Management of Paddy Soil towards Low Greenhouse Gas Emissions and Sustainable Rice Production in the Changing Climatic Conditions

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Additional information is available at the end of the chapter

Abstract

Climate change is a vital environmental issue for the twenty-first century, which may significantly affect rice productivity and accelerate greenhouse gas emissions from paddy ecosystem, which is of great environmental concern which is of great environmental concern. Methane (CH_4) and nitrous oxide (N_2O) are the most important greenhouse gases due to their radiative effects as well as global warming potentials (GWPs). CH_4 and N_2O gases are simultaneously emitted from rice fields to the atmosphere due to their favorable production, consumption, and transport systems. The intensive rice farming system has been creating excessive pressure on rice fields to produce more rice for the expanding world population, thereby deteriorating soil fertility status and rice paddy ecosystem balance by stimulating more CO_2, CH_4, and N_2O fluxes to the atmosphere. The extreme climatic variables such as high light intensity, high water vapor or relative humidity, high temperature, and drought stress may badly suppress beneficial microbial activity, soil nutrients, and water availability to rice plant; eventually, rice yield may be decreased drastically, and simultaneously, greenhouse gas emissions could be increased significantly. In this situation, conservation tillage, water saving irrigation technique such as alternate wetting and drying, soil amendments with biochar, vermicompost, azolla-cyanobacterial mixture, recommended silicate slag, and phospho-gypsum with minimum NPKSZn fertilizer (IPNS) should be introduced to the field level farmers for sustainable rice production and mitigating greenhouse gas emissions.

Keywords: paddy soils, greenhouse gases, climate change, rice yield, GWPs
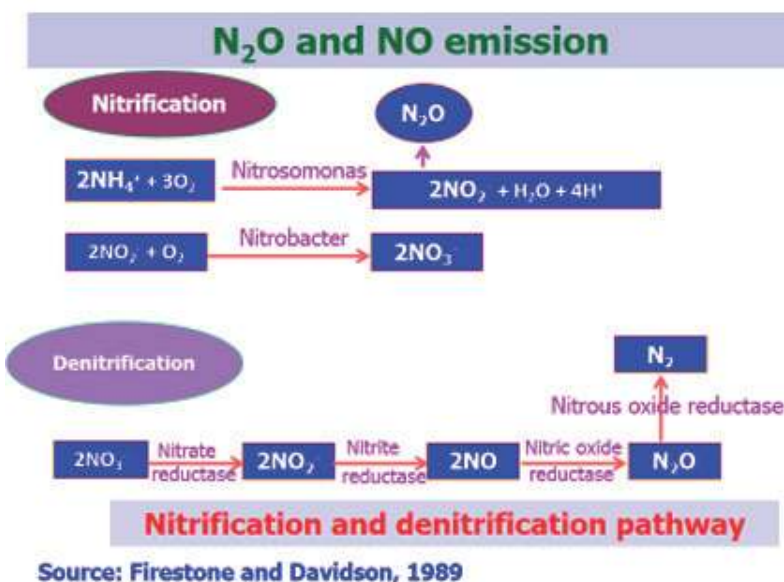
1. Introduction

World rice production especially in Southeast Asia and tropical Asia is highly vulnerable to climate change. Rice production systems contribute to global climate change through emissions of carbon dioxide (CO_2), methane (CH_4), and N_2O gases to the atmosphere and simultaneously
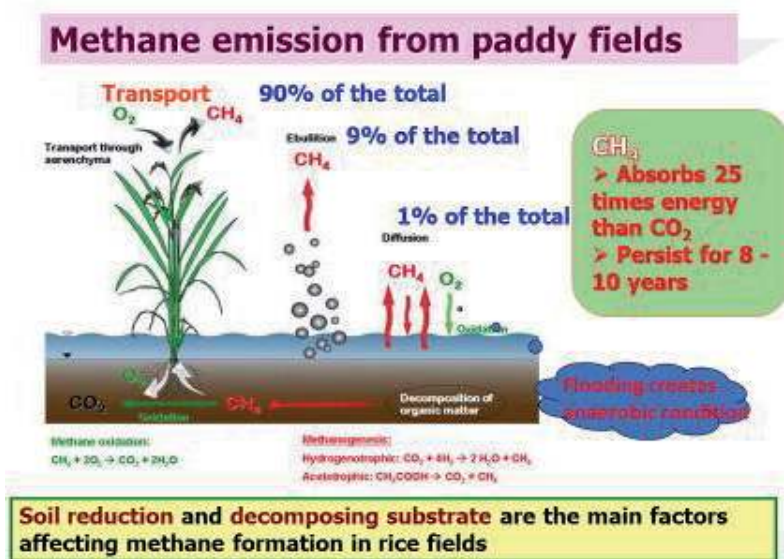
(a)

(b)

Figure 1. (a) Schematic diagram of methane production, oxidation, and emission from rice paddy field and (b) schematic diagram of N_2O, NO, and N_2 emissions from rice paddy field.

are affected by the changed climatic variables. Rice is the major cereal crop for more than half of the world's population and its production needs to be increased 40% by the end of the 2030s to meet the increasing demand for the expanding population [1], which may further accelerate CH_4 and N_2O emissions to the atmosphere [2]. In 2012, worldwide rice production covered 163 million ha of cropland, where approximately 80 million ha were managed under continuous flood irrigation and contributed to 75% of the world's rice production [3]. China and India, most densely populated countries in the world, account for 20.0 and 28.5% of the global rice area, respectively [4]. In China, approximately 90% of the rice fields are irrigated [5], while in India, more than 46% of the rice fields are irrigated [6]. Unfortunately, the irrigated rice farming acts as one of the main sources of anthropogenic CH_4 emission to the atmosphere [7]. Therefore, IRRI is promoting water-saving alternate wetting and drying techniques for improving water use efficiency, while reducing CH_4 production in the rice rhizosphere.

