management	Continuous flooding	Alternate wetting and drying Mid-season drainage Intermittent drainage Control irrigation
Organic fertilizer management	No amendment	Biochar
	Fresh straw incorporation	Composted straw incorporation
	Fresh farmyard manure application (FYM)	Composted FYM application
	Straw incorporation shortly before cultivation	Straw incorporation in off-season
Inorganic fertilizer management	No N amendment	Nitrogen addition at 150–250 kg ha^{-1}
	Urea application	Ammonium sulphate application
	Only N application	N application with amendment inputs (silicate slag, phosphogypsum, coal ash)
	Surface application of urea	Urea deep placement (UDP)
Crop establishment method	Conventional tillage	No-tillage
	Transplanting	Direct seeding
Other agronomic practices	Traditional rice variety	Rice variety that reduces methane emission
	Conventional practice	Symbiosis ecosystem
	No application	Herbicide application

The CH_4 reduction potential of different management practices has been shown to vary (Guo et al., 2017). Water management is believed to be one of the most effective mitigation options while the application of recalcitrant or decomposed organic can also reduce the CH_4 emission although the reduction efficiency may be lower than water management (Liu et al., 2019; Tyagi et al., 2010). Similarly, the potentiality of other management practices for CH_4 emission may also vary suggesting a critical evaluation of their relative performance. Although several previous meta-analyses and reviews were published on the CH_4 emission reduction potentials, recent researchers and methods have not been included (Jiang et al., 2019; Liao et al., 2021) while the application of simple Gaussian and bootstrapping models could be effective in estimating the reduction potential, particularly when the number of observations is low (Hesterberg, 2011; Mia et al., 2020).

Rice is the main food crop and covers 80% of cultivable lands in Bangladesh. Moreover, it is grown under diverse conditions in three different rice cultivation seasons. Recently, the concentration of CH_4 in the atmosphere of Bangladesh has been shown to be quite high (Clark et al., 2021). Rice paddies are believed to be one of the major sources of CH_4 emissions in Bangladesh. To reduce the CH_4 emission from rice fields in Bangladesh, customized management practices are needed. However, the number of researches on CH_4 reduction from rice fields in Bangladesh is low making it difficult to formulate strategic policies for its reduction. Nevertheless, the results of global studies can be customized to the rice-growing conditions in Bangladesh. Here, we examined the mitigation potentials of CH_4 emission under different management practices using a statistical (Gaussian) model and bootstrapping technique. Further, the adoptability of these management practices in Bangladesh was evaluated to identify suitable management practices.

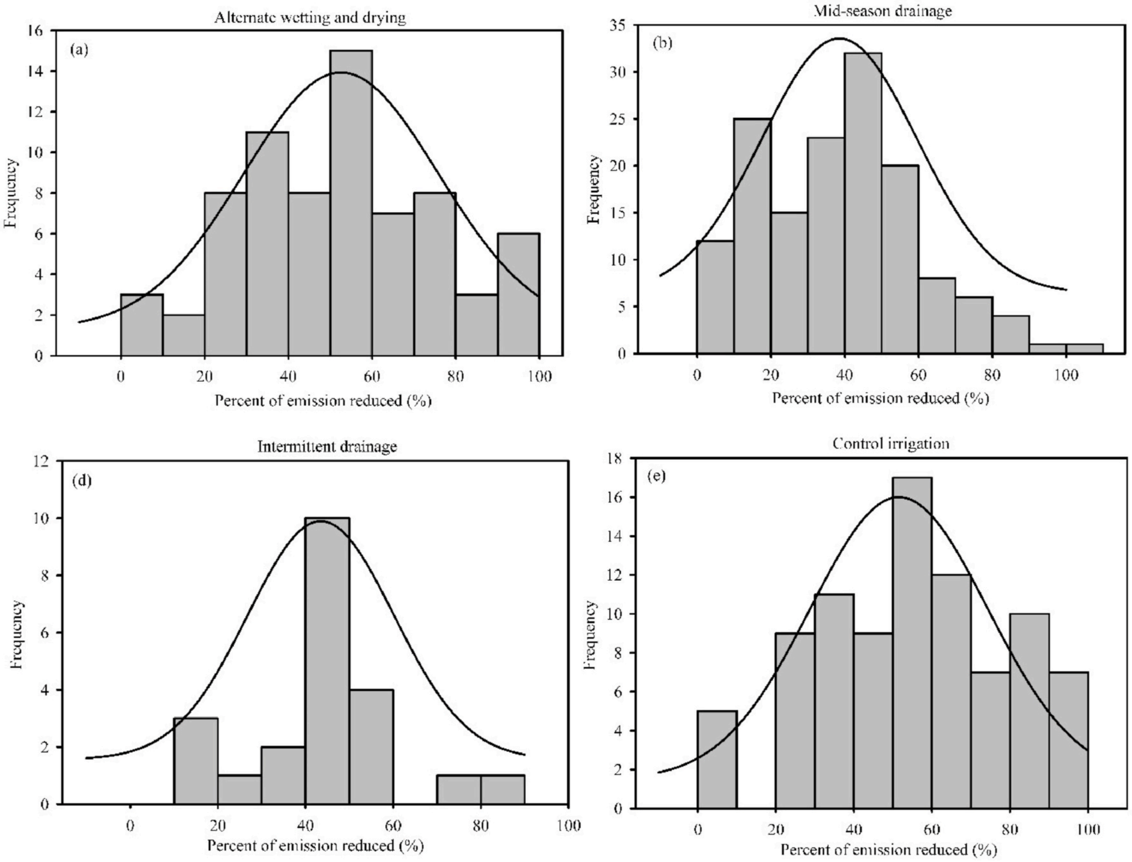

Fig. 1. Estimation of mean CH_4 emission reduction using Guassian model fitting to literature data.

2. Methodology

2.1. Data collection

A literature survey of peer-reviewed publications was carried out using Web of Science, Scopus, and Google Scholar. The literature search was restricted to peer-reviewed articles that were published before July 2021. While searching, keywords used for the initial searching included CH_4 reduction and management practices, *i.e.*, alternate wetting and drying, intermittent drainage, mid-season drainage, control irrigation, straw management, amendment input, compost, farmyard manure (FYM), nitrogen fertilizer input, no-tillage, biochar, herbicide application, symbiosis ecosystem, direct seeding, and rice variety. In total, we found 198 studies reporting 1052 observations. The data were categorized into five different management practices such as water, organic, and inorganic fertilizer management, crop establishment method, and different agronomic practices (Table 1 and supporting information, SI). Data on individual management practices were also separated. The fraction of CH_4 reduction with a specific management practice was calculated relative to their control treatment (Table 1).

2.2. Gaussian model

A Gaussian model to the literature data was fitted on the fraction of CH_4 reduction using SigmaPlot (Sigma Plot 11.0) to determine the mean CH_4 emission reduction and its associated error margin (Mia et al., 2020). The Gaussian equation is given as follows:

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{\left\{\frac{0.5(x-\mu)^2}{\sigma}\right\}} \quad \text{Eq.1}$$

where x is the observation, and the μ and σ are the mean and standard deviation of the population.

An example of the model fitting is presented in Fig. 1 while all other fitted data can be found in the supporting information (Figs. S5, S6, S7, and S8). When the number of observations was low and data did not meet the assumption (i.e., normal distribution) of Gaussian model fitting, we followed bootstrapping method to estimate the mean and associated error margin (details can be found in SI) (Hesterberg, 2011). Moreover, we compared our model fitting with analysis of variance (ANOVA) that provided reasonable estimates (Fig. S9).

