

Methane and nitrous oxide emission from irrigated rice fields: Proposed mitigation strategies

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Rice fields are major sources of CH_4 and N_2O . A number of practices have been suggested to minimize the emission of either of these gases, but simultaneous mitigation of these gases are not widely discussed. Mitigating CH_4 emission may increase N_2O emissions and vice versa. Reducing their emission and making the cumulative radiative forcing a minimum is a priority. The strategies should be effective, applicable on a large scale, technically feasible, economic, less time-consuming, environment friendly and should be easily acceptable. On the basis of the available literature on CH_4 and N_2O mitigation, the following measures are suggested by the author to mitigate the emissions of these two gases simultaneously from irrigated rice fields: (1) Application of mid-season drainage which does not coincide with high ammonium in soil, (2) application of urea and NH_4^+ -based fertilizers in

splits with nitrification inhibitors to increase N use efficiency, (3) replacement of ammonium sulphate with other sulphate sources to minimize CH_4 and N_2O emissions, (4) replacement of N broadcasting by foliar-N spray application, (5) sub-surface application of urea supergranules, (6) incorporation or deep placement of prilled urea instead of surface application, (7) application of well-composted organic matter in place of fresh organic matter and green manure, (8) use of single superphosphate (SSP) basally, which in addition to supplying phosphorus, could mitigate CH_4 production by supplying sulphur to soil and (9) cultivation of rice varieties with low gas transport capacities and low exudate formation. These practices can be taken up without much difficulty in irrigated rice fields and can reduce CH_4 and N_2O emission simultaneously.

METHANE (CH_4) and nitrous oxide (N_2O) are two important greenhouse gases and lead to chemical changes in the atmosphere¹⁻⁴. Although, atmospheric loading of N_2O is lower than CH_4 globally⁴, the former is a 310 times more potent greenhouse gas than CO_2 on a 100-year time-scale while CH_4 is only 21 times more potent⁴. During 1990–1999, CH_4 and N_2O concentrations have increased 0.007 and 0.0008 ppb yr^{-1} , respectively⁵.

Rice cultivation is an important source of CH_4 and N_2O (refs 6–9). Methane emission from the rice fields is estimated to be globally 37 Tg yr^{-1} by IPCC while N_2O emission is much lower as the total N_2O emission from overall cultivated area was put at 1.8–5.3 Tg yr^{-1} (ref. 10). Extent of N_2O emission from the rice field is much lower than CH_4 since N_2O is unstable in anaerobic environment of wet-land rice soils⁶⁻⁸. N_2O is trapped in the soil long enough to get denitrified to N_2 (ref. 11) but during intermittent drying of the rice fields, N_2O emission increases considerably^{9,12}. In contrast, CH_4 emission is pronounced under anaerobic condition while intermittent drainage appreciably reduces its emission^{13,14}. Around 80% of CH_4 produced in the soil can be converted to CO_2 in the oxidized zone in the surface soil of rice fields where CH_4 reaches by diffusion¹⁵. In irrigated rice fields, during drying cycles, CH_4 emissions decline due to low generation and more oxidation, while N_2O emission may

increase due to lesser reduction to N_2 . Again, on fresh irrigation, high amount of dissolved oxygen may help form a more pronounced oxidized zone in rice soil, favouring CH_4 oxidation.

Methane and nitrous oxide are simultaneously emitted as irrigated rice fields offer favourable conditions for their production and emission (Figure 1). But it is difficult to predict the extent of their emission, as it is controlled by the real-time field conditions that control the production and emission of the gases. Interestingly, the presence of methane in the rice soil itself may check nitrification¹⁶ and thus can possibly reduce N_2O formation. Although the inhibition of nitrification by methane is not too strong, appreciable amount of methane in rice soil may play an important role.

Emphasis should be now laid on the mitigation of CH_4 and N_2O from rice cultivation, which is one of the most important contributors to greenhouse gases in the atmosphere. It is estimated that irrigated rice accounts globally for 70–80% of CH_4 from the global rice area, while rain-fed rice (about 15%) and deepwater rice (about 10%) have much lower shares. So, irrigated rice represents the most promising target for mitigation strategies¹⁷. However, mitigation options for CH_4 and N_2O are different and minimizing one gas may increase the emission of the other. So, there is an urgency to prepare a set of mitigation options that might mitigate both the gases simultaneously and reduce the cumulative radiative force of the

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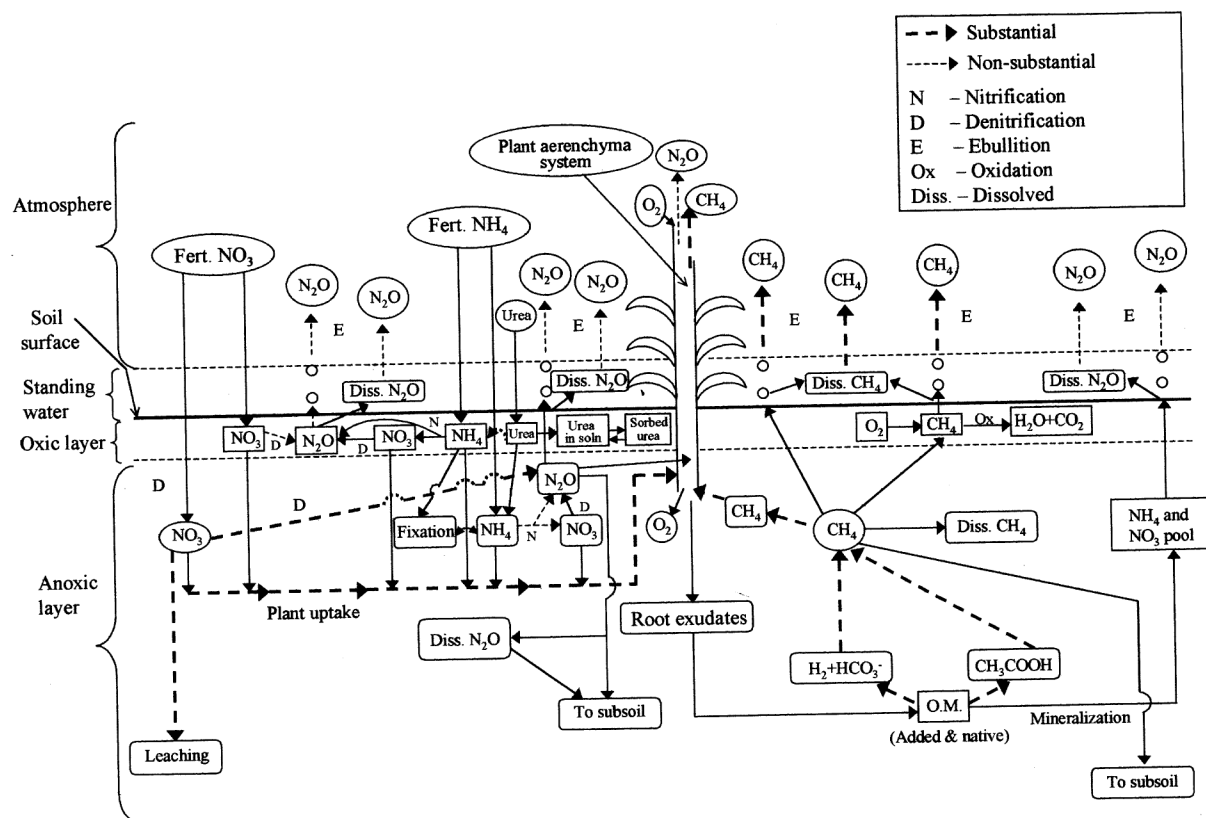