Rice paddy fields act as a source of greenhouse gases such as methane (CH_4) and nitrous oxides (N_2O) depending on soil organic matter status, land use and cropping intensity, irrigation water and drainage management practices, soil microbial populations and their activities, soil properties, and climatic variables. The management practices such as tillage operations, leveling, plant residue incorporation, irrigation frequency and standing water levels, drainage system, and organic and inorganic soil amendments followed in rice farming influence the amount of CH_4 and N_2O emitted to the atmosphere. Generally, CH_4 gas is produced under flooded or anoxic soil conditions (**Figure 1a**), while N_2O gas is produced through nitrification and denitrification processes depending on soil aerobic (oxygenated) and anaerobic conditions (**Figure 1b**).

Typically, N_2O emissions are low under flooded fields, while CH_4 emissions are high, a trade-off relationship observed which is largely dependent on paddy soil water level, redox status, soil organic matter content, and external sources of organic and inorganic soil amendments. Ali et al. reported that the total GWP of CH_4 and N_2O gases was decreased by 7–27% and 6–34% with calcium carbide, phospho-gypsum, and silicate fertilizer amendments under continuous and intermittent irrigations, respectively [8]. However, biochar amendments increased the overall GWP of CH_4 and N_2O gases, which simultaneously increased rice yield [8].

2. Climatic change and greenhouse gas emissions

Greenhouse gases (GHGs), mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), have been contributing to about 80% to the current global radiative forcing [9]. Agricultural activities contribute to approximately 20% of the present concentrations of atmospheric GHGs [10], especially the emissions of CH_4 and N_2O from paddy fields [9]. Methane (CH_4) and nitrous oxide (N_2O) are the two most important GHGs from agriculture, with global-warming potentials (GWP) of 25 and 298 CO_2-equivalents, respectively, on a 100-year time horizon. Apart from the water vapor, CH_4 is a major greenhouse gas contributing 20% toward global warming with almost 25-fold higher global warming potential than carbon dioxide [11]. The concentrations of atmospheric CH_4 and N_2O have increased from 722 and 270 ppb in the pre-industrial period to 1853 and 328.9 ppb in 2016, respectively [12]. China, the largest rice-producing country, accounts for about 28% of global rice production [4] and

the total CH_4 and N_2O emissions from paddy fields are estimated to be 6.4 Tgyr^{-1} and 180 Ggyr^{-1}, respectively [13]. Although the global estimates of CH_4 emission from rice cultivation vary within 20–150 $TgCH_4$ year^{-1}, the global average CH_4 is about 100 $TgCH_4$ year^{-1} [14] and may increase further due to the expansion of rice cultivation as well as intensification of rice agriculture for the increasing world population [15]. Therefore, it is very important to understand the mechanism of CO_2, CH_4, and N_2O exchange and their main controlling factors for developing appropriate strategies to mitigate GHG emissions.

3. Characteristics of paddy soils

Paddy soils are mostly alluvial soils and low humic gley soils (or Entisols and Inceptisols). In addition, vertisols, reddish-brown earths or Alfisols, red-yellow podzolic soils or Ultisols, and latosols or Oxisols are utilized for paddy rice cultivation. Paddy soils are found mainly on alluvial lands such as deltas and flood plains of big rivers, coastal plains, fans, and lower terraces. In general, paddy soils are resistant to erosion when they are terraced and there are ridges around the field, as measures to retain surface water. Paddy fields in the lowlands receive new sediments deposited from run-off that carries eroded topsoil down from the uplands, thus sustaining soil fertility and productivity. The paddy soils have medium to high organic matter (1.5–3.97 g/kg), available phosphorus (11.7–19.9 mg/kg), available potassium (61.6–132.9 mg/kg), and cation exchange capacity (15.5–33.1 cmol/kg). The most common practice in paddy rice cultivation is flooding or temporary water logging of the land surface. Soil redox potential (Eh) or electron activity in soil gradually decreases after flooding, which causes significant methane production at around −200 mV [16], and creates high risk of gaseous N losses through denitrification (**Figure 2**).
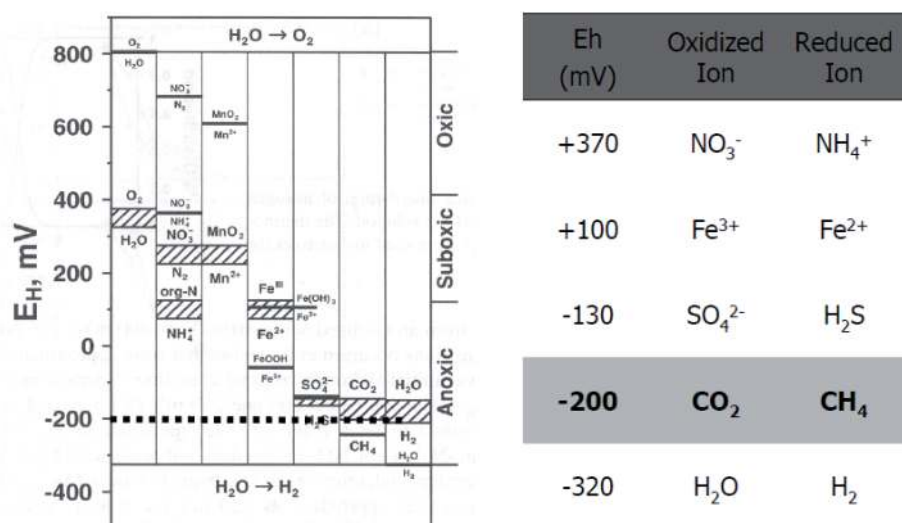
Figure 2. Paddy soil redox status, sequential reduction and oxidation of inorganic nitrogen, manganese, and iron in flooded soil, and methane gas formation [16].