2.3. Statistical analysis

One-way ANOVA was used to examine the statistically significant difference in the effectiveness between major management practices while Tukey's HSD test ($\alpha = 5\%$) was applied to separate the means.

2.4. Adaptability analysis

An index-based assessment was applied to analyze the adoptability of different CH_4 emission reduction technologies, *i.e.*,

$$\text{Adoptability index} = \sum \left(\textit{Technology availability}, \textit{ soil and land type suitability}, \textit{ climatic suitability}, \textit{ and farmers}' \textit{ ability to use a techonology}\right)$$

For this assessment, a total of 100-point adoptability score was applied whereas a 25% score was used for each of the criteria. The method of assessment can be found in SI (S4).

2.5. Description of rice cultivation in Bangladesh

In Bangladesh, rice is grown in three possible rice growing seasons namely *Aus, Aman,* and *Boro* (Siddique et al., 2016) while different rice

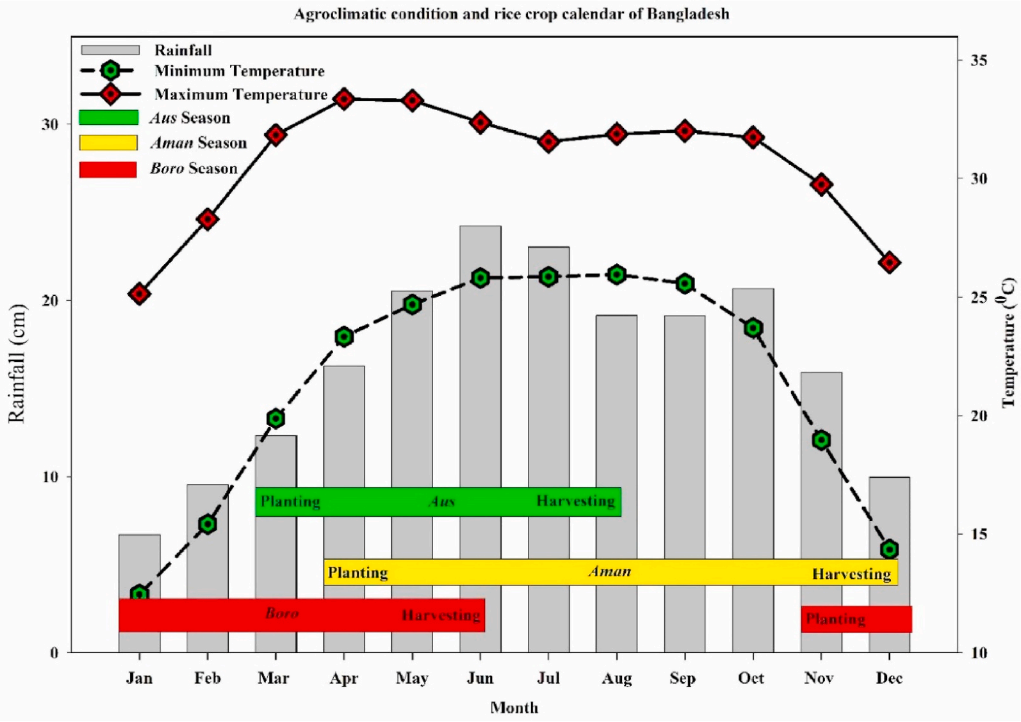

Fig. 2. Rice growing seasons in Bangladesh with their agro-climatic conditions.

varieties, *i.e.,* local, high yielding variety (HYV), and hybrid are cultivated. Different rice cultivars are adapted to different rice ecosystems. The rice grown in different ecosystems are discussed below-

2.5.1. *Aus rice*

Aus is the pre-monsoon upland rice-growing season where rice is usually cultivated under rainfed conditions. The temperature of this rice-growing season is high (Fig. 2) and rainfall is sporadic. *Aus* rice is cultivated following broadcasting (direct seeding) and transplanting techniques. Usually, local cultivars are broadcasted between February and March after the pre-monsoon shower and harvested between June and July in high land to medium high lands while HYV is transplanted in the high land to lowlands in April and harvested in June and July (Shelley et al., 2016). However, the coverage of *Aus* rice is only ~9% (1.2 million ha) (BBS, 2020a). Of the total *Aus* cultivation area, modern varieties cover 89% and local varieties occupy 11%. The production of rice grown in *Aus* season is about 3.7 million MT which is ~7.5% of total production. The share of modern varieties and local varieties is 94% and 6%, respectively.

2.5.2. *Aman rice*

The monsoon-season rainfed rice is known as *Aman*, which is the most dominant rice in terms of coverage. *Aman* rice is grown between June to December when most of the growing period remains flooded although at the late growing period the rice fields may get dried (Uddin et al., 2019) (Fig. 2). Similar to *Aus*, both local and modern *Aman* varieties are mostly cultivated following transplanting technique although local *Aman* is grown following broadcasting technique at a limited scale. However, the coverage of modern varieties (HYV and hybrid) is large with more than 80% of *Aman* growing area while total coverage is 5.5 million ha and production is about 14.2 million MT (BBS, 2020b).

2.5.3. *Boro season*

Boro rice is cultivated in a range of lands from low-lying waterlogged lands to high lands between December and June. In the *Boro* season, low temperature prevails at the early stage while the temperature increases with time reaching the maximum at the end of the season (Fig. 2) (Mosleh and Hassan, 2014; Sarker et al., 2017). Rice cultivation in the *Boro* season is quite diverse since local landraces, HYV, and hybrid are all cultivated in this season. Generally, local landraces are usually cultivated in low-lying lands where floodwater accumulates during the rainy season and remains waterlogged until the end of the rice-growing season. On the other hand, the HYV and hybrid varieties are grown in medium highland to very lowland with irrigation (BBS, 2019). The total coverage of *Boro* rice is 4.7 million ha and production is about 19.6 million MT (BBS, 2020c). In contrast to *Aman*, the coverage of HYV and hybrid varieties is 79% and 20%, respectively of total *Boro* cultivation area. The average yield of HYV and hybrid is relatively estimating at 3.98 and 4.40 t ha^{-1}, respectively (BBS, 2020b).

3. Results and discussion

3.1. *Methane emission from rice fields-mechanisms and management practices*

3.1.1. *Methane production and emission*

CH_4 is produced in the rice field through various processes. The most important process is the microbial breakdown of organic compounds under anaerobic conditions, which is usually maintained in rice fields (Oremland, 1988). In anaerobic conditions, methanogenic bacteria utilize carbon substrates and produce CH_4 following the equations shown below. A number of intermediate products (*e.g.,* H_2/CO_2, formate, methanol, methylamines, acetate) is also produced during these biochemical conversions (Le Mer and Roger, 2001; Yao et al., 1999).