Figure 1. Mechanisms of CH_4 and N_2O emissions from an irrigated rice field under flooded condition.

two gases to the maximum possible extent. The options have to be carefully considered so that the crop yield is not affected. In this review, I discuss different factors affecting emissions of CH_4 and N_2O from irrigated rice field and how mitigation of one may increase the other. I also offer a set of management strategies for irrigated rice field, which could effectively mitigate the emissions of both.

An overview of the factors affecting emissions of CH_4 and N_2O from irrigated paddy fields

Methane and nitrous oxide are emitted simultaneously from irrigated rice fields since the biochemistry of submerged soils support the production of both the gases¹⁸. Several studies have been conducted to measure the simultaneous emissions of CH_4 and N_2O from irrigated rice fields^{8,19–33}. These studies give an insight into the nature of the emissions of the two gases and the factors influencing the emissions. Many reviews have been published on the emissions of CH_4 and N_2O from soils and their mitigation^{34–48}. Some of these papers have dealt with in detail the factors affecting the production of these gases in soils in general, but very few have concentrated on simultaneous emissions of the two gases. Since both the gases are emitted simultaneously from irrigated rice

fields, there is a need to discuss the contrast and similarities in conditions that lead to the emissions of these gases. There are many interplaying factors, e.g. soil water content, nutrient application, organic matter in soil, soil type (mainly texture), soil pH, soil redox potential, soil and floodwater temperature, plant type and population, land management practices, which influence the production and emissions of the gases from irrigated rice fields. Production of the gases in soil may be far more than the actual emissions, as these gases get entrapped in soil^{36,49}, where they can undergo many changes, namely, oxidation (CH_4 converted to CO_2 by methanotrophs) and denitrification (N_2O denitrified to N_2 by denitrifiers). Here, I present a summary of the factors affecting the production and emissions of CH_4 and N_2O from irrigated paddy fields (Table 1).

The dilemma: Will the mitigation of CH_4 increase the emission of N_2O and vice-versa?

Considerable amount of research has been done on the mitigation of CH_4 and N_2O emissions from agricultural ecosystems in general, as agriculture is one of the greatest contributors of these two gases in the atmosphere. Mitigation of one of these gases from irrigated rice fields by altering management practices, viz. water manage-

Table 1. A comparative evaluation of factors influencing production and emissions of methane and nitrous oxide in irrigated paddy fields

Factor	Impact on methane production and emission	Impact on nitrous oxide production and emission
Water regime		
<i>Soil submergence</i>	Enhanced production and emission ¹⁸	Enhanced the production by denitrification but N ₂ O can be converted to N ₂ , reducing emission ¹¹
<i>Intermittent drainage</i>	Reduced the formation drastically by influxing O ₂ in soil ⁶⁹ thereby reducing emission ⁸²	Increased the production ³³ and emission ^{9,12} by nitrification of NH ₄ ⁺ during drying. Aerobic–anaerobic cycling triggers interchangeable nitrification and denitrification, enhancing N ₂ O emission ⁵⁶
Soil temperature	Emission doubled from 20 to 25°C (ref. 83) and was maximum at about 37°C (ref. 84) With rising temperature, solubility of gases in water decreases increasing the probability of emission	Emission increased during temperature increase from 5 to 40°C (refs 85, 86) Same is true for N ₂ O
Organic matter application	Production and emission increased drastically with organic matter addition ^{45,49}	Production and emissions increase with addition ^{87,88} due to enhanced denitrification ^{89,90} and nitrification of released NH ₄ ⁺ under partially aerobic and aerobic conditions ^{91,92}
Fertilizer type		
<i>Urea</i>	Reported to have both increased ^{8,93} and decreased ⁶ emissions than control	Increased emissions, sometimes more than ammonium sulphate ⁸
<i>Ammonium sulphate</i>	Increased ⁹⁴ and decreased emissions ⁵⁸ . Ammonium increases growth of methanogens, helping produce more CH ₄ (ref. 95) and also inhibits CH ₄ oxidation, leading to more emission ^{15,61,96} . Sulphate may help decrease CH ₄ formation by activating sulphate reducers in soil which compete for the same substrates with methanogens ⁹⁷	Increased emissions, sometimes more than urea ^{6,64,101}
<i>Ammonium nitrate</i>	Inhibited production ⁹⁸	NA
<i>Potassium nitrate</i>	Reduced emission compared to urea and ammonium sulphate ⁸	Resulted in more emissions than urea and ammonium sulphate ⁸
<i>Calcium sulphate</i>	Mitigated emission ⁹⁹	NA
<i>Single superphosphate</i>	Mitigated emission ¹⁰⁰	NA
Fertilizer application technique		
<i>Urea incorporated</i>	Mitigated emission compared to surface application ⁵⁸	Mitigated emission compared to surface application ¹⁰²
<i>Urea surface applied</i>	More emission compared to incorporation ⁵⁸	Increased emission when compared to incorporation and deep placement ¹⁰²
<i>Urea deep placement</i>	NA	Mitigated emission compared to surface application ¹⁰²
<i>Ammonium sulphate incorporated in soil</i>	Emission lowered by 62% (ref. 58)	NA
<i>Ammonium sulphate raked into upper soil</i>	Emission lowered by 43% (ref. 58)	NA
<i>Ammonium sulphate surface applied</i>	Emission lowered by 6% (ref. 58)	NA
Nitrification inhibitors, urease inhibitors and slow release fertilizers		
<i>Urea supergranules</i>	Mitigated emission ¹⁰³	NA
<i>Nimin-coated urea</i>	Mitigated emission ⁷⁶ and even increased emission ⁶⁸	Mitigated emission ⁹
<i>Neem-coated urea</i>	NA	Mitigated emission ⁹
<i>Dicydiamide (DCD)</i>	Mitigated emission ⁸	Mitigated emission ^{9,64}
<i>Thiosulphate</i>	NA	Mitigated emission ⁶⁴
<i>Encapsulated calcium carbide (ECC)</i>	Mitigated emission ³¹	Mitigated emission ¹⁰²
<i>Hydroquinone</i>	NA	Mitigated emission ³¹
<i>Tablet urea</i>	Mitigated emission ⁸⁰	Increased emission compared to prilled urea ⁵⁶
Rice plants	Increase production by providing root exudates ⁴⁵ and increase emissions by providing conduits ^{34,83}	Increase production by enhancing denitrification ^{104,105} and increase emission by providing conduits ¹⁰⁶
Soil texture	Heavy soils may entrap more and allow more oxidation, emitting less ³⁶	More entrapment in heavy soils leads to denitrification to N ₂ and lesser emission while sandy soils emit significantly more ¹⁰⁷
Land preparation	Intercultural operations may increase emissions but it is less frequent in direct-seeded rice due to more plants per unit area, less weed growth and little mechanical weeding ³⁶	Intercultural operations will increase emission, as N ₂ O may move up within the soil more rapidly and escape to the atmosphere
Soil pH	A range between 7.5 and 8.5 is optimum for production ¹⁰⁸	Optimal pH for production is 8.5 with a sharp decrease below 6.5 (ref. 109) although may exist up to 3.5 (ref. 110)
Soil redox potential (Eh)	Production starts at –150 to –160 mV (ref. 5)	Significant production over +250 mV (ref. 50) while below +200 mV, it is not significant ³³
Soil chemical condition	Appreciable amount of Mn ²⁺ , NO ₃ ⁻ , SO ₄ ²⁻ or Fe ³⁺ mitigates production by preventing soil reduction ¹¹¹	NO ₃ ⁻ in soil may increase production by favouring denitrification ⁴⁵ while others do not