In paddy fields, the kinetics of the reduction processes are strongly affected by the composition and texture of soil and its content of inorganic electron acceptors. After flooding, microbial reduction processes sequentially use NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} as electron acceptors, accompanied by the emission of the trace gases N_2O, N_2, H_2S, and CH_4 due to reduction-induced increasing pH-NH_3 (**Figure 2**). Microorganisms drive redox reactions in soil by using organic carbon and electron acceptors for their metabolic activities. Methane is produced at the terminal step under anaerobic decomposition of organic matter and due to the reduction of CO_2 into CH_4 in wetland soils. Soil Eh values decreased rapidly after flooding within 5–7 weeks then stabilized toward −200 to −240 mV and produced significant amount of methane [17]. High concentrations and fluxes of dissolved organic matter (DOM) in paddy soils from plant debris trigger microbial activity and thus the emission of greenhouse gases. Therefore, the objectives of this thematic topic are to highlight the feasible field management practices for sustainable rice production and recommend appropriate strategies to mitigate GHG emissions from paddy soils in the changing climate.

4. Materials and methods

4.1. Measurement of CH_4 and N_2O emissions from the paddy field

The static closed chamber technique was used to measure CH_4 and N_2O emissions during rice growing period [18]. The chambers were made of PVC and consisted of two parts: an upper transparent compartment (100 cm height, 30 cm width, and 30 cm length) was placed on a permanently installed bottom collar (10 cm height, 30 cm width, and 30 cm length). Three replicate chambers were used. Each of these chambers was placed in each plot. Each chamber was installed with a battery-operated fan to homogenize the air inside the chamber headspace, a thermometer to monitor temperature changes during the gas-sampling period, and a gas-sampling port with a neoprene rubber septum at the top of the chamber for collecting gas samples from the headspace. Gas samples were collected twice daily (**Figure 3**), sampling during 9.00 am to 12.00 and 12.30 pm to 3.30 pm. A 100-mL plastic syringe equipped with a 3-way stopcock was used to collect gas samples from the chamber headspace 0, 15, and 30 min after chamber deployment. Gas samples were collected twice a day. The collected gas samples were immediately transferred to 100-mL air-evacuated aluminum foil bags (Delin Gas Packaging Co., Ltd., Dalian, China) sealed with a butyl rubber septum and transported to the laboratory for analysis of CH_4 and N_2O concentrations by Gas Chromatograph (**Figure 4**).

4.2. Determination of CH_4 and N_2O concentrations in the headspace air samples

CH_4 and N_2O concentrations in the headspace air samples were determined by a gas chromatograph (Shimadzu GC-2014, Kyoto, Japan) packed with a Porapak Q column (2 m length, 4 mm OD, 80/100 mesh, stainless steel column) (**Figure 4**). A flame ionization detector (FID) and an electron capture detector (ECD) were used for the determination of CH_4 and N_2O concentrations, respectively. Helium (99.9% purity) was used as a carrier gas (30 ml min^{-1}), and a make-up gas (95% argon and 5% CH_4) was used for the ECD. Calibration was conducted with 1.01, 7.99, and 50.5 μl CH_4 l^{-1} in He and 0.2, 0.6, and 1.0 μl N_2O l^{-1} in He (CRM/RM Information Center of China) as primary standards.

Figure 3. (A) Prototype and (B) gas sampling in rice planted paddy field through the closed chamber technique [18].

4.3. Estimation of CH$_4$ and N$_2$O fluxes, GWPs, and greenhouse gas intensity (GHGI)

CH$_4$ and N$_2$O fluxes from the paddy field were expressed as the increase/decrease in CH$_4$ and N$_2$O mass per unit surface area per unit time. CH$_4$ and N$_2$O fluxes were estimated by the following equation [19]: $F = MV*dc/dt*H*(273/(273 + T))$; where F is the CH$_4$ or N$_2$O flux (mg CH$_4$ m^{-2} h^{-1} or µgN$_2$O m^{-2} h^{-1}), M is the molar mass of the respective gas (16 for CH$_4$ and 44 for N$_2$O), V is the molar volume of air at a standard state (22.4 l mol^{-1}), dc/dt is the change in headspace CH$_4$ and N$_2$O concentration with time (µmolmol h^{-1}), H is the height of the chamber above the water surface (m), and T is the air temperature inside the chamber (°C).

Figure 4. Injecting air samples into GC for determination of CH_4 and N_2O concentrations.

The total CH_4 or N_2O emission from paddy fields was the summation of methane and nitrous oxide emissions in all growth stages of rice crop.

4.4. Estimation of GWPs of CH_4 and N_2O

To estimate the GWP, CO_2 is typically taken as the reference gas, and an increase or reduction in emission of CH_4 and N_2O is converted into "CO_2-equivalents" by means of their GWPs. In this study, we used the IPCC factors to calculate the combined GWPs for 100 years [GWP = $(25 × CH_4) + (298 × N_2O)$], kg CO_2-equivalents ha^{-1} from CH_4 and N_2O under various agricultural practices. In addition, the greenhouse gas intensity (GHGI) was calculated by dividing GWP by grain yield for rice [20, 21].