CO_2 is reduced by H_2 to CH_4

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Or CH_4 can be emitted through the reduction of acetate

$$CH_3COO^- + H^+ \rightarrow CO_2 + CH_4$$

And a summary could be written as:

$$2\,(CH_2O) \rightarrow CO_2 + CH_4$$

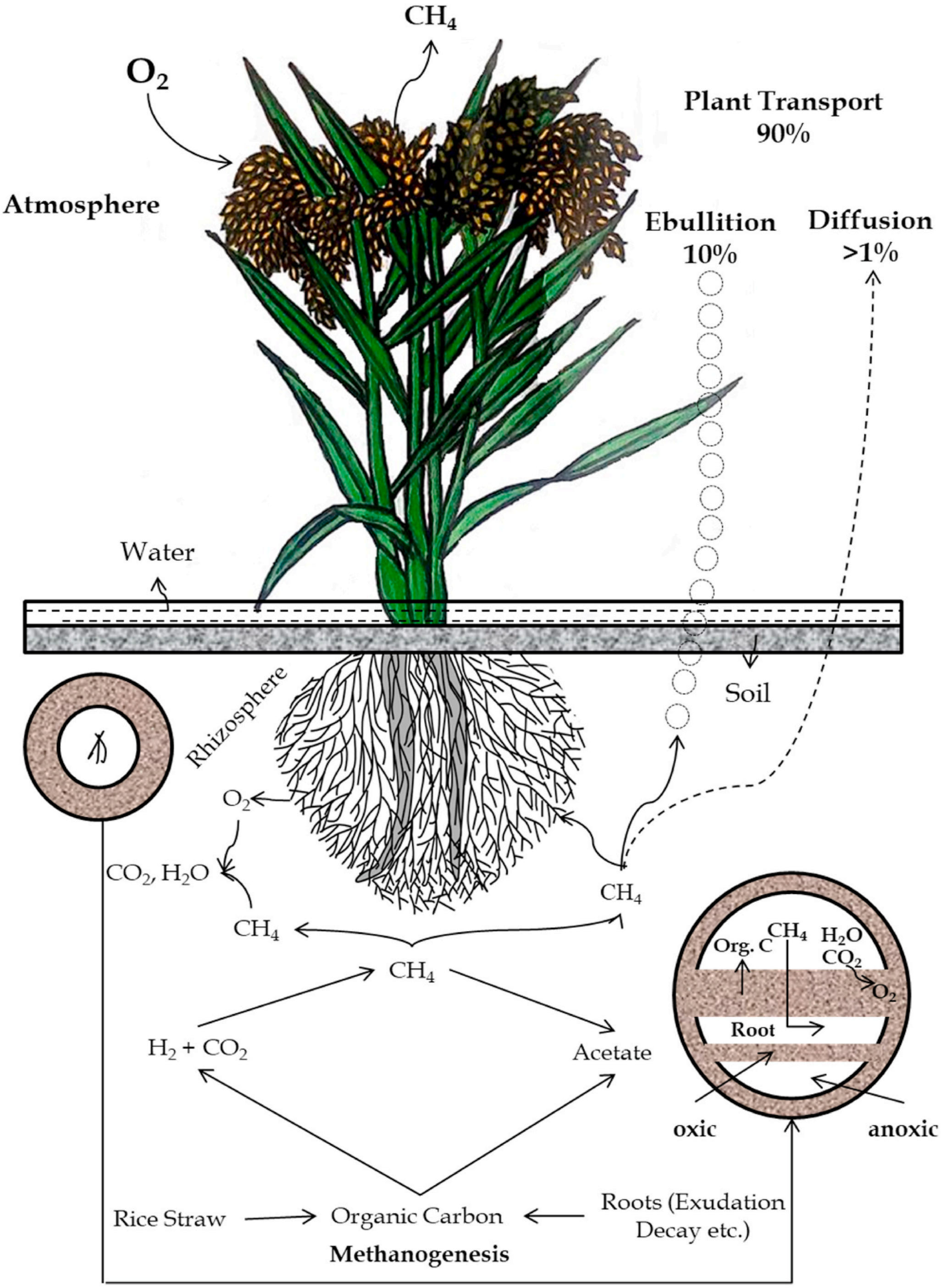

Fig. 3. Methane production, oxidation and emission pathways from rice fields (synthesized following Holzapfel-Pschorn and Seiler (1986)).

When the rice field is converted from anaerobic to aerobic conditions, these methanogenic bacteria can survive. These organisms start to multiply when the field is re-flooded (Fetzer et al., 1993; Fukui and Takii, 1990).

CH_4 is emitted from rice paddies to the atmosphere via three pathways *i.e.,* ebullition, diffusion, and plant mediated transport (Fig. 3) (Holzapfel-Pschorn et al., 1986; Schütz et al., 1989). Among the three pathways of CH_4 emission from rice field, plant-mediated transport is the primary mechanism for CH_4 transport from soil to the atmosphere and contribute around 90% of total CH_4 emission (Akinbile et al., 2012; Khosa et al., 2010). CH_4 ebullition (gas transport via gas bubbles) occurs only during the early growth stages of rice accounting for ~10% of the total emission (Rajkishore et al., 2015; Sandin, 2005). The diffusion of CH_4 from a rice field in the atmosphere is relatively small estimating only up to 2%.

3.2. Estimation of reduction potentials of CH_4 emission

3.2.1. Reduction potentials of CH_4 emission for different water management practices

Different water management practices were compared to the continuous flooding treatment (control). Our estimate showed that water management practices reduced area scaled CH_4 emission on average by 46.53% (Table 2). Among the four water management

Table 2

Estimated CH_4 emission reduction potentials of different management practices (data used from 198 publications).

Management practices	Sub-category	Number of observations		% of emission reduction (SD)	% of yield-scale emission reduction (SD)	Mechanisms involved
		Area-scaled	Yield scaled			
Water management	Alternate wetting and drying	71	51	52.59 (23.22)	55.19 (21.43)	−Creates oxic condition into the rice soil −Suppressed the activities of methanogenesis −Facilitates O_2 diffusion into the soil −Increase soil redox potential (Eh)
	Mid-season drainage	147	98	38.54 (21.00)	43.50 (19.13)	
	Intermittent drainage	22	7	43.47 (16.66)	45.80 (1.90)	
	Controlled irrigation	79	48	51.52 (22.70)	52.30 (20.79)	
Overall		319	204	46.53 (20.90)^{A}	49.20 (15.81)^{A}	
Inorganic fertilizer management	N application with amendment inputs (silicate slag, phosphogypsum, coal ash etc.)	93	49	14.89 (9.58)	26.27 (12.54)	−Increases aeration and stabilization of soil C −Improves soil Eh −Higher content of active iron oxides −Increases sulphate and nitrate ionic compound
	Nitrogen addition at 100–250 kg ha^{-1}	210	152	38.04 (2.31)	41.01 (19.67)	−Enhances methanotroph activity and population
	Urea deep placement	18	10	25.53 (11.74)	36.06 (12.25)	−Stimulates CH_4 oxidation by soil methanotrophs
	Ammonium sulphate application	17	12	44.00 (20.81)	48.99 (16.83)	−Enhances the competition for substrate between methanogens and sulphate reducing bacteria
Overall		338	223	30.61 (11.11)^{A}	38.07 (13.23)^{A}	
Crop establishment method	No-tillage	79	47	38.69 (3.56)	41.76 (24.38)	−Increases bulk density of topsoil −Prolongs CH_4 diffusion −Increases CH_4 oxidation
	Direct seeding	129	97	49.88 (28.40)	53.92 (23.08)	−Creates aerobic conditions −Reduces diffusion of CH_4 gas
Overall		208	144	44.29 (15.98)^{A}	47.84 (23.73)^{A}	
Organic fertilizer management	Biochar	31	21	39.76 (32.95)	32.58 (15.40)	−Improves soil aeration with its porous structure −Buffer soil redox potential −Changes in the soil N cycle −Increase ammonia-oxidizing archaea and bacteria −Decrease soil dissolved organic carbon
	Composted straw incorporation	13	6	46.50 (11.16)	41.15 (11.06)	−Converts the organic substrates into a humus-like material
	Composted FYM application	15	14	48.48 (4.47)	56.59 (5.79)	
	Straw incorporation in off-season	11	11	44.14 (7.48)	47.91 (2.67)	−Ensures aerobic decomposition of organic substrate
Overall		70	52	44.72 (14.01)^{A}	49.08 (6.59)^{A}	
Other agronomic practices	Herbicide application	20	10	30.95 (4.87)	33.87 (5.56)	−Increase the soil redox potential −Reduces methanogens population
	Symbiosis ecosystem	15	7	32.13 (6.96)	36.78 (3.90)	−Accelerates O_2 diffusion to soil −Increases aerobic organisms −Increases soil redox potential
	Rice variety that reduces methane emission	72	47	43.11 (28.55)	43.33 (23.25)	−Increases O_2 diffusion with larger root surface −Provies greater yield potential −Matures early
Overall		107	64	35.40 (13.46)^{A}	37.99 (10.94)^{A}	

