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Influence of Soil Amendments on Mitigating Methane Emissions and Sustaining Rice Productivity in Paddy Soil Ecosystems of Bangladesh

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Abstract

Two field experiments were conducted at two different rice ecosystems, one in the upland rice field of Bangladesh Agricultural University farm, Mymensingh and the another one in the low lying area of Bhaluka, Mymensingh to investigate the effects of soil amendments on mitigation of methane emissions and sustaining rice productivity. The experimental treatments were urea (250 kg ha^{-1}), urea plus coal ash (1t ha^{-1}), urea plus phosphogypsum (90 kg ha^{-1}), urea plus silicate fertilizer (150 kg ha^{-1}), ammonium sulphate 400 kg ha^{-1}, ammonium sulphate plus silicate fertilizer (150 kg ha^{-1}), urea (25% less than the recommended doze) plus cyanobacteria plus azolla (1t ha^{-1}). In case of BAU upland rice field, the total seasonal CH_4 emission was decreased by 12-21% and rice grain yield was increased by 4.0- 18.0% respectively, whereas 11.0-26.0% reduction in total CH_4 emission and 4.5-24.0% increase in rice grain yield was recorded from the low lying rice field of Bhaluka with the application of soil amendments. Among the amendments silicate fertilization with urea and silicate in combination with ammonium sulphate reduced total CH_4 flux by 18-23% and 21-26% respectively, whereas rice grain yield was increased by 18-24% and 16-18%, respectively in both ecosystems. Although maximum reduction in total seasonal CH_4 flux was recorded with silicate and sulfate of ammonia amendment in paddy soil, however soil acidity was developed which might affect soil fertility and rice productivity in the future. Therefore, silicate fertilizer could be introduced with the nitrogenous fertilizer sources, preferably with 50% urea plus 50% ammonium sulphate for reducing CH_4 emissions and increasing rice productivity under both irrigated upland and lowland rice field ecosystems.

Kew words: Methane emission, Rice, Soil amendment

Introduction

Rice is the main food crop in Bangladesh. Rain fed (Tropical Monsoon) lowland and irrigated rice farming mainly dominates rice productivity that contributes significant amount of CH_4 emissions to the atmosphere. The impacts of climate change on agricultural food production are global concerns and crucial for the economy of Bangladesh, as 35% of country's GDP comes from agriculture sector. CH_4 emission from the lowland and irrigated rice field is a major environmental problem, which causes global warming due to its radiative effects (IPCC 2001). Bangladesh is a low-lying deltaic country in South Asia. Rice cropping intensity is very high, e.g., three times in a year, which may degrade the environment due to continuous emissions of greenhouse gases, e.g., CH_4 gas from rice field. Total rice production in Bangladesh was 34.28 million tons in FY2008-09 (BBS, 2009), where Boro rice contributed 57% (18.5 million tons), T. Aman rice 33% and Aus rice 10%. Bangladesh will require more than 55.0 million tons of rice to meet the food demand of the expected total population (233.0 millions) by the year 2050 (Basak, 2009). Therefore, the area under rice cultivation especially boro rice field must be expanded, which may cause significant CH_4 emissions and eventually may accelerate the global warming effects. Silicate slag, which is a byproduct of steel industry, is used in manufacturing of silicate fertilizer that contains high amount of available silicate, active iron, free iron and manganese oxides, may act as electron acceptors. Ali *et al.* (2009) reported that CH_4 flux was significantly decreased during rice cultivation by silicate amendment in paddy soils. Phospho-gypsum, a byproduct of phosphate fertilizer manufacturing industry, is another 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 (Hori *et al*., 1990, 1993;. Cyanobacteria are important biotic components of the wetland paddy ecosystem, commonly found as floating assemblages (a water fern harbouring a cyanobacterium, *Anabaena azollae*) in rice paddies. It has already reported that cyanobacterial mixture plus *Azolla microphylla* applied to flood water rice field, enhanced CH_4 oxidation and eventually decreased CH_4 emission (Bharati *et al*, 2000; Prasanna *et al*., 2002).

In the present context of Bangladesh, no basic information on reducing CH_4 emissions from rice field are available. Our rice farmers must upgrade and well equip themselves with the scientific principles of rice paddy ecosystems management. So, the present research work was undertaken to investigate the influence of soil amendments on CH_4 emission and rice productivity in lowland and upland paddy soil ecosystems.