5. Results and discussion

The mean rice statistics and cumulative methane emissions in the rice producing countries are presented in **Table 1.**

It is known that China, India, Indonesia, Bangladesh, and Vietnam have been playing a dominating role in total rice production (**Table 1**), which may impose a threat to the environment by stimulating CH_4 emissions. Phospho-gypsum, a by-product of the phosphate fertilizer manufacturing industry, is a feasible soil amendment to supplement mainly calcium and sulfur for rice cultivation. The high content of sulfate in phospho-gypsum might prevent CH_4 formation as well as CH_4 emissions due to stronger competitor for substrates (hydrogen or acetate) than methanogens. It was reported that silicate slag and phospho-gypsum in combination with Azolla-cyanobacteria significantly decreased CH_4 flux while improved rice rhizospheric redox status (**Figure 5**) [18, 23]. Ali et al. reported that biochar amendments in paddy soils of Japan and Bangladesh decreased seasonal cumulative N_2O emissions by 31.8 and 20.0%, respectively, followed by 26.3 and 25.0% reduction with biochar plus Azolla-cyanobacteria amendments (**Table 2**) [18]. Seasonal cumulative CH_4 emissions and global warming potentials were significantly decreased due to Azolla-cyanobacterial inoculation with phospho-gypsum and

Country	Harvested area (Mha)	Total production (Mt)	Yield (kg ha^{-1})	CH$_4$ emission(kg ha^{-1})
India	43	146	43,400	110.1
China	29	195	6500	180
Indonesia	12	63	4900	210
Bangladesh	11	46	4200	100
Vietnam	7	40	5300	180
Brazil	2	12	44,300	60
Colombia	0.5	2	4600	210
Peru	0.4	3	7200	240
Argentina	0.2	1	6600	280
Uruguay	0.2	1	7600	280

Source: M indicates million [22].

Table 1. Mean rice statistics (2004–2014) in the main rice producer countries in Asia, Latin America, and the Caribbean (LAC).
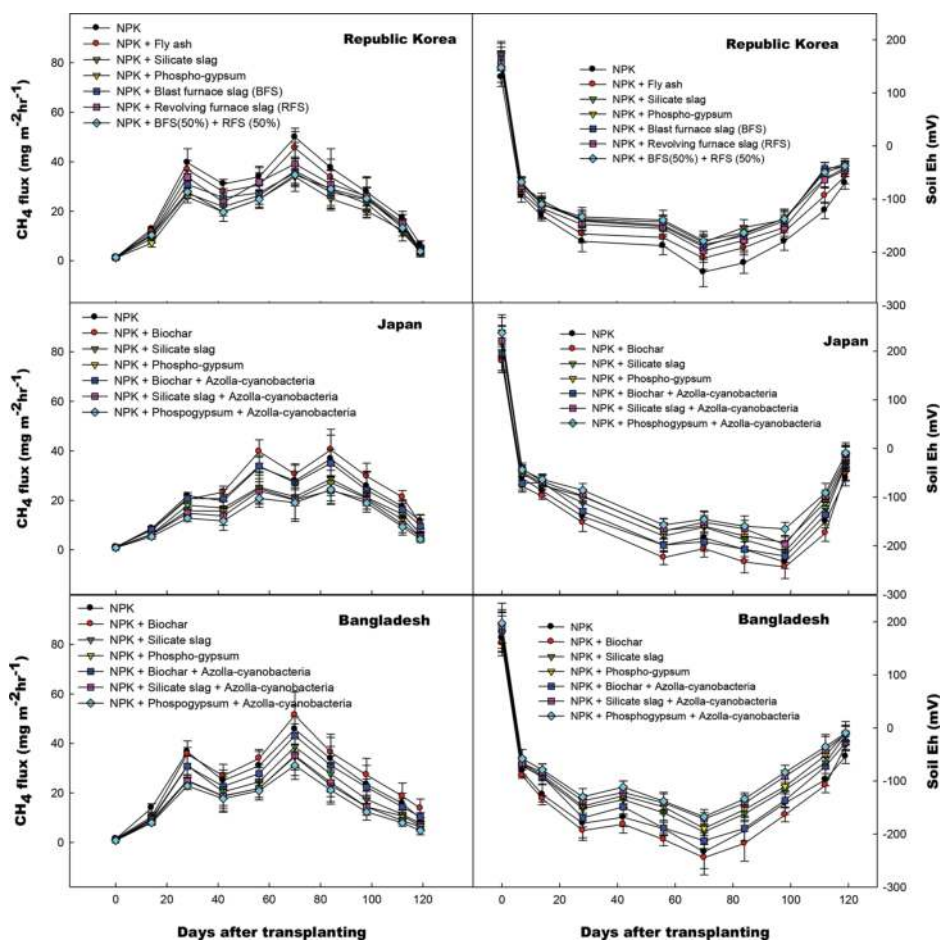

Figure 5. Trends of CH$_4$ flux and soil Eh with different soil amendments during rice cultivation in Bangladesh, Japan, and Korea [18, 23].

silicate slag amendments [18]. Combined effects of blast furnace slag and revolving furnace slag amendments also showed decreasing effects on GWPs (**Table 2**).

Silicate slag and biochar amendments in different soils of Japan also reduced cumulative CH_4 flux, while increased rice growth and yield parameters (**Table 3**) [23].