NA, Not available.

ment, may lead to an increase in the other. Changes in water regime principally controls soil redox potential which primarily influences the production of the two gases³³. Nitrous oxide is produced at much higher soil Eh (+ 250 mV) while CH₄ production is initiated at -150 mV (refs 50, 51) and since these conditions are contrasting, there is a chance of higher emission of one of the gases while mitigating the other³³. They have found negative correlation between CH₄ and N₂O emissions from a paddy field. Cai *et al.*⁶ have reported a clear trade-off effect between CH₄ and N₂O emissions from an irrigated paddy field and have suggested that it is important to evaluate the integrative effects of water management and fertilizer application for mitigating greenhouse gas emissions in order to attenuate the greenhouse effect contributed by rice paddy fields. Bronson *et al.*⁷ reported that although mid-season drainage mitigated CH₄ emissions by 60%, it led to a sharp increase in N₂O emissions from the rice fields in Philippines. In a pot experiment with paddy soil, continuous flooding led to more CH₄ and lesser N₂O emissions than normal irrigation while under moist irrigation CH₄ emissions reduced and N₂O emissions increased as compared to flooded and normal irrigated conditions⁵². Similar emission trade-offs has been reported by other researchers also^{22,23,25,53}. Minimization of the emissions is necessary to have a minimum environmental damage, e.g. atmospheric radiative forcing and ozone depletion. Management practices have to be so adjusted that emissions of both the gases are effectively mitigated and have the least atmospheric radiative forcing. How mitigating one gas can increase the emission of the other, is discussed in the following sections.

Water management

CH₄ can be mitigated by intermittent drainage, i.e. by stopping irrigation and allowing the standing water to drain from the field. The extent of mitigation is likely to vary appreciably depending on different factors, e.g. soil texture, percolation rate, frequency of drainage, duration of dry period, etc. Field drying at mid-tillering stage has been shown to reduce CH₄ emission by 15–80% as compared to continuous flooding, without a significant effect on grain yield. The net impact of mid-tillering drainage was diminished when (i) rainfall was strong during the drainage period and (ii) emissions were suppressed by very low levels of organic substrate in the soil⁵⁴. Mid-season drainage reduced CH₄ emission by 43%, which can be explained by the influx of oxygen into the soil. The practice of direct seeding instead of transplanting resulted in a 16–54% reduction in CH₄ emission, but the mechanisms for the reducing effect were not clear. Drainage can be artificially enhanced by underground pipe drainage and by modifying soil physical conditions⁵⁵.

On the other hand, drainage will result in appreciable emission of N₂O (refs 7, 21), which can be produced via

both nitrification and denitrification concurrently⁵⁶. Soil NH₄⁺ might accumulate due to slow nitrification of added and native soil NH₄⁺ and from the mineralization of soil organic matter. In that case, nitrification would produce appreciable amount of N₂O during dry cycles. Organic matter also can be mineralized during drainage and N₂O may be produced. Denitrification can produce N₂O from NO₃⁻ at soil saturation or field capacity during drainage and/or at even drier soil conditions in anaerobic micro-sites⁵⁷. On the other hand, if continuous flooding is maintained to control N₂O emission, CH₄ emission will increase considerably³³.

Fertilizer application

Soil reduction can be arrested by adding any electron acceptor to the soil, e.g. SO₄²⁻, NO₃⁻, etc. SO₄²⁻ is a plant nutrient and can supply the much needed nutrient in S deficient soils. SO₄²⁻ can also arrest CH₄ formation by decreasing the activity of methanogens by restricting the availability of substrates in submerged soils. Methane emission has been significantly reduced by the application of sulphate through ammonium sulphate^{58,59}, sodium sulphate⁵⁹ and gypsum⁶⁰ while a non-significant reduction with potassium sulphate was reported by Wassman *et al.*³⁷. Although, ammonium can reduce CH₄ oxidation and thereby can increase CH₄ emission^{61,62}, the presence of sulphate overwhelms this effect and reduces overall CH₄ emission. In a Beijing rice field, an organic amendment plus (NH₄)₂SO₄ as the base fertilizer and (NH₄)₂SO₄ as topdressing, applied in different amounts and growth stages, reduced methane emission by about 58% and increased rice yield by about 31.7%, when compared with no topdressing⁶³. But whether this practice can reduce N₂O emission also or not, have to be tested. Ammonium sulphate addition has enhanced N₂O emission significantly in rice fields because of nitrogen addition in NH₄⁺ form⁶⁴. So, sulphate sources (excluding ammonium sulphate) can be added to reduce methane emission from rice fields. On the other hand, NO₃⁻ application can also reduce the rate of CH₄ formation by slowing down the development of soil reduction. Addition of nitrate with irrigation water at 40 mg l⁻¹ has also reduced methane emission by 23% as compared to normal irrigation water⁶⁵. As NO₃⁻ is a plant nutrient, it will enhance crop production, but will also produce N₂O through denitrification in rice⁸.