Materials and Methods

Experimental field preparation and rice cultivation

Two field experiments were conducted at two different rice ecosystems, one in the upland rice field of Bangladesh Agricultural University farm, Mymensingh and the another one in the low lying area of Bhaluka, Mymensingh. The experiments were designed with randomized complete block design (RCBD). There were seven treatments, which were replicated three times in each experimental field. The experimental treatments were urea 250 kg ha^{-1}, urea 250 kg ha^{-1} + coal ash 1t/ha, urea 250 kg ha^{-1} + phospho- gypsum 90 kg ha^{-1} , urea 250 kg ha^{-1} + silicate fertilizer 150 kg ha^{-1}, sulphate of ammonia (SOA) 400 kg ha^{-1} , sulphate of ammonia (SOA) 400 kg ha^{-1} + silicate fertilizer 150 kg ha^{-1}, urea (190 kg/ha, 25% less than the recommended doze) + cyanobacterial bloom (cyanobacteria + azolla) 1 ton/ha , sulphate of ammonia (SOA) 400 kg ha^{-1} + cyanobacterial bloom (cyanobacteria + azolla) 1 ton/ha. The rice cultivar used in this experiment was BRRI Dhan-29. The selected silicate fertilizer was granular form, slag type with pH 9.5 and was composed mainly of CaO (41.8%), SiO_2 (33.5%) and Fe_2O_3 (5.4%). Average active and free iron concentrations were 3078 and 1571 mg Fe kg^{-1}, respectively. The basal nutrients fertilizer applied following the ratio N: P_2O_5: K_2O = 110: 45: 60 kg ha^{-1}. Dried rice straw was added into soils at the rate of 2 t ha^{-1} one week prior to flooding and mixed mechanically within 10 cm depth of the surface soil. The content of electron acceptors were 1.2%, 3.5%, 5.7%, 5.9%, 4.0% and 6.3% in urea, urea plus coal ash, urea plus silicate slag, urea plus phospho-gypsum, sulfate of ammonia, and silicate slag plus sulfate of ammonia, respectively. The selected soil amendments having electron acceptors were applied in the selected rice field two days before final land preparation (Ali *et al*, 2009). Cyanobacterial mixture plus azolla was inoculated in field plots at 1 Mg ha^{-1} after one week of rice transplanting and allowed to grow with rice plant as dual crop. Twenty eight days old rice seedlings of cultivar BRRI Dhan-29 were transplanted in the field 25 cm x 25 cm with single plant $hill^{-1}$.

CH_4 gas sampling and analysis

Gas sampling was carried out through closed-chamber method (Rolston, 1986) during rice cultivation. Three glass chambers were placed in each plot. Four holes at the bottom of each chamber were kept to facilitate water movement. The air gas samples from the transparent glass chamber (Diameter 62 cm, and height 112 cm) were collected by using 50 ml gas-tight syringes at 0, 15 and 30 minutes intervals after chamber placement over the rice planted plots. Gas samples were collected three times (8.00-12.00-16.00) in a day to get the average CH_4 emissions during the cropping season. CH_4 concentrations in the collected air samples were measured by Gas Chromatography (Shimadzu, GC-2010) packed with Porapak NQ column (Q 80-100 mesh) and a flame ionization detector (FID). The temperatures of column, injector and detector were adjusted at 100°C, 200°C, and 200°C respectively. Helium (He) and H_2 gases were used as carrier and burning gases, respectively.

Estimation of CH_4 Flux

CH_4 emission from irrigated rice field was calculated from the increase in CH4 concentrations per unit surface area of the chamber for a specific time intervals. A closed chamber equation (Rolston, 1986) was used to estimate CH_4 fluxes from each treatment.

$$\mathbf{F = \rho. V/A. \Delta c/\Delta t.273/T}$$

where, F= methane flux (mg CH_4 m^2 hr^{-1}), ρ = gas density (0.714 mg cm^{-3}),

V = volume of chamber (m^3), A = surface area of chamber (m^2),

H = height of the chamber (m), $\Delta c/\Delta t$ = rate of increase of methane gas concentration in the Chamber (mg m^{-3} hr^{-1}),

T (absolute temperature) = 273 + mean temperature in chamber (°C).