Among the amendments, biochar significantly decreased N_2O emission rates (**Figure 6**); however, it increased CH_4 emission rates (**Figure 1**). Silicate slag and phospho-gypsum amendments lowered N_2O emission rates compared to control treatment (NPK), although no significant differences were observed (**Figure 6**) [18].

5.1. Climate change and threats to rice production

The IPCC 4th Assessment Report (IPPC) states that Southeast Asia is expected to be seriously affected by the adverse impacts of climate change [11]. The frequency of floods, drought, cyclones, tornadoes, thunderstorm, and earthquake increased during the last 5 years, which badly affected the natural vegetation and forest covers, wild animals, wetlands, and land resources, and ultimately, agricultural productivity declined. In Indonesia, the Philippines, Thailand, and Vietnam, the annual mean temperatures are projected to rise by 4.8°C by 2100, and the global mean sea level will increase by 70 cm during the same period [24]. It has been reported that in Southeast Asia, small changes in the annual rainfall are expected to continue up to 2040 [25], and there will be an increase in the occurrence of severe weather including heat waves and precipitation events. Increases in tropical cyclone intensities by 10–20% are

Country (A)	Soil amendments (B)	Cumulative seasonal CH_4 emission g CH_4 m-2	Cumulative seasonal N_2O emission mg N_2O m-2	Global warming potential (GWP) kg CO_2 equivalent m-2	Grain Yield g m^{-2}	Yield scaled GWP/ Greenhouse gas intensity (GHGI) kg CO_2 equiv. kg^{-1} grain yield
Republic of Korea	NPK	16.3ab	45.3a	0.453a	423ef	1.076a
	NPK + Fly ash	16.9ab	43.7ab	0.435ab	454de	0.958ab
	NPK + Silicate slag	10.8de	42.7b	0.282e	515ab	0.548cd
	NPK + Phosphogypsum (PG)	11.1de	39.6	0.289de	495ab	0.584cd
	NPK + Revolving furnace slag (RFS)	11.9cd	41.8bc	0.309c	510bc	0.606cd
	NPK + Blast furnace slag (BFS)	14.7ab	41.3bc	0.379ab	478cd	0.793bc
	NPK + BFS (50%) + RFS (50%)	12.3c	40.5c	0.319ab	520bc	0.613cd
	NPK	14.65ab	28.9g	0.375bc	430e	0.879b
	NPK + Biochar	16.7ab	19.7i	0.423ab	475d	0.891ab
Japan	NPK + Silicate slag	12.5c	23.8h	0.326bc	540bc	0.604cd
	NPK + Phosphogypsum (PG)	11.7cd	24.6gh	0.301c	530bc	0.568cd
	NPK + Biochar + Azolla-cyanobacteria	13.5bc	21.3j	0.344ab	550ab	0.625cd
	NPK + Silicate slag + Azolla-cyanobacteria	11.37cd	24.5gh	0.293cd	590a	0.497e
	NPK + Phosphogypsum (PG) + Azolla-cyanobacteria	10.9e	25.7gh	0.281d	560ab	0.502d
	NPK	15.8ab	39.5cd	0.416b	410f	1.015a
Bangladesh	NPK + Biochar	17.3a	31.6ef	0.442ab	475d	0.931ab
	NPK + Silicate slag	12.9bc	33.9ef	0.3326bc	525bc	0.632cd
	NPK + Phosphogypsum (PG)	11.5cd	35.6de	0.298cd	510c	0.585cd
	NPK + Biochar + Azolla-cyanobacteria	14.3b	29.6f	0.366cd	515bc	0.711c
	NPK + Silicate slag + Azolla-cyanobacteria	11.6cd	34.7e	0.291cd	575ab	0.506d
	NPK + Phosphogypsum (PG) + Azolla-cyanobacteria	11.2d	36.6d	0.29cd	550b	0.527cd
ANOVA	A	***	***	***	***	***
	B	***	***	***	***	***
	A × B	**	**	**	*	**

Table 2. Cumulative seasonal CH_4 and N_2O emissions, global warming potentials (GWPs), and yield scaled GHG intensity under different soil amendments. Source: [18, 23].

Soil types (A)	Soil amendments (B)	Plant height	Root volume	Panicle No./hill	Panicle length	Grains No.	1000 grains wt.	Ripening ratio	Grain yield	Straw yield	Harvest index	Cumulative CH$_4$ flux	CH$_4$ evolved yield^{-1}
		cm	cm^3 hill^{-1}		cm	Panicle^{-1}	g	%	g/Pot	g/Pot	%	g/Pot	g CH$_4$ g^{-1} yield
Alluvial soil	NPK fertilizer	93.47	38.6	13.60	27.30	65.30	20.73	89.30	24.30	32.60	33.70	0.270	0.011
Matsuo Paddy field	NPK fertilizer + Biochar	94.33	40.9	14.90	27.60	68.60	21.20	90.60	27.10	33.86	35.30	0.282	0.010
	NPK fertilizer + Silicate sl	94.97	45.3	18.60	29.30	73.90	22.60	92.70	33.70	35.30	39.60	0.222	0.007
	NPK fertilizer + Biochar +	93.17	40.6	16.30	29.60	71.60	21.90	90.80	29.30	34.90	36.90	0.246	0.008
Gley soil	NPK fertilizer	89.17	38.3	13.60	27.10	61.90	20.30	88.60	23.60	34.30	32.30	0.240	0.010
(Shibayama paddy field)	NPK fertilizer + Biochar	90.87	40.9	14.60	27.60	68.90	21.90	89.90	26.60	37.50	32.70	0.249	0.009
	NPK fertilizer + Silicate sl	91.30	44.6	16.30	28.90	66.60	22.83	92.60	34.50	38.30	34.90	0.203	0.006
	NPK fertilizer + Biochar +	92.33	40.9	15.60	28.60	65.90	23.10	90.60	28.60	38.10	34.90	0.223	0.008
Andosol	NPK fertilizer	86.90	36.6	13.60	26.90	57.60	19.90	87.90	22.90	33.20	33.10	0.286	0.012
(Yokoshiba paddy field)	NPK fertilizer + Biochar	89.70	40.7	14.30	27.10	63.60	20.90	89.70	24.83	35.60	33.60	0.300	0.012
	NPK fertilizer + Silicate sl	90.90	45.6	17.60	28.10	69.30	22.10	90.60	27.80	36.90	34.60	0.240	0.009
	NPK fertilizer + Biochar +	92.60	43.9	16.60	27.90	63.30	21.80	89.10	26.60	34.60	35.10	0.262	0.010
ANOVA	A	**	**	ns	***	***	ns	ns	***	ns	*	*	*
	B	***	***	***	***	***	***	***	***	***	***	**	**
	A x B	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	*	*