Organic matter application

Addition of pre-composted organic matter, a humified substrate, is reported to have produced lesser CH₄ per unit carbon as compared to readily mineralizable carbon sources when added to soil⁶⁶. On the other hand, animal dung compost emitted more N₂O as compared to chemi-

cal fertilizers⁶⁷. Application of *Sesbania*, *Azolla* and compost resulted in emissions of 132, 65 and 68 kg CH₄ ha⁻¹, respectively, during the wet season in Cuttack, India, showing that methane emission can be mitigated, if green manures can be replaced by compost⁶⁸. Addition of rice straw compost increased CH₄ emission by only 23–30% as compared to the 162–250% increase in emissions with the use of fresh rice straw⁶⁹. In contrast, composts of cowdung and leaves decreased CH₄ fluxes⁷⁰. Inducing aerobic degradation through the addition of organic matter may significantly reduce CH₄ emission⁴⁵ but at the same time this might increase N₂O emission by nitrification of released ammonium.

Application of nitrification inhibitors and slow-release fertilizers

Nitrification inhibitors prevent the conversion of NH₄⁺-N into NO₃⁻-N (refs 71, 72) thereby reducing emissions of N₂O via nitrification directly and then by reducing the availability of NO₃⁻ for denitrification^{73,74}. Nitrification inhibitors were quite useful in mitigating N₂O emission from rice fields^{8,9,64}. Apart from artificially synthesized materials, some plant products have also been tested and found suitable to mitigate N₂O from rice fields⁹. Nitrification inhibitors such as dicyandiamide (DCD) and nitrpyrin inhibited the formation of CH₄ and simultaneously mitigated emissions of both the gases from rice fields^{59,75}. On the other hand, since nitrification inhibitors conserve soil NH₄⁺, there is a probability of increased CH₄ emission with inhibitors due to lesser CH₄ oxidation. In a study at Cuttack, India, application of nitrification inhibitor dicyandiamide (DCD) inhibited while nimin, another nitrification inhibitor, stimulated CH₄ emission from flooded rice field compared to the emissions with urea N alone. Methane oxidation decreased with soil depth, fertilizer-N and nitrification inhibitors⁶⁸. Nimin reportedly mitigated methane emission when added to rice fields with prilled urea as compared to prilled urea alone⁷⁶. It is difficult to predict whether CH₄ will be consumed or emitted, as it depends on the extent of inhibition on CH₄ formation and CH₄ oxidation. Slow release fertilizers also mitigated N₂O emission^{9,32,46} while no significant difference in methane emission was found between slow release (coated urea) and fast release (compound fertilizer) N sources⁷⁷.

Extent of CH₄ and N₂O mitigation by the proposed measures: Difficulties in prediction

Many strategies, proposed and practised by different researchers were developed to mitigate emissions of either CH₄ (refs 45, 59, 78, 79) or N₂O (refs 9, 43, 44, 64) from rice fields (Table 2) and so may not effectively mitigate both CH₄ and N₂O simultaneously. Management prac-

tices for irrigated rice could be suitably modified to mitigate emissions of both CH₄ and N₂O. An approach should focus on maximum possible mitigation of both the gases at the same time so that their cumulative radiative force is minimized. Any proposed strategy should be applied at field scale to examine how effectively it works and if they can be applied in farmers' fields without any adverse effect on yield and environment. As long as the economic return from rice is not affected by the practices, they could be implemented. A summary of the proposed strategies is presented in Table 3.

During the cultivation of irrigated rice, the proposed practices can be taken up in a definite sequence to attain appreciable reduction in emissions and good crop yield. They have to be field-tested to know exactly up to what extent they can reduce emissions. The proposed actions can only act as a guide leading to the goal of a maximum possible mitigation of both the gases. It is a difficult proposition to predict the extent of mitigation at present. Although, literature indicates the possible magnitudes of CH₄ and N₂O mitigations by some of the proposed practices under rice (Table 2), it is assumed by the author that when the proposed practices are applied in a certain sequence in an irrigated rice field (Table 4), the exact mitigation of the two gases would be difficult to surmise as many real-time factors will interplay. Soil water content, soil type, type and amount of fertilizer, fertilizer application method, rice variety and type of nitrification inhibitor will principally control the mitigation under field condition, as is evident from widely varied results in field condition from similar mitigation practices. The most effective CH₄ mitigation practice seems to be intermittent drainage, which has mitigated CH₄ up to even 80% but can be as low as 7% possibly because mitigation seems to be strongly dependent on the timing, frequency and span of drainage⁸⁰. Methane can also be strongly mitigated by sulphate application through different sources but can have widely varying values ranging from 9 to 73%⁵⁴. Nitrification inhibitors have been found to have limited success in CH₄ inhibition but can at the same time reduce N₂O emission, the extent of which has been found to vary widely in rice (9–53%)^{8,64}. So, it is evident that the extent of mitigation will be highly site- and practice-specific. Moreover, prediction on simultaneous CH₄ and N₂O mitigations would have to be made from available mitigation studies, which are more often on any one of the gases. On the other hand, some of the proposed mitigation practices here have not been widely tested, e.g. foliar N spray, deep placement of urea supergranules (USG) or urea pellets or urea briquettes on either CH₄ or N₂O emissions and effect of sulphate on N₂O. It will not be out of place to suggest that a quantitative assumption on the concomitant mitigation of the two gases will possibly not match with the actual mitigation in the field, when the proposed practices are practically taken up.