Different letters indicate significant differences at the 5% level of probability.

practices, alternate wetting and drying were the most efficient (a 52.59% reduction) practice in reducing area-scaled CH_4 emission (Table 2). Controlled irrigation was also almost equally efficient in CH_4 emission reduction (51.52%) while the estimated reduction for intermittent drainage and mid-season drainage practices were 43.47% and 38.54%, respectively. The overall yield-scaled CH_4 reduction was estimated at 55.19%, a ~9% more reduction than area-scaled CH_4 emission while similar trends were followed for all subclasses of water management practices. These reductions were primarily attributed to the creation of aerobic conditions in the rice field through facilitating oxygen (O_2) diffusion from the atmosphere into the soil. An improvement in aeration could increase soil reduction potential (Eh), and shift the soil microbial community from methanogen to methanotrophs with consequences for CH_4 reduction (Fig. S1). Although different water management practices can increase in aeration into soil and thus, effectively reduce CH_4 emission, it could increase CO_2 and N_2O emission substantially (Islam et al., 2020; Liu et al., 2019). Therefore, the trades-off between CH_4 reduction and CO_2 and N_2O emission should carefully be considered for estimating and adopting any water management strategies since the net emission factor of a management practice may not be carbon negative. In our study, we did not consider these trades-off between emissions of CH_4 and other GHGs.

3.2.2. *Reduction potentials of CH_4 emission for different fertilizer management practices*

The type, rate, and mode of fertilizer application in rice can significantly affect CH_4 emission. Across all studies, organic matter management substantially reduce area- and yield-scaled CH_4 emission by ~45% and 49%, respectively than control treatments. Composted FYM reduced area-scaled CH_4 emission by 48.48% than the fresh application of FYM while this reduction was 46.50% and 44.14%, respectively when straw was incorporated after composting and in the off-season instead of its application in rice growing season (Table 2). A similar trend was observed in yield-scaled CH_4 emission. However, the yield-scaled CH_4

Table 3
Suitability analysis of CH_4 emission reduction practices for rice cultivation in *Boro* season in Bangladesh.

Major management practices	Current practices (Based on IPCC, 2019 CH_4 emission inventories)	Practice can be adopted	Adaptability score for rice type		Remarks[a]
			Local	**HYV & Hybrid**	
In-season water management	Flooded irrigation −79% area under HYV Boro cultivation −20% area under hybrid Boro cultivation	Alternate wetting and drying	–	60	−Can be adopted in HL to MLL area
		Mid-season drainage	–	56	
		Intermittent irrigation	–	54	
		Control irrigation	–	54	
Pre-season water management	Flooded	Scopes are minimal	–		−Can be adopted to only high lands
	Short drainage <180 d	Scopes are minimal	–		
Organic fertilizer management	Straw incorporation −Local-Average 2.06% straw left in per ha −HYV and Hybrid-Average 1.70% left in per ha	Composted straw incorporation	54	68	−Can be adopted in all cultivated areas
		Straw incorporation in off-season	45	45	−Can be adopted in all cultivated areas
		Biochar	–	54	−Can be applied only to rice grown in HL to MLL
	Application of compost and FYM −average 2.5 t ha^{-1} applied	Composted FYM application	–	66	−Can be applied only to rice grown in HL to MLL
Inorganic fertilizer management	Application of urea in the split −Usually, urea is applied in 3 (three) splits. Average 87 kg ha-1 in every split.	Nitrogen addition at 150–250 kg ha^{-1}	52	54	−All cultivated area
		Urea deep placement (UDP)	42	63	−Can be applied only to rice grown in HL to MLL
		Ammonium sulphate application	–	58	−May depend on the availability and be applied only in the alkaline soils
		N application with amendment inputs (silicate slag, phosphogypsum, coal ash)	–	33	−Can be applied only to rice grown in HL to MLL
Crop establishment method	Tillage practices −99% of land in HYV and hybrid Boro	Non-puddled strip transplantation	–	51	−Can be applied to a small fraction of lands provided technological intervention. The use of a mechanical transplanter will quickly promote this technology
	Transplanting	Direct seeding in dry & wet soil	–	52	−Can be adopted in a larger fraction of lands provided associated technologies are available for better crop establishment and weed control.
Other agronomic practices	−Traditional land-races rice varieties	Cultivation of short duration and high-yielding rice varieties	46	41	−Modern varieties can be adopted while CH4 mitigating cultivars are not available yet
	−Modern rice varieties	Herbicide application	55	55	−Can be applied to HL to MLL area
		Symbiosis ecosystem	60	–	−MLL to VLL can be adopted

[a] Land classification based on the depth of flooding during monsoon; H-High lands (above flood level), MHL-Medium high lands (flooding depth 0–90 cm), MLL-Medium low lands (flooding depth 90–180 cm), LL-Low lands (flooding depth 180–270 cm), and VLL-Very low lands (flooding depth >290 cm).

emission was lower with biochar application compared to area-scaled emission. These changes in CH_4 emission after organic managements have mainly occurred due to the application of a non-labile form of organic matter (composted FYM and straw) and supply of organic matter (*i.e.,* straw) when soils are not anaerobic to form CH_4 (Nakajima et al., 2016). However, biochar application might have improved soil aeration by carrying air in its large pores while biochar could buffer soil redox potential, change microbial community and nutrient dynamics (Zhang et al., 2012).

Average across all studies, management of inorganic fertilizer reduced area and yield-scale CH_4 emission by 30.61% and 38.07%, respectively (Table 2). The area-scaled reduction was 44% when ammonium sulphate was applied instead of urea while application of N at an optimum rate (100–250 kg ha^{-1}) reduced it by 38.04% compared to no N amendment. Sulphate has been shown to reduce CH_4 emission by suppressing the methanogenesis and contributing to anaerobic CH_4 oxidation. This mainly happen due to the change of soil redox potential (Eh), pH, and possible toxicity to the CH_4 producing bacteria. Nitrogen application low rates promotes CH_4 emission (Fig. S2) while N application at higher rates (100–250 kg N ha^{-1}) diminishes it. Although, there are debates on the possible mechanism, NH_4^+ concentration in the soil solution shown to stimulate CH_4 oxidation in a range of conditions (Linquist et al., 2012). Moreover, the deep placement of N reduced area-scaled CH_4 emission by 25.53% compared to the surface application. When N is placed into the soil, it has been shown to stimulate CH_4 oxidation by soil methanotrophs (Liu et al., 2020) (Fig. S1). Compared to N application alone, N application with amendment inputs decreased CH_4 emission by 14.89%. The lower CH_4 emission from the amended paddy soil was due to an improvement in aeration, stabilization of soil C, and soil redox potential. Moreover, electron acceptors cites are increased since amendment inputs often carry active iron oxides, sulphate and nitrate ionic compounds (Wang et al., 2016; Yao et al., 2013).