Table 3. Rice plant growth, yield components, and cumulative CH$_4$ flux under biochar and silicate amendments in different field sites of Japan. Source: JSPS Report by Ali [23].
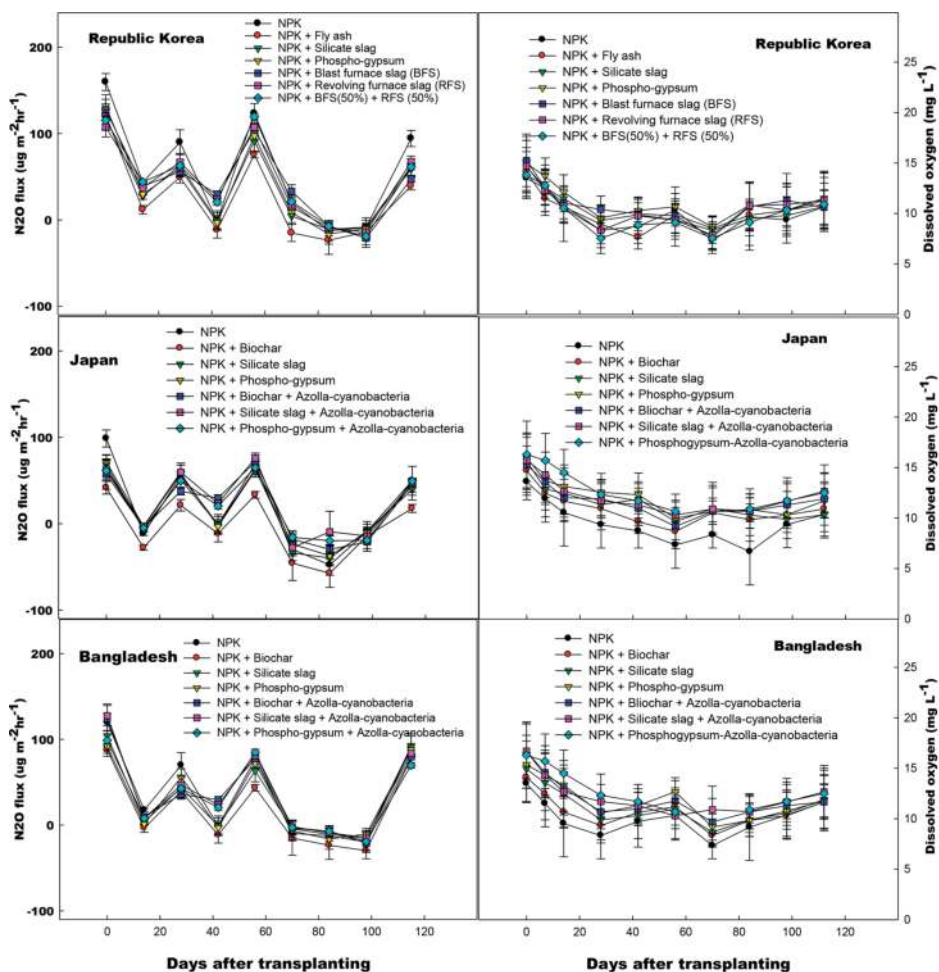

Figure 6. Trends of N$_2$O flux and DO concentrations under different soil amendments during rice cultivation in Bangladesh, Japan, and Korea [18].

Treatments	Flood water paddy field (Showair Union)						Flood water paddy field (Tetulia Union)					
	Grain yield (kg/ha)	Straw yield (kg/ha)	Gross return (Tk./ha)	Total variable cost (Tk./ha)	Net return (Tk./ha)	BCR	Grain yield (kg/ha)	Straw yield (kg/ha)	Gross return (Tk./ha)	Total variable cost (Tk./ha)	Net return Tk./ha	BCR
Control (no top dressing, no ducklings)	2143	4146	44,940	30,333	14,606	1.48	2106	4126	44,196	30,266	13,930	1.46
NPKS (100%) + ducklings	2576	5106	104,086	49,450	54,636	2.12	2496	4840	100,353	49,450	50,903	2.04
NPKS (50%) + bioslurry with oyster shell + ducklings	2446	4850	101,358	49,750	51,608	2.04	2433	4883	99,108	49,750	49,558	2.0
NPKS (50%) + vermicompost + ducklings	2776	5516	108,291	50,733	57,558	2.14	2693	5370	104,551	47,400	57,151	2.20
NPKS (50%) + azolla-cyanobacterial mixture + duckling	2650	5283	105,641	48,333	57,308	2.20	2603	5183	102,658	48,334	54,325	2.14
Significance level	**	**	**	*	*	*	*	*	*	*	*	*