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Table 2. A summary of available data on CH₄ and N₂O mitigation in rice by different practices

Moisture regime	Mitigation strategy	Specific practice	Mitigation (%)*	Remarks	Reference
<i>Methane (CH₄)</i>					
Irrigated	Nitrification inhibitor	Encapsulated calcium carbide (ECC)	90	Greenhouse experiment; Duration – 30 days	112
Irrigated	Fertigation [†]	Nitrate in irrigation water	23	Duration – mid-June to early August	65
Irrigated	Urea + NI	Coated calcium carbide	36	Duration – 77 days; Location – Louisiana	59
		Dicyandiamide (DCD)	14		
	Sulphate	Sodium sulphate	28–35		
Irrigated	Sulphate	Gypsum	55–70	Location – IRRI, Philippines	60
Irrigated	Nitrate	KNO ₃	50	Duration – 93 days; Location – Louisiana, US	113
Irrigated	Drainage	Mid-season drainage	60	Duration – December 1992 to April 1994	7
				Location – Philippines	
Irrigated	Drainage	Intermittent drainage	10	Calculated mitigation, assuming intermittent drainage in 33% of poorly drained rice soils in China, based on 1990 emissions from rice agriculture	79
Irrigated	Sulphate	Ammonium sulphate (AS)	58	Duration – April to October	63
				Location – Beijing, China	
Irrigated	Sulphate	Ammonium sulphate	42–60	Duration – rice season; Location – Jiangsu, China	6
Irrigated	Drainage	Seasonal drainage	63–72	Duration – rice season; Location – SW Agril. Univ. and S China Agril. Univ., China	14
Irrigated	Urea + NI	DCD	22	Duration – 105 days	8
	AS + NI	DCD	13	Location – New Delhi, India	
Irrigated	Iron addition	Fe(OH) ₃	46	Duration – June 13 to October 13	114
				Pot experiment	
Irrigated	Urea + urease inhibitor + NI	Hydroquinone + DCD	66	Pot experiment with low-land rice soil	31
Irrigated	Sulphate	Ammonium sulphate	25–36	Duration – 1994–1998 rice seasons	69
		Phosphogypsum	72	Location – Central Luzon, Philippines	
	Drainage	Mid-season drainage	43		
	Seeding	Direct seeding	16–54		
Irrigated	Iron addition	Ferrihydrite		Greenhouse experiment	115
		15 g kg ⁻¹ soil	43		
		30 g kg ⁻¹ soil	84		
Irrigated	Drainage	Mid-season drainage	44	Duration – 1995–98 rice seasons	116
				Location – Hangzhan, China	
	Irrigation	Intermittent irrigation	30% less than mid-season drainage		
Irrigated	Drainage	Mid-season drainage	23	Duration – 1995–98 rice seasons	117
				Location – Beijing, China	
Irrigated	Drainage	Seasonal drainage	42–67	Duration – Rice season;	17
				Location – Los Banos, Philippines	
Irrigated	Drainage	Mid-season drainage	7–80	Duration – rice season	54
	Sulphate	Ammonium sulphate	10–67	Locations – China, India, Indonesia, Thailand,	
		Phosphogypsum	9–73	Philippines	
Irrigated	Drainage	Mid-tillering drainage	15–80	Duration – 1994–96 rice seasons	80
				Location – Los Banos, Philippines	
Irrigated	Slow release N	Tablet urea	10–39	Location – Jakenan, Indonesia	80
<i>Nitrous oxide (N₂O)</i>					
Irrigated	Urea + NI	ECC	44	Greenhouse experiment; Duration – 30 days	112
Irrigated	Slow release N	Wax-coated calcium carbide	73	Location – Griffith, Australia; Direct seeded flood	118
Irrigated	Slow release fertilizer	Polyolefin-coated fertilizer (POF)	80	field experiment, Duration – 110 days	119
				Location – Japan, Basal application	
Irrigated	Urea + NI	DCD	53	Duration – 105 days; Location – New Delhi, India	8
	AS + NI	DCD	46		
Irrigated	Sulphate	Phosphogypsum	100	Location – Louisiana, USA; Applied at 2.5, 5 and 10 tons/ha	28
Irrigated	Urea + urease inhibitor (UI) + NI	Urea + hydroquinone + DCD	50	Pot experiment with low-land rice soil	31
Irrigated	Urea + NI	DCD	11	Duration – 98 days	64
	AS + NI	Thiosulphate	9	Location – New Delhi, India	
		DCD	26		

*Calculated as percent reduction of emission as compared to without mitigation practice; NI, Nitrification inhibitor.

[†]Fertilizer mixed with irrigation water; NA, Not available.

Table 3. Strategies for simultaneous mitigation of CH₄ and N₂O emissions from irrigated rice

Strategy	Basic working mechanism	Remarks
Phosphorus (P) application through single superphosphate (SSP), which reduces CH ₄ emission from rice ¹⁰⁰	S in SSP forms sulphate and reduce methane emission	Effect of P and N ₂ O emissions from rice is unknown. But, in maize, sorghum and soybean, N ₂ O emission was reduced by P application ¹²⁰
Application of ammonium fertilizers in the reduced zone	Ammonium sulphate reduces CH ₄ emissions by 63% (ref. 58). In reduced zone, it will not affect CH ₄ oxidation and there will be negligible nitrification and denitrification to produce N ₂ O	Ammonium and urea can be deep-placed at planting and once later, through mud ball placement at 10–12 cm below ground at the base of the seedlings in row-transplanted rice ¹²¹
Application of N in splits at critical growth stages ¹²²	In initial stages, low doses of N are advisable as N uptake by rice is low then ¹²³ and this will help reduce N ₂ O	Split application should be done on dry field and no immediate irrigation should follow to reduce wastage of fertilizer
Addition of nitrification inhibitors (NI) with urea and ammonium fertilizers	NI will minimize N ₂ O emission via nitrification directly and denitrification indirectly and may inhibit CH ₄ formation also	DCD, neem-coated urea, ECC, nitrapyrin, etc. may be applied along with fertilizers
Application of foliar urea-N in water-logged conditions ¹²¹	Foliar-N spray may reduce N ₂ O emissions from soil and reduced methane fluxes by 45, 60 and 20% in ammonium sulphate, ammonium chloride and urea broadcasted plots, respectively ¹²⁴	Concentration of urea solution should be carefully chosen to prevent foliar damage ¹²¹
Addition of SO ₄ ²⁻ through gypsum, sodium sulphate, potassium sulphate, etc.	Sulphate inhibits methane formation, reducing CH ₄ emission	Excessive sulphate application may lead to Akiochi
Mid-season drainage should be practised when it does not coincide with high soil ammonium	Mid-season drainage reduces CH ₄ formation and enhances CH ₄ oxidation but high soil ammonium may increase N ₂ O emission via nitrification	To prevent NH ₄ ⁺ accumulation, urea and ammonium should be applied in splits and soil ammonium should be regularly monitored. Mid-season drainage should not reduce yield
Irrigation by good-quality water	High DO in irrigation water will help maintain an oxidized zone in soil helping CH ₄ oxidation	Wastewater irrigation may considerably increase CH ₄ and N ₂ O emissions and so should be avoided
Plant population should be optimum	Nutrient uptake will be good and N ₂ O and CH ₄ emissions through plants will be low	Nutrient and water management and cultural practices can be practised with a greater ease
Rice varieties with low gas transport, low exudate production and high harvest index ⁴⁵ are preferable	These varieties will control emission of both the gases	Many rice varieties have not been tested for their gas transport potentials. Sometimes, seeds of the desired varieties may not be available
Application of slow-release N, especially S and rock phosphate-coated urea ¹²¹	Neem coated, shellac coated, wax coated ¹²¹ , nimin coated ¹²⁵ , etc. can also be used. Neem-based products can also act as nitrification inhibitors	These products can be indigenously produced with locally available materials
Deep placement of urea supergranules (USG), urea pellets and urea briquettes ¹²¹	Can be deep-placed at 8–10 cm below ground ¹²² in reduced zone to maximize N recovery and reduce N ₂ O loss ¹²⁶ . Subsurface application of urea supergranules reduces methane flux over control ¹⁰³	Cost of USG is not much higher than prilled urea
Pre-incubated urea (urea : moist soil = 1 : 6) can be applied after keeping it for 2–3 days ¹²¹	This ensures release of NH ₄ ⁺ via hydrolysis of urea and its fixation during pre-incubation and thus applied NH ₄ ⁺ is not lost quickly from soil	Can be broadcasted on field
Incorporation and deep placement of prilled urea	These practices have reduced emission of N ₂ O + N ₂ from flooded rice ¹⁰²	Rice yield may also improve due to increased N-use efficiency
Avoidance of green manure addition in soil. Compost is a better option	Green manure is fresh organic matter, which might increase methane emissions	Green manure is applied in rice in many countries to get higher yield
Allow the growth of aquatic weeds and algae in floodwater	Algae can impart O ₂ in floodwater and maintain the oxidized zone, helping CH ₄ oxidation	Algal immobilization of added N may decrease N use efficiency. Algae should not be incorporated in soil which might increase CH ₄ emission