3.2.3. Reduction potentials of CH_4 emission for different crop establishment methods

The results showed that direct seeded practices significantly decreased the area-scaled CH_4 emission by 49.88% while these practices reduced yield-scale emission by 53.92% (Table 2) compared to the conventional transplanting technique. In contrast, no-tillage reduced area-scale and yield-scale CH_4 emission by 38.69% and 41.76% respectively compared to conventional tillage. The reduction in CH_4 emission by no-tillage/minimum tillage was attributed to the shifting of methanogenesis to the methanotrophic process, reducing the diffusion of CH_4 from soils to the atmosphere (Cheng-Fang et al., 2012; Sapkota et al., 2015). In contrast, the direct dry seeding method may reduce the activity of CH_4-producing bacteria since rice is grown under aerobic conditions (Gupta et al., 2016).

3.2.4. Reduction potentials of CH_4 emission for different agronomic practices

Average across all studies, growing of HYV rice varieties reduced both area and yield-scaled CH_4 emission by 43%. This may be attributed to an enhanced O_2 diffusion through prolific growth of rice plants (Jiang et al., 2017). Compared to rice only culture, the symbiosis ecosystem such as combined rice-ducks/fish culture reduced CH_4 emission by ~32%, possibly because of accelerated air exchange between the soil and the atmosphere. Compared to without application, herbicide application (e.g., Butachlor) reduced CH_4 emission by ~30% by

Table 4

Suitability analysis of CH_4 emission reduction strategies for *Aus* rice cultivation in Bangladesh.

Major management practices	Current practices (Based on IPCC, 2019 CH_4 emission inventories)	Practice can be adopted	Adaptability score		Remarks[a]
			Local	HYV & Hybrid	
In-season water management	Regular Rainfed	Scopes are minimal	–	–	
Pre-season water management	Flooded	Scopes are minimal	–	–	
	Long drainage >180 d	Scopes are minimal	–	–	
Organic fertilizer management	Straw incorporation −Local-1.44% straw left in the field −HYV-0.76% left in the field	Composted straw incorporation	59	59	−Can be adopted to HL to MLL
		Straw incorporation in off-season	45	45	−Can be adopted to HL to MLL
		Biochar	38	38	−Can be adopted to HL to MLL
	−Application of compost and FYM −average 2.5 t ha^{-1} applied	Composted FYM application	59	59	−Can be adopted to HL to MLL
Inorganic fertilizer management	Application of urea in split −Applied urea in 3 (three) splits. Average 44 kg ha^{-1} in every split	Nitrogen addition at 150–250 kg ha^{-1}	61	59	All cultivated area
		Urea deep placement	–	55	−Can be adopted to HL to MLL
		N application with amendment inputs (silicate slag, phosphogypsum, coal ash)	54	54	−Can be adopted to HL to MLL
Crop establishment method	−Tillage practices	Non-puddled strip transplantation	65	65	−Can be adopted to HL to MLL
	−Transplanting	Direct seeding on dry & wet soil	63	57	−Can be adopted to HL to MLL
Other agronomic practices	−Traditional land-races rice varieties −Modern rice varieties	Cultivation of short duration and high-yielding rice varieties	–	41	Modern varieties can be adopted while CH_4 mitigating cultivars are not available yet.
		–	–	–	
	-Hand/mechanical weeding	Herbicide application	–	62	Can be applied to HL to MHL

[a] Land classification based on depth of flooding during monsoon; H-High lands (above flood level), MHL-Medium high lands (flooding depth 0–90 cm), MLL-Medium low lands (flooding depth 90–180 cm), LL-Low lands (flooding depth 180–270 cm), and VLL-Very low lands (flooding depth >290 cm).

inhibiting the growth of methanogens (Jiang et al., 2015).

3.3. Possible CH_4 emission strategies for Bangladesh

In Bangladesh, rice is cultivated in three different seasons under diverse conditions, and therefore, the adoption of CH_4 emission reduction technologies could also vary (detail can be found in SI). The possible methods are discussed below-

3.3.1. Boro season

Based on the suitability analysis of different management options, only a few management practices can be applied to local rice, grown in the *Boro* season (Table 3). For instance, pre-and in-season water management practices can hardly be possible to use since the local rice is mainly grown as deep-water rice in low and very low lands where the land remains flooded from June to December (i.e., pre and growing period of the rice). For similar reasons, no other crop establishment methods except transplanting (single or double) are possible to adopt for this rice cultivation. However, symbiotic techniques (e.g., rice-fish culture, rice-fish-duck culture) can be adopted to reduce CH_4 emissions from these wetlands (suitability score 60). In contrast to local rice, most of the CH_4 emission strategies can potentially be adapted to high yield variety (HYV) and hybrid since these rice is usually grown in high lands to medium high lands where flood water recedes before planting of these rice cultivars. For instance, management strategies including pre and in-season water management (such as alternate wetting and drying, mid-season drying, etc.), fertilizer management (organic and inorganic), and conservation tillage and crop establishment methods (e.g., direct seeding/direct dry seeding) can be adopted (Rahman et al., 2008). Among the management strategies, alternate wetting and drying, composted organic matter amendment (straw, and FYM), urea deep placement and application of ammonium sulphate seems most feasible

Table 5
Suitability analysis of CH_4 emission reduction strategies for *Aman* rice in Bangladesh.

Major management practices	Current practices (Based on IPCC, 2019 CH_4 emission inventories)	Practice can be adopted	Adaptability score		Remarks
			Local	HYV & Hybrid	
In-season water management	Regular rainfed	Scopes are minimal	–	–	
Pre-season water management	Flooded	Scopes are minimal	–	–	
Organic fertilizer management	Straw incorporation	Composted straw incorporation	59	61	−All cultivated area
	−Local-1.32% straw left in the field	Straw incorporation in off-season	38	40	−Can be used in HL to MHL
	−HYV-0.69% left in the field	Biochar	45	45	−All cultivated area
	Application of compost and FYM −average 2.5 t ha^{-1} applied	Composted FYM application	54	63	−Can be used in HL to MHL
Inorganic fertilizer management	Application of urea in split	Nitrogen addition at 150–250 kg ha^{-1}	59	59	−All cultivated area
	−Applied urea in 3 (three) splits.	Urea deep placement (UDP)	45	45	−Can be applied to MHL to MLL
	Average 57 kg ha^{-1} in every split.	Ammonium sulphate application	54	54	−Can be applied to MHL to MLL
		N application with amendment inputs (silicate slag, phosphogypsum, coal ash)	33	33	−Can be applied to MHL to MLL
Crop establishment method	Tillage practices	Scopes are minimal	–	–	
	Transplanting	Scopes are minimal	–	–	
Other agronomic practices	−Traditional land-races rice varieties −Modern rice varieties	Cultivation of short duration and high-yielding rice varieties	–	41	−Modern varieties can be adopted while CH4 mitigating cultivars are not available yet
		Herbicide application	62	59	−Can be applied to HL to MHL
	Conventional practices	Symbiosis ecosystem	57	57	−MLL area can be adopted

Land classification based on depth of flooding during monsoon; H-High lands (above flood level), MHL-Medium high lands (flooding depth 0–90 cm), MLL-Medium low lands (flooding depth 90–180 cm), LL-Low lands (flooding depth 180–270 cm), and VLL-Very low lands (flooding depth >290 cm).

technologies to adopt during *Boro* season since they got higher scores in our suitability analysis. For instance, composted straw incorporation received the highest score (68 out of 100) (Table 3). Altogether, it seems that the adoptability of any CH_4 reduction strategies largely depends on the land type since major management strategies including water management, crop establishment method, and fertilizer management have limited scope to use if the land remains flooded.