Table 4. Overall productivity of rice duck farming in wetland paddy ecosystem of Dingaputa Haor, Netrokona district by Ali [28].

anticipated, and temperatures are projected to continue to increase by about 0.7–0.9°C [25]. Furthermore, sea levels have risen by 1–3 mm/year, marginally higher than the global average [24]. Rice production systems of this region have become increasingly threatened by the effects of climate change as a large portion of the rice-growing areas are located in especially vulnerable regions. A decrease of 10% in rice yield has been found to be associated with every 1°C increase in temperature [24], while the yield of dry-season rice crops in the Philippines decreased by as much as 15% for each 1°C increase in the growing season mean temperature. These temperature and aggravating climate change effects may cause a decline in the world rice production, which have already shown negative effects on agricultural production. By 2100, Indonesia, the Philippines, Thailand, and Vietnam are projected to experience a potential fall of about 50% in rice yield due to the occurrence of extreme climatic events [24, 26]. Furthermore, rice yield would be affected severely due to sea level rise and intrusion of saline water in the coastal area, which will hamper rice growth and yield. Rising sea levels in association with heavy monsoon rainfall will create serious waterlogging and prolonged stagnant floods in major rice-growing, low lying mega-deltas in Southeast Asia, which ultimately deteriorate rice production in the deltas since only a few low-yielding rice varieties have evolved to withstand such conditions [27]. The recent natural disasters such as flash floods caused by water of Indian Meghalaya state and excessive rainfall in the low lying ha or areas of Bangladesh [28] badly affected the only cultivated rice crop, the Boro rice (winter rice), at this region; however, due to rice duck mixed farming, the overall productivity and net profit were recovered to some extent (**Table 4**).

6. Management of rice paddy ecosystem to cope with climate change and sustainable rice production

6.1. Soil conservation with suitable cover crops and minimum tillage or no tillage

Soil conservation practices such as suitable cover crops, mulches, and minimum tillage (one or two plowing with proper leveling) may be introduced in rice farming not only to control soil erosion and land degradation, while reduce production costs to sustain rice productivity. In addition, conservation tillage will improve environmental quality by lowering GHG emissions (less air pollution) through decreasing the use of diesel fuel and nonburning of rice residues [29]. It has also reported that the no-tillage system in Korean paddy field with silicate fertilization decreased total seasonal CH_4 flux by 53 and 36%, while maximizing grain yield by 18 and 13% over the control tillage and control no-tillage systems, respectively [30]. Soil properties were also improved with silicate fertilization under the no-tillage system. It was [31] reported that tillage (after the harvest of late rice) with the incorporation of stubble (3.5 t ha^{-1}) in the winter fallow season significantly decreased both the net GWP and the GHGI while maintained a high grain yield (13.0–13.3 t ha^{-1} yr^{-1}) in the double-cropping rice system.

6.2. Introducing direct seeded rice (DSR) and puddle rice transplanting (PRT) methods

Direct seeded rice (DSR) is a process of establishing a rice crop which is done by seeds sown in the field rather than by transplanting seedlings from the nursery. The practice of direct

seeding instead of transplanting resulted in a 16–54% reduction in CH_4 emission [32]. CH_4 emission was more significantly reduced under dry-direct seeding compared to wet-direct seeding. However, grain yield in direct seeded rice (DSR) was found lower than Puddle transplanted rice (PTR), probably due to poor crop stand, high percentage of panicle sterility, and higher weed and root-knot nematode infestation [33]. It was also observed that grain yield of direct-seeded rice (9.0 Mg ha^{-1}) was identical to grain yield of transplanted-flooded rice [34]. Average yield penalty of around 10% was observed for the direct seeded rice (DSR) compared with puddle transplanted rice [34]. It was reported [35] that over the rice-growing season, cumulative CH_4 emissions were significantly higher in puddle transplanted rice compared to the direct seeded rice production system.

6.3. Water management for sustainable rice production and minimizing GHG emissions

Water management influences rice yield and CH_4 and N_2O emissions from rice cultivation systems. Irrigated rice fields are an integral part of the rice production system in Asian countries, which contribute about 75% to global rice production. Single or multiple drainages during a rice growing season (e.g., AWD) are reported to reduce CH_4 emissions by 48–93% compared to those observed under continuous flooding systems [36, 37]. Mid-season drainage and intermittent flooding were found effective for increasing productivity and quality of rice as well as reducing methane emissions in Japan [38]. The AWD field showed the same yield as continuous flooded field, but saved 16–24% in water costs and 20–25% in production costs. Most farmers in China, Japan, and South Korea have been practicing this mid-season drainage (5–7 days dry out) to increase rice yield and decrease GHG emissions. Mid-season drainage and intermittent irrigations may reduce methane emissions by about 50%. It was also reported [39] that the AWDI treatment (irrigation applied when water level in the pipe fell 15 cm) showed superiority for the rice yield performance and seasonal CH_4 emission reduction, water savings, and maximum water productivity index. However, the AWD irrigation technique increased the N_2O emission by 97%, especially in DS [40].