Table 4. Proposal of three different sets of management practices which can be followed alternatively in sequence, in irrigated rice for concomitant mitigation of CH₄ and N₂O

Alternative 1	Alternative 2	Alternative 3
Basal incorporation of composted organic matter	Basal incorporation of composted organic matter	Basal incorporation of composted organic matter
Basal incorporation of SSP	Basal incorporation of SSP	Basal incorporation of SSP
Basal application of slow-release urea or urea with nitrification inhibitors	Application of prilled urea and through incorporation in the soil	Sub-surface application of urea supergranules or urea briquettes
Incorporation of gypsum	Incorporation of potassium sulphate	Incorporation of phosphogypsum
Transplanting of rice varieties with low gas transport capacity and low-exudate formation	Transplanting of rice varieties with low-gas transport capacity and low exudate formation	Transplanting of rice varieties with low gas transport capacity and low exudate formation
Maintenance of optimum plant population	Maintenance of optimum plant population	Maintenance of optimum plant population
Drying of field when inhibitor is no longer effective* and soil NH ₄ is low	Drying of field when soil NH ₄ is low [†]	Drying of field when soil NH ₄ is low
Interculture operations to be kept at minimum required	Interculture operations to be kept at minimum required	Interculture operations to be kept at minimum required
Foliar-N spray at critical stages of crop need	Top dressing and good incorporation of ammonium sulphate with nitrification inhibitors during drainage	Top dressing and good incorporation of ammonium sulphate with nitrification inhibitors during drainage

*Has to be determined through laboratory studies or to be found out from available literature.

[†]Soil NH₄⁺ content should be analyzed just before mid-season drainage.

Concluding remarks: Applicability of the proposed strategies

There are several formidable obstacles to incorporate these mitigation practices into local rice farming⁴⁵. The strategies should be so formulated that they are effective, applicable, technically feasible, economic, less time-consuming and at the same time, easily understood and accepted by farmers. We have to consider different associated factors, viz. labour requirement, effects on rice yield and soil fertility and short- and long-term environmental sustainability, under both up-land and low-land conditions. Although nitrification inhibitors can mitigate the production of both the gases, in many countries they are not used in farmers' fields due to lack of publicity, non-availability, high price or apathy. Ghosh⁸ has shown that in an irrigated paddy field, total radiative forcing of CH₄ can be much more than N₂O and mitigating N₂O emission by nitrification inhibitors is a much costlier option when compared to mitigation of CH₄. This implies that emphasis should be more on mitigating CH₄ emission from irrigated paddy field, since it is less costly and its emission is much higher than N₂O. Slow release N-fertilizers like coated urea preparations, USG, urea briquettes etc. have remained only as researcher's tools without being popularized in countries like India, China, Pakistan, Bangladesh, Thailand, Indonesia, Malaysia, Philippines, etc., where rice is the most important cereal crop and covers large areas under cultivation. Hou *et al.*³³ have proposed that production of both the gases can be minimized if soil Eh can be controlled in a range of

– 100 mV and + 200 mV, where it is too high for CH₄ production and favourable for N₂ production rather than N₂O. Soil Eh can be effectively controlled by manipulating water management, which can only be done in areas having assured water supply. However, many areas designated as irrigated lack consistent water supply. Moreover, in rainy seasons, it is difficult to follow water management practices in field. Some practices like deep placement of fertilizers, local preparation of coated fertilizers have extensive labour requirement, which is not always available at cheap rates. Above all, it is difficult to convince the farmers to follow these practices until and unless they show some economic benefits.

A reduction in the application of N fertilizers and organic fertilizers would possibly reduce methane and N₂O emissions from rice fields, but would also reduce total rice production unless the area under rice cultivation is increased. Reducing the period of inundation, growing alternative crops, aeration of water and alternating rice crops with other crops in the dry season are suggested methods of reducing methane emission⁸¹. They have also suggested dry seeding in place of transplanting, for CH₄ mitigation. Dry seeding is getting increasingly popular among farmers due to labour savings although it has a lower yield potential than transplanting⁶⁹. But this practice has to be tested for its effects on N₂O emissions. To implement a rice cultivation system based on the proposed practices, institutional and political support is needed which is virtually absent in many countries. Further studies to verify the mitigation options should focus on the feasibility for local farmers.