3.3.2. *Aus and Aman season*

In *Aus* and *Aman* season, there is little scope to reduce CH_4 emission through adopting water management strategies since these rice are grown as rain-fed while crop establishment method and fertilizer management could potentially be applied (Tables 4 and 5). In *Aus* season, direct drying seeding can be one of the important means to crop establishment since this rice is grown during the dry period of the year (March–June) (suitability score 63). In contrast, *Aman* rice is grown during monsoon, therefore, the scope of replacing transplanting with direct seeding is minimal. Because the land remains flooded. However, organic matter management after composting can be applied to both of the seasons equally while nitrogen fertilizer management (e.g., urea deep placement) can be adopted provided technologies are available at a reasonable cost (Ali et al., 2008, 2012). Moreover, symbiotic techniques (rice-fish/duck culture) can be applied in the medium high land to low lands in both of the seasons with more feasibility during the *Aman* season. Although there has been significant progress in modern rice cultivars adoption (more than 99% in *Boro* season, 81% in *Aman* season, and 88% in *Aus* season), there are still some scopes to increase coverage of modern varieties that could potentially reduce yield normalized CH_4 emission (BBS, 2020a, b, c).

4. Limitation of the study and future research directions

Although this study synthesized a large data pool for generalizing the effects, it would be more useful if it was possible to assess each of the management strategies in relation to diverse rice-growing zones of Bangladesh. However, we tried to synthesize the suitability of a few potential technologies (S5). Moreover, research is needed to examine the suitability of proposed methods under the conditions of Bangladesh before advocating their large-scale adoption.

5. Conclusions

CH_4 is one of the most potent greenhouse gases that is emitted from rice fields. Hundreds of studies are conducted for identifying suitable technologies to mitigate CH_4 emission. Our synthesis of literature data showed that water management, organic matter management, and reduced tillage practice are the most effective methods for CH_4 emission reduction. When these technologies are customized to the situation of Bangladesh, water management and crop establishment methods seem most feasible. Altogether, our study provides fundamental insights into global CH_4 reductions strategies with their customization to the context of Bangladesh.

Credit author statement

Milton Kumar Saha: Conceptualization, Methodology, Software, Data Visualization, Writing, Editing; Shamim Mia: Conceptualization, Methodology, Software, Writing, Editing and Response to Reviewers Comments; AKM Abdul Ahad Biswas: Conceptualization, Methodology, Supervision; Md. Abdus Sattar: Conceptualization, Methodology, Supervision; Abdul Kader: Software, Editing, Writing; Zhixiang Jiang: Software, Editing, Writing

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.

Acknowledgments

We would like to thank all authors whose work is included in the analysis, especially those who provided us additional data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.114755.

References

Akinbile, C.O., Yusoff, M.S., Haque, A.A.M., Maskir, N.S., 2012. An appraisal of methane emission of rice fields from Kerian Agricultural Scheme in Malaysia. Res. J. Environ. Sci. 6, 107–117. https://doi.org/10.3923/rjes.2012.107.117.

Akter, M., Deroo, H., Kamal, A.M., Kader, M.A., Verhoeven, E., Decock, C., Boeckx, P., Sleutel, S., 2018. Impact of irrigation management on paddy soil N supply and depth distribution of abiotic drivers. Agric. Ecosyst. Environ. 261, 12–24. https://doi.org/10.1016/j.agee.2018.03.015.

Ali, M., Farouque, M., Haque, M., Ul Kabir, A., 2012. Influence of soil amendments on mitigating methane emissions and sustaining rice productivity in paddy soil ecosystems of Bangladesh. J. Environ. Sci. Nat. Res. 5, 179–185. https://doi.org/10.3329/jesnr.v5i1.11574.

Ali, M.A., Oh, J.H., Kim, P.J., 2008. Evaluation of silicate iron slag amendment on reducing methane emission from flood water rice farming. Agric. Ecosyst. Environ. 128, 21–26. https://doi.org/10.1016/j.agee.2008.04.014.

Allen, L.H., Albrecht, S.L., Colón-Guasp, W., Covell, S.A., Baker, J.T., Pan, D., Boote, K.J., 2003. Methane emissions of rice increased by elevated carbon dioxide and temperature. J. Environ. Qual. 32, 1978. https://doi.org/10.2134/jeq2003.1978.

Aulakh, M.S., Wassmann, R., Bueno, C., Rennenberg, H., 2001. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. Plant Soil 230, 77–86. https://doi.org/10.1023/A:1004817212321.

Badr, O., Probert, S.D., O'Callaghan, P.W., 1991. Atmospheric methane: its contribution to global warming. Appl. Energy 40, 273–313. https://doi.org/10.1016/0306-2619(91)90021-O.

BBS, 2020a. Estimate of Major Crops: Aus 2019-2020. Statistics and Informatics Division (SID). Ministry of Planning Government, Government of the People's Republic of Bangladesh.

BBS, 2020b. Estimate of Major Crops: Aman 2019-2020. Statistics and Informatics Division (SID). Ministry of Planning Government, Government of the People's Republic of Bangladesh.

BBS, 2020c. Estimate of Major Crops: Boro 2019-2020. Statistics and Informatics Division (SID). Ministry of Planning Government, Government of the People's Republic of Bangladesh.

BBS, 2019. Yearbook of Agricultural Statistics-2019. Statistics and Informatics Division (SID). Ministry of Planning Government, Government of the People's Republic of Bangladesh.

Bhattacharyya, P., Roy, K.S., Neogi, S., Dash, P.K., Nayak, A.K., Mohanty, S., Baig, M.J., Sarkar, R.K., Rao, K.S., 2013. Impact of elevated CO_2 and temperature on soil C and N dynamics in relation to CH_4 and N_2O emissions from tropical flooded rice (Oryza sativa L.). Sci. Total Environ. 461–462, 601–611. https://doi.org/10.1016/j.scitotenv.2013.05.035.

Cai, Y., Zheng, Y., Bodelier, P.L.E., Conrad, R., Jia, Z., 2016. Conventional methanotrophs are responsible for atmospheric methane oxidation in paddy soils. Nat. Commun. 7, 1–10. https://doi.org/10.1038/ncomms11728.

Cheng-Fang, L., Dan-Na, Z., Zhi-Kui, K., Zhi-Sheng, Z., Jin-Ping, W., Ming-Li, C., Cou-Gui, C., 2012. Effects of tillage and nitrogen fertilizers on CH_4 and CO_2 emissions and soil organic carbon in paddy fields of central China. PLoS One 7, 1–9. https://doi.org/10.1371/journal.pone.0034642.