Investigation of soil chemical properties

Soil redox potential (Eh) and water pH were measured every week interval by Eh meter (PRN-41, DKK-TOA Corporation) and pH meter (Orion 3 star, Thermo electron corporation), respectively, during rice cultivation. Changes in the organic matter content and dissolved organic carbon (Wakley and Black method; Allison 1965), available silicate (1 M Na-acetate pH 4.0, UV spectrometer) and available phosphate (Lancaster method, RDA 1988), water soluble and ferrous iron (Water extraction , 2M Na-acetate solution; 1,10 Phenanthroline method), exchangeable Ca^{2+}, Mg^{2+}, and K^+ (1 M NH_4-acetate pH 7.0, AA, Shimazu 660), nitrate and ammonium ion concentrations were determined through standard analytical methods**.** Ferrous iron concentrations in fresh soil samples were determined by 2M Na-acetate extraction method (Modified from Kumada and Asami, 1958). The total iron, active iron and free iron concentrations in the dried soil at harvesting time were determined by modified acid (12 M HCl) digestion, acid ammonium oxalate in darkness and citrate dithionite bicarbonate dissolution procedures, respectively (Loeppert and Inskeep, 1996).

Investigation of rice plant growth and yield characteristics

Rice growth and yield components were recorded under different treatments and locations. Yield components such as panicle number per hill, number of grains per panicle, ripened grains, 1000 grain weight, harvest index and grain yield/ha were determined at the harvesting stage.

Statistical analysis

Statistical analyses were conducted using SAS software (Anonymous, 1990). Rice growth, yield, soil properties and methane emission data were subjected to the analysis of variance and regression. Fisher's protected least significant difference (LSD) was calculated at the 0.05 probability level for making treatment mean comparisons.

Results and Discussion

CH_4 flux measured at 21 days after rice transplanting was low, which increased significantly with plant growth and the development of soil reductive condition in both upland rice field of BAU and lowland rice field of Bhaluka, respectively. The highest CH_4 peak was observed at flowering to heading stage (77-91 days after rice transplanting) in both locations of BAU and Bhaluka rice fields, respectively (Fig.1). However, CH_4 emission rate was comparatively higher from the lowland rice field than that of upland rice field during rice cultivation period.