1. Crutzen, P. J., *J. R. Meteor. Soc. London*, 1970, **96**, 320–325.
2. Cicerone, R. J. and Oremland, R. S., *Global Biogeochem. Cycl.*, 1989, **2**, 299–327.
3. Bouwman, A. F., in *Soils and the Green House Effect* (ed. Bouwman, A. F.), John Wiley and Sons, New York, 1990, pp. 61–127.
4. IPCC, *Climate Change (1995): Scientific Technical Report Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (eds Watson, R. T., Zinyowera, M. C. and Ross, R. H.), Cambridge and New York, 1996, p. 880.
5. IPCC, *Climate Change: A Scientific Basis, Intergovernmental Panel on Climate Change* (eds Houghton, J. T. et al.), Cambridge University Press, UK, 2001.
6. Cai, Z. C., Xing, G. X., Yan, X. Y., Xu, H., Tsuruta, H., Yagi, K. and Minami, K., *Plant Soil*, 1997, **196**, 7–14.
7. Bronson, K. F., Neue, H. U., Singh, U. and Abao, E. B. Jr., *Soil Sci. Soc. Am. J.*, 1997, **61**, 981–987.
8. Ghosh, S., Ph D thesis, Indian Agricultural Research Institute, New Delhi, 1998.
9. Majumdar, D., Kumar, S., Pathak, H., Jain, M. C. and Kumar, U., *Agric. Ecosyst. Environ.*, 2000, **81**, 163–169.
10. IPCC – Intergovernmental Panel on Climate Change, *Climate Change. The supplementary report to the IPCC scientific assessment*, 1994.
11. Granli, T. and Bockman, O. C., *Nor. J. Agric. Sci.*, 1994, 128.
12. Shao, K. S., *Rural Eco-Environ. (Suppl.)*, 1993, 19–22.
13. Yagi, K. and Minami, K., *Soil Sci. Plant Nutr.*, 1990, **36**, 599–610.
14. Cai, Z. C., Xu, H., Lu, W., Liao, Z. W., Wei, C. F. and Xie, D. T., *Chin. J. Appl. Ecol.*, 1998, **9**, 171–175.
15. Conrad, R. and Rothfuss, F., *Biol. Fertil. Soils*, 1991, **12**, 28–32.
16. McCarty, G. W. and Bremner, J. M., *Biol. Fertil. Soils*, 1991, **11**, 231–233.
17. Wassmann, R., Neue, H. U., Lantin, R. S., Makarim, K., Chareonsilp, N., Buendia, L. V. and Rennenberg, H., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 13–22.
18. Ponnampetuma, F. N., *Adv. Agron.*, 1972, **24**, 29–96.
19. Lindau, C. W., DeLaune, R. D., Patrick, W. H. Jr. and Bollich, P. K., *Soil Sci. Soc. Am. J.*, 1990, **54**, 1789–1794.
20. Lindau, C. W., Patrick, W. H. Jr., DeLaune, R. D. and Reddy, K. R., *Plant Soil*, 1990, **219**, 269–276.
21. Chen, G. X., Huang, G. H., Huang, B., Yu, K. W., Wu, J. and Xu, H., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 41–45.
22. Hou, A. X., Chen, G. X., Wu, J., Wang, Z. P., Hou, A. X., Chen, G. X., Wu, J. and Wang, Z. P., *Chin. J. Appl. Ecol.*, 1997, **8**, 270–274.
23. Li, Y., Erda, L., Minjie, R. and Li, Y., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 47–50.
24. Lu, W., Zhang, F. N., Liao, Z. W., Lu, W. S. and Liao, Z. W., *Chin. J. Appl. Ecol.*, 1997, **8**, 275–278.
25. Yang, J., He, L. P., Yang, C., Chen, Y. F., Lu, X. J. and Wu, S. Z., *J. South China Agril. Univ.*, 1997, **18**, 62.
26. Hou, A. X., Chen, G. X. and Wu, J., *Chin. Rice Res. Newsl.*, 1998, **6**, 10–11.
27. Hou, A. X., Chen, G. X., Wu, J., Wang, Z. P. and van Cleemput, O., *Chin. Rice Res. Newsl.*, 1998, **6**, 7–9.
28. Lindau, C. W., Wickersham, P., DeLaune, R. D., Collins, J. W., Bollich, P. K., Scott, L. M. and Lambremont, E. N., *Agric. Ecosyst. Environ.*, 1998, **68**, 165–173.
29. Winchester, J. W., Fan, S. M. and Li, S. M., *Water Air Soil Pollut.*, 1988, **37**, 149–155.
30. Cai, Z. C., Xing, G. X., Shen, G. Y., Xu, H., Yan, X. Y., Tsuruta, H., Yagi, K. and Minami, K., *Soil Sci. Plant Nutr.*, 1999, **45**, 1–13.
31. Zhou, L. K., Xu, X. K., Chen, J., Li, R. H. and Cleemput, O. V., *Chin. J. Appl. Ecol.*, 1999, **10**, 189–192.
32. Abao, E. B. Jr., Bronson, K. F., Wassmann, R. and Singh, U., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 131–139.
33. Hou, A. X., Chen, G. X., Wang, Z. P., van Cleemput, O. and Patrick, W. H. Jr., *Soil Sci. Soc. Am. J.*, 2000, **64**, 2180–2186.
34. Seiler, W. A., Holzapfel-Pschorn, R., Conrad, R. and Schaeffe, D., *J. At. Chem.*, 1984, **1**, 241–268.
35. Eichner, M. J., *J. Environ. Qual.*, 1990, **19**, 272–280.
36. Neue, H., *BioScience*, 1993, **43**, 466–473.
37. Wassmann, R., Papen, H. and Rennenberg, H., *Chemosphere*, 1993, **26**, 201–218.
38. Sahrawat, K. L. and Keeney, D. R., *Adv. Soil Sci.*, 1986, **4**, 103–148.
39. Singh, J. S. and Singh, S., *Trop. Ecol.*, 1995, **36**, 145–165.
40. Mosier, A. R., Duxbury, J. M., Freney, J. R., Heinemeyer, O. and Minami, K., *Plant Soil*, 1996, **181**, 95–108.
41. Sharma, C., Gupta, P. K. and Parashar, D. C., *Trop. Ecol.*, 1996, **37**, 153–166.
42. Beauchamp, E. G., *Can. J. Soil Sci.*, 1997, **77**, 113–123.
43. Cole, C. V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, M., Sauerbeck, D. and Zhao, Q., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 221–228.
44. Freney, J. R., *Nutr. Cycl. Agroecosys.*, 1997, **48**, 155–160.
45. Yagi, K., Tsuruta, H. and Minami, K., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 213–220.
46. Bockman, O. C. and Olf, H. W., *Nutr. Cycl. Agroecosys.*, 1998, **52**, 165–170.
47. Pathak, H., *Curr. Sci.*, 1999, **77**, 359–369.
48. Majumdar, *Curr. Sci.*, 2000, **79**, 1435–1439.
49. Majumdar, D., Kumar, S. and Jain, M. C., *Asia Pacific J. Environ. Dev.*, 1999, **6**, 81–95.
50. Masscheleyn, P. H., Delaune, R. D. and Patrick, W. H. Jr., *Chemosphere*, 1993, **26**, 251–260.
51. Wang, Z., Delaune, R. D., Masscheleyn, P. H. and Patrick, W. H. Jr., *Soil Sci. Soc. Am. J.*, 1993, **57**, 382–385.
52. Yan, X. Y., Shi, S. L., Du, L. J. and Xing, G. X., *Acta Pedolog. Sin.*, 2000, **37**, 482–489.
53. Seneviratne, G., Holm, L. H. J. and van Holm, L. H. J., *Soil Biol. Biochem.*, 1998, **30**, 1619–1622.
54. Wassmann, R., Buendia, L. V., Lantin, R. S., Bueno, C. S., Lubigan, L. A., Umali, A., Nocon, N. N., Javellana, A. M. and Neue, H. U., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 107–119.
55. Tabuchi, T., in *Soil Physics and Rice*, Los Banos, IRRI, 1985, pp. 147–159.
56. Suratno, W., Murdiyarso, D., Suratmo, F. G., Anas, I., Saeni, M. S., Rambe, A., Manning, W. J. and Dempster, J. P., *Environ. Pollut.*, 1998, **102**, 159–166.
57. Arah, J. R. M. and Smith, K. A., *J. Soil Sci.*, 1989, **40**, 139–149.
58. Schutz, H., Holzapfel-Pschorn, A., Conrad, R., Rennenberg, H. and Seiler, W., *J. Geophys. Res.*, 1989, **94**, 16405–16416.
59. Lindau, C. W., Bollich, P. K., DeLaune, R. D., Mosier, A. R. and Bronson, K. F., *Biol. Fertil. Soils*, 1993, **15**, 174–178.
60. Denier van der Gon and Neue, H. U., *Global Biogeochem. Cycl.*, 1994, **8**, 127–134.
61. Hutsch, B. W., Webster, C. P. and Powlson, D. S., *Soil Biol. Biochem.*, 1993, **25**, 1307–1317.
62. Willison, T. W., Webster, C. P., Goulding, K. W. T. and Powlson, D. S., *Chemosphere*, 1995, **30**, 539–546.
63. Shao, K. and Li, Z., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 139–146.
64. Kumar, U., Jain, M. C., Pathak, H., Kumar, S. and Majumdar, D., *Biol. Fertil. Soils*, 2000, **32**, 474–478.
65. Kitada, K., Ozaki, Y., Akiyama, Y. and Yagi, K., *Jpn. J. Soil Sci. Plant Nutr.*, 1993, **64**, 49–54.
66. Tsutsuki, K. and Ponnampetuma, F. N., *Soil Sci. Plant Nutr.*, 1987, **33**, 13–33.