6.4. Diverse farm management practices, soil amendments, and rice cropping systems

Feasible management approaches based on agroecosystem have to be adopted to sustain agricultural productivity in the changing climatic conditions. For example, the ground cover rice production system (GCRPS), through which paddy soils are covered by thin plastic films to conserve soil moisture nearly at saturated status, is a promising technology to increase yields with less irrigation water. However, increased soil aeration and temperature under GCRPS may cause more CH_4 to N_2O emissions compared to conventional techniques. Yao et al. [41] reported that the GHG emissions for the ground cover rice production system (GCRPS, i.e., paddy soils being covered by thin plastic film) were found significantly lower (1973 kg CO_2 eq ha^{-1}) than that of traditional cultivation (4186 kg CO_2 eq ha^{-1}). Total seasonal CH_4 emissions under GCRPS were on average 80% lower as compared to the traditional rice cultivation. The yield-scaled GHG emissions from GCRPS were further reduced from 377 to 222 kg CO_2 eq Mg^{-1} as N_2O emissions greatly decreased while yields increased. The system of rice intensification (SRI), an agro-ecological methodology, could be a feasible technique to sustain

rice productivity by changing the management of plants, soil, water, and nutrients. Successful application of SRI of increased paddy yield by 50–100% while using less inputs, in particular water, (farmers were able to reduce their water requirements by about 25–50%) [42] has already been reported. Suitable rice cropping patterns, rotations, and mixed rice-duck-fish farming hold the potential scope to sustain agricultural productivity and controlling GHG emissions in the changing climatic conditions. For example, in the Philippines, fish or ducks have been raised with rice as well as legumes such as mung bean (*Vigna radiata*), groundnut (*Arachis hypogaea*), and soybean (*Glycine max*) after two rice dropping. Rotation of crops that have their most drought-sensitive phase in different phases of the growing season may prove a valuable adaptation to limited water resources. Haque et al. reported that the nonrice-based cropping patterns had lower GWPs than the rice-rice-based cropping patterns [43]. Ali et al. reported that CH_4 emissions from wetland paddy ecosystems were significantly decreased by integrated rice duck farming [28]. It has been reported that azolla application in rice field increased CH_4 emission, probably due to the exudation of azolla root and decomposition of dead azolla. In contrast, reverse report on CH_4 emission was also found from rice soil ecosystems, probably due to the increase in redox potential in the root region and dissolved oxygen concentration at the soil-water interface. Azolla cover increased N_2O emission from rice paddies due to N-fixation by azolla providing a source for N_2O production through nitrification and de-nitrification, especially when the azolla died [44]. CH_4 emissions have been reported to increase when crop residues are incorporated prior to planting due to higher amounts of readily available carbon stimulating soil microbial activity. Sander et al. reported that incorporation of rice residues immediately after harvest and subsequent aerobic decomposition of the residues before soil flooding for the next crop reduced CH_4 emissions by 2.5–5 times and also improved nutrient cycling in paddy field [45]. It was also reported that residue incorporation accelerated CH_4 and N_2O emissions from irrigated rice field compared to residues (ryegrass and serradella) left on the soil surface. The open burning of crop residues emits CO_2, CH_4, and N_2O. Ali et al. [17] reported that silicate slag and phospho-gypsum amendments with nitrogenous fertilizer in rice cultivation significantly decreased seasonal CH_4 flux by 16–20% and increased rice yield by 13–18% in Korean paddy soil, whereas 12–21% reduction in total seasonal CH_4 flux and 5–18% increase in rice grain yield were found in the upland rice paddy soils of Bangladesh [46]. Seasonal cumulative CH_4 and N_2O emissions, GWPs, and yield scaled greenhouse gas emissions were decreased by combined application of Azolla-cyanobacterial mixture with silicate slag, phospho-gypsum, and biochar amendments in rice paddy soils of Japan, Korea, and Bangladesh (**Table 2**) [18]. Site-specific nutrient management (SSNM) for rice developed by IRRI (2006) in Asia [47] enables rice farmers to tailor nutrient management to the specific conditions of their fields, and provides a framework for nutrient-based management practices for rice. The increase in annual grain yield with use of SSNM in on-farm evaluation trials averaged 0.9 t/ha in southern India, 0.7 t/ha in the Philippines, and 0.7 t/ha in southern Vietnam [48]. Climatic stress tolerant rice cultivars such as drought, salt/saline, and submergence tolerant rice cultivars have to be developed to cope in the real field stress situation. It was reported [49] that indica-type rice cultivars had significantly higher yield-scaled GWP (1101 kg CO_2 equiv. Mg^{-1}) compared to Japonica (711 kg CO_2 equiv. Mg^{-1})-type rice cultivar. It was also reported that AWD irrigation practice reduced CH_4 emissions by 24–41%, 26–48% compared with continuous flooding, however, an increase in N_2O emission

was observed in both seasons [50]. It was also reported that biochar application in paddy soil significantly decreased N_2O emission, while increased CH_4 emission [51].

7. Conclusion

In the context of global climate change, environment friendly agricultural management practices such as conservation tillage, rice seedling transplanting or direct line seeding, alternate wet and dry irrigation (AWDI), mid-season drainage, soil amendments with biochar, vermicompost, silicate slag and phospho-gypsum, site specific rice based cropping patterns and integrated plant nutrients system (IPNS) should be followed to ensure food security, while mitigating greenhouse gas emissions and global warming potentials. Furthermore, Azolla-cyanobacterial dual cropping with rice, introducing N-fixing legumes and duckling rearing with flood water rice cultivation could be practiced to sustain overall agricultural productivity and minimizing greenhouse gases intensity in the changing climatic conditions.

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