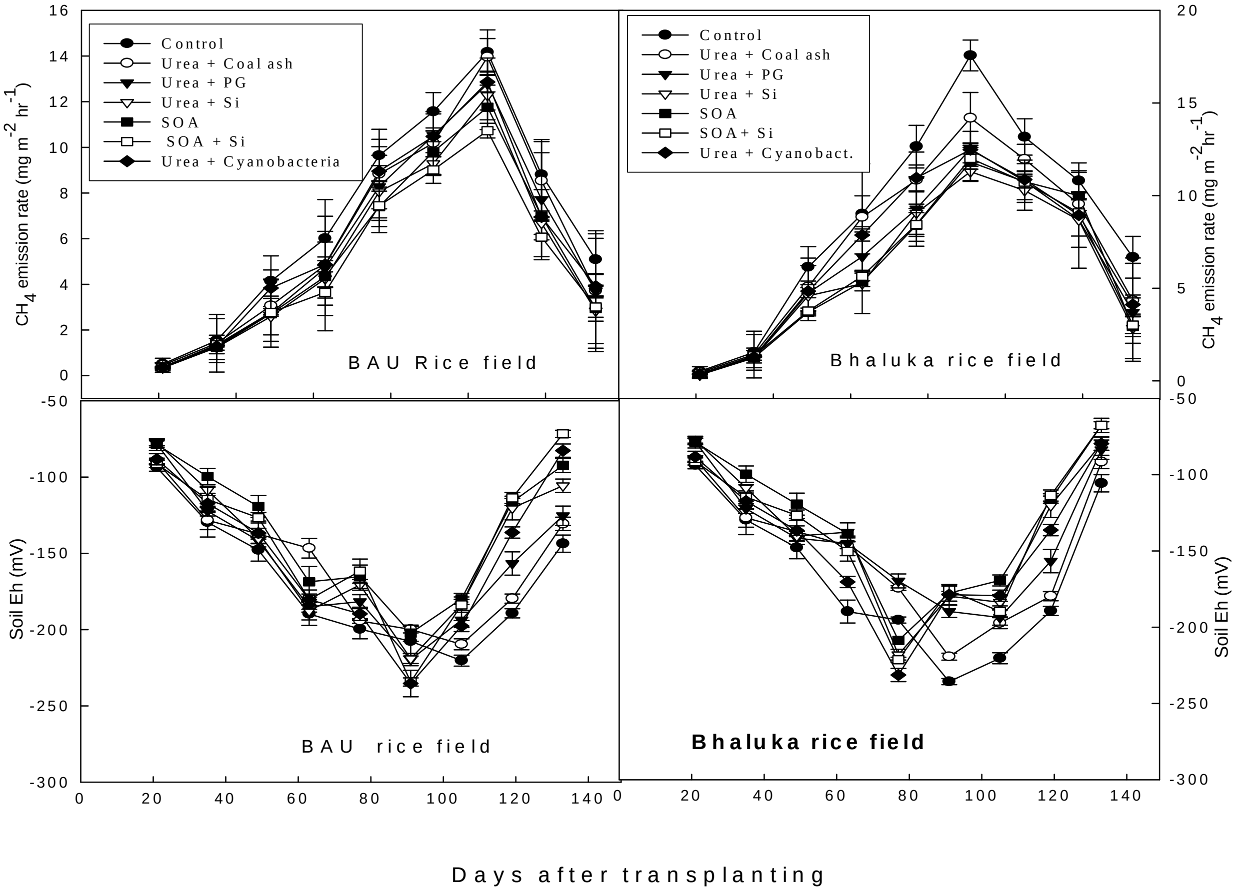

Fig. 1. Trends of CH_4 emission rate and soil Eh during rice cultivation at BAU and Bhaluka rice field

This was probably due to the development of intense reduced conditions, e.g., redox potential value (soil Eh) -220 mV to -240 mV in the rice rhizosphere (Fig.1) and the availability of soil organic carbon. Soil amendments such as silicate fertilization with urea and ammonium sulfate, phospho- gypsum amendment with urea significantly decreased (*$p<0.05$) CH_4 emission rate as compared to other treatments during rice cultivation (Fig.1). At ripening stage, CH_4 emission rates decreased sharply in both locations (Fig 1), which seems to be related with plant aging and improved soil porosity, being supported by Aulakh *et al.* (2000).

Silicate fertilization with urea and silicate plus ammonium sulphate amendments significantly stimulated the growth and yield components of rice, thereby significantly increased the grain yield as compared to other treatments (Table 1). Among the treatments, silicate amendment with urea increased maximum rice grain yield from the control plot 4189 to 4963 kg ha^{-1} (18% yield increased), 4450 to 5520 kg ha^{-1} (24% yield increased) in BAU and Bhaluka rice field, respectively (Table 1). The seasonal total CH_4 flux from the upland BAU rice field was 105.5 kg ha^{-1} under the control treatment, which was decreased by 11.8%, 14.7%, 18%, 15%, 20.8% and 13.5% with urea plus coal ash, urea plus phosphogypsum, urea plus silicate fertilizer, ammonium sulphate , ammonium sulphate plus silicate fertilizer, and cyanobacterial bloom with urea amendments respectively; whereas rice grain yield was increased by 6%, 11%, 18%, 5%, 16% and 7% respectively, (Table 1). In case of lowland rice field of Bhaluka the seasonal total CH_4 flux was 129.0 kg CH_4 ha^{-1} under the control treatment, which was decreased by 13%, 18%, 23%, 21%, 26%, and 11% with urea plus coal ash, urea plus phosphogypsum, urea plus silicate fertilizer, SOA, SOA and silicate fertilizer and cyanobacterial bloom with urea amendments, respectively whereas rice grain yield was increased by 7%, 12.8%, 24%, 4.5%, 18% and 8%, respectively (Table 1).

Among the treatments urea plus silicate fertilizer and ammonium sulfate plus silicate fertilizer significantly reduced total methane flux and increased rice grain yield. Although phospho-gypsum and ammonium sulfate amendments effectively reduced CH_4 emissions, however developed soil acidity, therefore, silicate fertilization with urea could be the best amendment for mitigating CH_4 emissions and increasing rice productivity.