Ciais, Philippe, Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., 2013. Carbon and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK and New York, NY, USA, pp. 465–570.

Clark, A., Wu, J., Devnath, A., 2021. Mysterious Plumes of Methane Gas Appear over Bangladesh. BloombergQuint.

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

Fetzer, S., Bak, F., Conrad, R., 1993. Sensitivity of methanogenic bacteria from paddy soil to oxygen and desiccation. FEMS (Fed. Eur. Microbiol. Soc.) Microbiol. Ecol. 12, 107–115. https://doi.org/10.1111/j.1574-6941.1993.tb00022.x.

Frenzel, P., Rothfuss, F., Conrad, R., 1992. Oxygen profiles and methane turnover in a flooded rice microcosm. Biol. Fertil. Soils 14, 84–89. https://doi.org/10.1007/BF00336255.

Fukui, M., Takii, S., 1990. Survival of sulfate-reducing bacteria in oxic surface sediment of a seawater lake. FEMS (Fed. Eur. Microbiol. Soc.) Microbiol. Lett. 73, 317–322. https://doi.org/10.1016/0378-1097(90)90765-I.

Guo, J., Song, Z., Zhu, Y., Wei, W., Li, S., Yu, Y., 2017. The characteristics of yield-scaled methane emission from paddy field in recent 35-year in China: a meta-analysis. J. Clean. Prod. 161, 1044–1050. https://doi.org/10.1016/j.jclepro.2017.06.073.

Gupta, D.K., Bhatia, A., Kumar, A., Das, T.K., Jain, N., Tomer, R., Malyan, S.K., Fagodiya, R.K., Dubey, R., Pathak, H., 2016. Mitigation of greenhouse gas emission from rice–wheat system of the Indo-Gangetic plains: through tillage, irrigation and fertilizer management. Agric. Ecosyst. Environ. 230, 1–9. https://doi.org/10.1016/j.agee.2016.05.023.

Hesterberg, T., 2011. Bootstrap. Wiley Interdisciplinary Rev.: Comput. Stat. 3, 497–526. https://doi.org/10.1002/wics.182.

Holzapfel-Pschorn, A., Conrad, R., Seiler, W., 1986. Effects of vegetation on the emission of methane from submerged paddy soil. Plant Soil 92, 223–233. https://doi.org/10.1007/BF02372636.

Holzapfel-Pschorn, A., Seiler, W., 1986. Methane emission during a cultivation period from an Italian rice paddy. J. Geophys. Res. 91, 11803. https://doi.org/10.1029/JD091iD11p11803.

Islam, S.M.M., Gaihre, Y.K., Islam, M.R., Akter, M., Al Mahmud, A., Singh, U., Sander, B. O., 2020. Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh. Sci. Total Environ. 734, 139382. https://doi.org/10.1016/j.scitotenv.2020.139382.

Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., van Groenigen, K.J., Linquist, B., 2019. Water management to mitigate the global warming potential of rice systems: A global meta-analysis. Field Crop. Res. 234, 47–54. https://doi.org/10.1016/j.fcr.2019.02.010.

Jiang, J., Chen, L., Sun, Q., Sang, M., Huang, Y., 2015. Application of herbicides is likely to reduce greenhouse gas (N_2O and CH_4) emissions from rice-wheat cropping systems. Atmos. Environ. 107, 62–69. https://doi.org/10.1016/j.atmosenv.2015.02.029.

Jiang, Y., van Groenigen, K.J., Huang, S., Hungate, B.A., van Kessel, C., Hu, S., Zhang, J., Wu, L., Yan, X., Wang, L., Chen, J., Hang, X., Zhang, Y., Horwath, W.R., Ye, R., Linquist, B.A., Song, Z., Zheng, C., Deng, A., Zhang, W., 2017. Higher yields and lower methane emissions with new rice cultivars. Global Change Biol. 23, 4728–4738. https://doi.org/10.1111/gcb.13737.

Khosa, M.K., Sidhu, B.S., Benbi, D.K., 2010. Effect of organic materials and rice cultivars on methane emission from rice field. J. Environ. Biol. 31, 281–285.

Kumar, M., Yadav, A.N., Saxena, R., Rai, P.K., Paul, D., Tomar, R.S., 2021. Novel methanotrophic and methanogenic bacterial communities from diverse ecosystems and their impact on environment. Biocatal. Agric. Biotechnol. 102005.

Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. Eur. J. Soil Biol. 37, 25–50. https://doi.org/10.1016/S1164-5563(01)01067-6.

Li, Z., Yagi, K., Sakai, H., Kobayashi, K., 2004. Influence of elevated CO_2 and nitrogen nutrition on rice plant growth , soil microbial biomass , dissolved organic carbon and dissolved CH_4. Plant Soil 258, 81–90. https://doi.org/10.1023/B:PLSO.0000016538.28110.d8.

Liao, P., Sun, Y., Zhu, X., Wang, H., Wang, Y., Chen, J., Zhang, J., Zeng, Y., Zeng, Y., Huang, S., 2021. Identifying agronomic practices with higher yield and lower global warming potential in rice paddies: a global meta-analysis. Agric. Ecosyst. Environ. 322, 107663. https://doi.org/10.1016/j.agee.2021.107663.

Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., van Kessel, C., van Groenigen, K. J., 2012. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. Field Crop. Res. 135, 10–21. https://doi.org/10.1016/j.fcr.2012.06.007.

Liu, T.Q., Li, S.H., Guo, L.G., Cao, C.G., Li, C.F., Zhai, Z.B., Zhou, J.Y., Mei, Y.M., Ke, H.J., 2020. Advantages of nitrogen fertilizer deep placement in greenhouse gas emissions and net ecosystem economic benefits from no-tillage paddy fields. J. Clean. Prod. 263 https://doi.org/10.1016/j.jclepro.2020.121322.

Liu, X., Zhou, T., Liu, Y., Zhang, X., Li, L., Pan, G., 2019. Effect of mid-season drainage on CH_4 and N_2O emission and grain yield in rice ecosystem: a meta-analysis. Agric. Water Manag. 213, 1028–1035. https://doi.org/10.1016/j.agwat.2018.12.025.

Lu, Y., Wassmann, R., Neue, H.U., Huang, C., Bueno, C., 2000. Methanogenic responses to exogenous substrates in anaerobic rice soils. Soil Biol. Biochem. 32, 1683–1690. https://doi.org/10.1016/S0038-0717(00)00085-7.

Mia, S., Alam, Md.R., Sattar, Md.A., Dijkstra, F.A., 2020. Nutrient loading in the river systems around major cities in Bangladesh: A quantitative estimate with consequences and potential recycling options. Statistics for Data Science and Policy Analysis. Springer Singapore, pp. 111–128.

Minami, K., 1994. Methane from rice production. Fert. Res. 37, 167–179. https://doi.org/10.1007/BF00748935.

Mosleh, M., Hassan, Q., 2014. Development of a remote sensing-based "Boro" rice mapping system. Rem. Sens. 6, 1938–1953. https://doi.org/10.3390/rs6031938.

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 659–740.

Nakajima, M., Cheng, W., Tang, S., Hori, Y., Yaginuma, E., Hattori, S., Hanayama, S., Tawaraya, K., Xu, X., 2016. Modeling aerobic decomposition of rice straw during the off-rice season in an Andisol paddy soil in a cold temperate region of Japan: effects of soil temperature and moisture. Soil Sci. Plant Nutr. 62, 90–98. https://doi.org/10.1080/00380768.2015.1121116.