Table 1. Rice yield components, grain yield, and total CH_4 flux of paddy soil ecosystems at harvest

Locations (A)	Soil amendments (B)	No. of panicles m^{-2}	No. of grains/ panicle	Ripening ratio	Grain Yield (kg ha^{-1})	Straw Yield (kg ha^{-1})	Seasonal CH_4 flux (kg CH_4 ha^{-1})
BAU Site (Upland)	Urea alone	345	119	84.5	4189	4050	105.5
	Urea + coal ash	378	127	88.9	4457	4125	93.0
	Urea + phosphogypsum	423	138	89.5	4676	4370	90.0
	Urea + silicate slag	441	149	93.5	4963	4560	86.5
	Ammonium sulphate	399	123	87.5	4276	4045	89.0
	Ammonium sulphate + silicate slag	433	135	92.5	4875	4390	83.5
	Urea + Cyanobacteria + azolla	420	127	90.5	4493	4125	91.3
Bhaluka Site (Lowland)	Urea alone	357	123	86.6	4450	4125	129.0
	Urea + coal ash	399	133	90.5	4780	4250	112.0
	Urea + phosphogypsum	427	148	91.3	5021	4325	105.0
	Urea + silicate slag	462	155	92.5	5520	4550	98.6
	Ammonium sulphate	420	135	89.9	4650	4310	102.0
	Ammonium sulphate + silicate slag	441	151	93.1	5245	4770	95.5
	Urea + cyanobacteria + azolla	433	139	91.5	4820	4650	114.5
ANOVA	A	***	**	**	***	*	***
	B	***	**	**	***	*	***
	A × B	*	*	*	*	ns	*

Notes: *, ** and *** means significant at 5%, 1% and 0.1%, levels, respectively; ns means not significant.

Silicate fertilizer, phospho-gypsum and sulfate of ammonia amendments significantly ($p<0.05$) increased soil porosity and improved soil redox potential (Eh) status as compared to that of control (Table 2), which could be due to their higher content active iron oxide, ferric and sulfate ions in the amended paddy soil, which acted as oxidizing agents as well as electron acceptors (Table 2). The soil pH significantly ($P<0.001$) increased with silicate fertilization, probably due to release of base cations such as Ca^{2+} from the applied amendment. Similar trends of changes in soil Eh and flood water pH were reported by Ali *et al.* (2008). The available P_2O_5 and SiO_2, exchangeable cations such as Ca, Mg and K etc., and the concentrations of active iron, free iron and ferrous iron oxides in soil significantly ($P<0.001$) increased under the silicate and phospho-gypsum amendments with urea and ammonium sulfate (Table 2). This implies that the silicate and phospho-gypsum amendments supplied large amount of ferric oxides and sulfate ions which acted as oxidizing agents and electron acceptors, thereby suppressed CH_4 production rates from the anoxic paddy soils, being supported by Watanabe and Kimura (1999); Jackel and Schnell (2000). The interaction of soil amendments with the ecosystems significantly improved the soil physico-chemical properties, which ultimately decreased total seasonalCH_4 emissions and increased rice grain yield.

Table 2. Chemical properties of rice paddy soils at rice harvesting stage

Soil Properties	BAU rice field							Bhaluka rice field							$LSD_{0.05}$
	Urea sole	Urea + Coal ash	Urea + PG	Urea + Silicate	SOA	SOA + Silicate	Urea + CB	Urea sole	Urea + Coal ash	Urea + PG	Urea + silicate	SOA	SOA + silicate	Urea + CB	
Soil porosity	0.51	0.52	0.54	0.56	0.52	0.55	0.54	0.50	0.51	0.52	0.54	0.52	0.54	0.53	0.01
Soil pH	6.6	6.8	6.7	7.0	6.7	6.8	6.8	6.7	6.9	6.8	7.2	6.6	6.9	6.9	0.03
Soil Eh	-89	-78	-65	-63	-60	-57	-71	-93	-80	-63	-67	-58	-55	-75	4.9
OM (g kg $^{-1}$)	24.9	25.5	26.0	26.9	25.1	27.5	27.0	25.3	25.7	26.0	26.9	26.1	27.5	28.1	2.94
Available P_2O_5 (mg kg^{-1})	58.5	69.5	87.5	109.0	93	115.0	109	61.5	70.5	89.5	118	97.0	129.0	112	12.0
Available SiO_2 (mg kg^{-1})	65.0	89.5	107	131.0	103	129	110	61.5	98.0	91.0	139.5	99.0	115.0	121	2.70
Ex.Ca ($cmol^+$ kg^{-1})	3.9	4.5	6.9	5.6	4.3	6.3	5.1	3.6	4.3	5.1	6.1	6.3	5.1	5.3	0.35
Ex.Mg ($cmol^+$ kg^{-1})	1.2	1.5	1.6	1.6	1.3	1.5	1.5	1.1	1.2	1.4	1.5	1.30	1.4	1.6	0.11
Ex.K ($cmol^+$ kg^{-1})	0.24	0.31	0.35	0.39	0.33	0.36	0.35	0.27	0.34	0.41	0.45	0.43	0.47	0.39	0.03
Active iron (g Fe kg^{-1}) [a]	10.8	10.9	11.5	13.5	10.9	12.5	10.9	10.7	11.3	12.5	14.9	12.9	14.9	11.0	0.36
Ferrous iron (mg Fe^{2+} kg^{-1})[b]	89.3	129	147	179	187	195	149	97.5	148	187	191	183	193	135	19.4
Water soluble SO_4^{2-} (mg kg-1)	33.5	77.5	147	131	145	163	55.9	39.5	85.9	165.0	145	151	173.0	67.5	13.5

Note: OM denotes organic matter; CB denotes Cyanobacteria; SOA means sulfate of ammonia, [a] Acid ammonium oxalate in darkness, (Loeppert and Inskeep, 1996), [b] 2 M Na–acetate extractble (Loeppert and Inskeep, 1996).

Table 3. Correlation of CH_4 emissions with selected plant parameters and soil properties

Parameters (n= 21)	Correlation coefficient (r)	
	BAU rice field	**Bhaluka rice field**
Panicle number	-0.484	-0.493*
Grain yield	-0.547*	-0.641**
Organic carbon	0.172	0.0445
Soil Porosity	-0.649**	-0.729***
Soil pH	-0.656**	0.743**
Soil Eh	-0.753***	-0.683**
Active Fe	-0.588*	-0.615**
Ferrous Fe	-0.695***	-0.743***
Water soluble SO_4^{2-}	-0.738***	-.689***

CH_4 flux showed a strong positive correlation with the availability of soil organic carbon, while there were negative correlations with soil porosity, soil pH, soil Eh, the content of active iron and ferrous iron oxides, sulphate ion in soil at rice harvesting stage (Table 3). The increased carbon sources in paddy soil enhanced CH_4 emissions (Hou *et al.*, 2000; Neue *et al.*, 1996). Rice grain yield was negatively correlated with seasonal CH_4 flux (Table 3), which was supported by Denier van der Gon *et al.* (2002).

Discussion

In this study CH_4 emission patterns were more or less similar in both upland and lowland rice ecosystems, however, CH_4 emission rates were significantly higher from the lowland rice field of Bhaluka as compared to upland rice field of BAU. This is likely due to the development of intense anoxic conditions (redox potential value -240 mV) and increased availability of labile organic carbon in the lowland rice field ecosystem of Bhaluka, being supported with the findings of Schutz *et al.*(1989) and Wassmann *et al.* (1993).

The applied soil amendments significantly decreased the seasonal CH_4 emissions during rice cultivation under both ecosystems. Among the amendments silicate slag and phospho-gypsum significantly decreased CH_4 emission rate due to their high content of free iron oxides and SO_4^{-2} ions which acted as electron acceptors. The concentration of active iron, SO_4^{-2} and ferrous iron oxides significantly ($p<0.001$) increased in the amended paddy soil (Table 2). Soil porosity increased in the amended paddy soil ecosystems, which might have decreased methane emissions through increasing methane oxidation in the rice rhizosphere.

Ali *et al.* (2008) found that silicate fertilization in rice farming decreased total CH_4 flux by 16-20%, while increased rice productivity by 13-18% under conventional tillage system. Jugsujinda and Patrick (1996) reported that the ferric iron (Fe^{3+}) reduction process delayed or suppressed methane production, although methane production rate was maximum at neutral soil pH in combination with low soil redox potential (Eh -250 mV). In this study, seasonal CH_4 emissions showed strong negative correlations with the active iron, SO_4^{-2} and ferrous iron concentrations in soil at harvesting stage (Table 3). This implies that the released iron and sulfate ions from the applied soil amendments acted as electron acceptors and eventually suppressed CH_4 emissions as supported by Jackel and Schnell (2000).

Conclusions

Among the amendments, silicate fertilization with urea and silicate in combination with sulfate of ammonia increased rice grain yield by 18-24% and 16-18%, whereas decreased total seasonal CH_4 flux by 18-23% and 21-26%, respectively. Conclusively, silicate fertilization with urea and sulfate of ammonia could be an effective strategy for reducing CH_4 emissions during rice cultivation under lowland and upland paddy soil ecosystems.

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