Oremland, R.S., 1988. Biogeochemistry of Methanogenic Bacteria. Biology of Anaerobic Microorganisms.

Oyediran, G., Adachi, K., Senboku, T., 1996. Effect of application of rice straw and cellulose on methane emission and biological nitrogen fixation in a subtropical paddy field: I. methane emission, soil-ara, and rice plant growth. Soil Sci. Plant Nutr. 42, 701–711. https://doi.org/10.1080/00380768.1996.10416617.

Rahman, L., Islam, M.N., Rahman, M.S., Islam, M.S., 2008. Plant Varieties of Bangladesh: Morphological and Molecular Characterization. Seed Wing. Ministry of Agriculture, Government of the People's Republic of Bangladesh.

Rajkishore, S.K., Vignesh, N.S., Doraisamy, P., Maheswari, M., 2015. Methane emission from rice ecosystems : 100 Years of research. Ecoscan 9, 183–195.

Sandin, S., 2005. Present and Future Methane Emissions from Rice Fields in Đ Ông Ng Ạ C Commune. Göteborg University, Hanoi, Vietnam.

Sapkota, T.B., Jat, M.L., Shankar, V., Singh, L.K., Rai, M., Grewal, M.S., Stirling, C.M., 2015. Tillage, residue and nitrogen management effects on methane and nitrous oxide emission from rice–wheat system of Indian Northwest Indo-Gangetic Plains. J. Integr. Environ. Sci. 12, 31–46. https://doi.org/10.1080/1943815X.2015.1110181.

Sarker, M.A.R., Alam, K., Gow, J., 2017. Performance of rain-fed Aman rice yield in Bangladesh in the presence of climate change. Renew. Agric. Food Syst. 1–9 https://doi.org/10.1017/S1742170517000473.

Schütz, H., Seiler, W., Conrad, R., 1989. Processes involved in formation and emission of methane in rice paddies. Biogeochemistry 7, 33–53. https://doi.org/10.1007/BF00000896.

Shelley, I.J., Takahashi-Nosaka, M., Kano-Nakata, M., Haque, M.S., Inukai, Y., 2016. Rice cultivation in Bangladesh: present scenario, problems, and prospects. J. Int. Cooperation Agri. Dev. 14, 20–29.

Siddique, M.A., Khalequzzaman, M., Islam, M.M., Fatema, K., Latif, M.A., 2016. Molecular characterization and genetic diversity in geographical indication (GI) rice (*Oryza sativa* L.) cultivars of Bangladesh. Bangladesh Rice J. 39, 1–11.

Smartt, A.D., Brye, K.R., Norman, R.J., 2016. Methane emissions from rice production in the United States — a review of controlling factors and summary of research. Greenhouse Gases. https://doi.org/10.5772/62025.

Sun, B.F., Zhao, H., Lü, Y.Z., Lu, F., Wang, X.K., 2016. The effects of nitrogen fertilizer application on methane and nitrous oxide emission/uptake in Chinese croplands. J. Integrative Agri. 15, 440–450. https://doi.org/10.1016/S2095-3119(15)61063-2.

Tyagi, L., Kumari, B., Singh, S.N., 2010. Water management - a tool for methane mitigation from irrigated paddy fields. Sci. Total Environ. 408, 1085–1090. https://doi.org/10.1016/j.scitotenv.2009.09.010.

Uddin, M.J., Hooda, P.S., Mohiuddin, A.S.M., Smith, M., Waller, M., 2019. Land inundation and cropping intensity influences on organic carbon in the agricultural soils of Bangladesh. Catena 178, 11–19. https://doi.org/10.1016/j.catena.2019.03.002.

Wang, B., Li, Y., Wan, Y., Qin, X., Gao, Q., Liu, S., Li, J., 2016. Modifying nitrogen fertilizer practices can reduce greenhouse gas emissions from a Chinese double rice cropping system. Agric. Ecosyst. Environ. 215, 100–109. https://doi.org/10.1016/j.agee.2015.09.008.

Wang, B., Xu, Y., Wang, Z., Li, Z., Guo, Y., Shao, K., Chen, Z., 1999. Methane emissions from ricefields as affected by organic amendment, water regime, crop establishment, and rice cultivar. Environ. Monit. Assess. 57, 213–228. https://doi.org/10.1023/A:1006039231459.

Wang, Z.P., DeLaune, R.D., Patrick, W.H., Masscheleyn, P.H., 1993. Soil redox and pH effects on methane production in a flooded rice soil. Soil Sci. Soc. Am. J. 57, 382. https://doi.org/10.2136/sssaj1993.03615995005700020016x.

Wassmann, R., Aulakh, M.S., 2000. The role of rice plants in regulating mechanisms of methane missions. Biol. Fertil. Soils 31, 20–29. https://doi.org/10.1007/s003740050619.

Watanabe, A., Kimura, M., 1998. Effect of rice straw application on CH4 emission from paddy fields: IV. Influence of rice straw incorporated during the previous cropping period. Soil Sci. Plant Nutr. 44, 507–512. https://doi.org/10.1080/00380768.1998.10414474.

Wuebbles, D.J., Hayhoe, K., 2002. Atmospheric methane and global change. Earth Sci. Rev. 57, 177–210. https://doi.org/10.1016/S0012-8252(01)00062-9.

Xie, B., Zheng, X., Zhou, Z., Gu, J., Zhu, B., Chen, X., Shi, Y., Wang, Y., Zhao, Z., Liu, C., Yao, Z., Zhu, J., 2010. Effects of nitrogen fertilizer on CH4 emission from rice fields: multi-site field observations. Plant Soil 326, 393–401. https://doi.org/10.1007/s11104-009-0020-3.

XIong, Z.-Q., Xing, G.-X., Zhu, Z.-L., 2007. Nitrous oxide and methane emissions as affected by water, soil and nitrogen. Pedosphere 17, 146–155. https://doi.org/10.1016/S1002-0160(07)60020-4.

Yao, H., Conrad, R., Wassmann, R., Neue, H.U., 1999. Effect of soil characteristics on sequential reduction and methane production in sixteen rice paddy soils from China, the Philippines, and Italy. Biogeochemistry 47, 269–295. https://doi.org/10.1007/BF00992910.

Yao, Z., Zheng, X., Wang, R., Dong, H., Xie, B., Mei, B., Zhou, Z., Zhu, J., 2013. Greenhouse gas fluxes and NO release from a Chinese subtropical rice-winter wheat rotation system under nitrogen fertilizer management. J. Geophys. Res.: Biogeosciences 118, 623–638. https://doi.org/10.1002/jgrg.20061.

Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, Jinwei, Zheng, Jufeng, Zhang, X., Han, X., Yu, X., 2012. 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 Crop. Res. 127, 153–160. https://doi.org/10.1016/j.fcr.2011.11.020.

Zhang, B., Tian, H., Ren, W., Tao, B., Lu, C., Yang, J., Banger, K., Pan, S., 2016. Methane emissions from global rice fields: magnitude, spatiotemporal patterns, and environmental controls. Global Biogeochem. Cycles 30, 1246–1263. https://doi.org/10.1002/2016GB005381.

Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. Global Biogeochem. Cycles 19, 1–9. https://doi.org/10.1029/2004GB002401.

Global Monitoring Laboratory, 2021–. (Accessed 27 July 2021).