67. Chao, C. C. and Chao, C. C., *Taiwanese J. Agric. Chem. Food Sci.*, 2001, **39**, 275–283.
68. Adhya, T. K., Bharati, K., Mohanty, S. R., Ramakrishnan, B., Rao, V. R., Sethunathan, N. and Wassmann, R., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 95–105.
69. Corton, T. M., Bajita, J. B., Grospe, F. S., Pamplona, R. R., Asis, C. A. Jr., Wassmann, R., Lantin, R. S. and Buendia, L. V., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 37–53.
70. Agnihotri, S., Kulshreshtha, K. and Singh, S. N., *Environ. Monitoring and Assessment*, 1999, **58**, 95–104.
71. Bronson, K. F., Touchton, J. T., Hauck, R. D. and Kelley, K. R., *Soil Sci. Soc. Am. J.*, 1991, **55**, 130–135.
72. Prasad, R. and Power, P. J., *Adv. Agronomy*, 1995, **54**, 233–281.
73. Aulakh, M. S., Rennie, D. A. and Paul, E. A., *Soil Biol. Biochem.*, 1984, **16**, 351–356.
74. Bronson, K. F., Mosier, A. R. and Bishnoi, S. R., *Soil Sci. Soc. Am. J.*, 1992, **56**, 161–165.
75. Salvas, P. L. and Taylor, B. F., *Curr. Microbiol.*, 1980, **4**, 305.
76. Rath, C. K., Das, S. N. and Thakur, R. S., *J. Sci. Ind. Res.*, 2000, **59**, 107–113.
77. Sugii, H., Abdul, H., Acquaye, S., Cheng, W., Inubushi, K., Cheng, W. G. and Hadi, A., *Technical Bulletin of Faculty of Horticulture (Chiba University)*, 1999, **53**, 7–13.
78. Minami, K., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 203–211.
79. Kern, J. S., Zitong, G., Ganlin, Z., Huizhen, Z. and Guobao, L., *Nutr. Cycl. Agroecosys.*, 1997, **49**, 181–195.
80. Wassmann, R., Lantin, R. S., Neue, H. U., Buendia, L. V., Corton, T. M. and Lu, Y., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 23–36.
81. Ranganathan, R., Neue, H. U., Pingali, P. L., Peng, S. and Ingram, K. T., in *Climate Change and Rice* (eds Ingram, K. T., Neue, H. U. and Ziska, L. H.), 1995, pp. 122–135.
82. Sass, R. L., Fisher, F. M., Wang, Y. B., Turner, F. T. and Jund, M. F., *Global Biogeochem. Cycl.*, 1992, **6**, 249–262.
83. Holzapfel-Pschorn, A. and Seiler, W., *J. Geophys. Res.*, 1986, **91**, 11803–11814.
84. Sass, R. L., Fisher, F. M., Turner, F. T. and Jund, M. F., *Global Biogeochem. Cycl.*, 1991, **5**, 335–350.
85. Bremner, J. M. and Blackmer, A. M., in *Biochemistry of Ancient and Modern Environments* (ed. Delwiche, C. C.), Australian Academy of Science, Canberra, Australia, 1981, pp. 279–291.
86. Blackmer, A. M., Robbins, S. J. and Bremner, J. M., *Soil Sci. Soc. Am. J.*, 1982, **46**, 937–942.
87. Terry, R. E., Tate, R. L. and Duxbury, J. M., *Am. Polln. Contr. Assoc. J.*, 1981, **31**, 1173–1176.
88. Duxbury, J. M., Bauldin, D. R., Terry, R. E. and Tate, R. L., *Nature*, 1982, **275**, 602–604.
89. Beauchamp, E. G., Trevors, J. T. and Paul, J. W., *Adv. Soil Sci.*, 1989, **10**, 113–142.
90. Abeliovich, A. and Vonshak, A., *Arch. Microbiol.*, 1992, **158**, 267–270.
91. Bremner, J. M. and Blackmer, A. M., *Science*, 1978, **199**, 295–297.
92. Freney, J. R., Denmead, O. T. and Simpson, J. R., *Soil Biol. Biochem.*, 1979, **11**, 167–173.
93. Banik, A., Sen, M. and Sen, S. P., *Biol. Fertil. Soils*, 1996, **21**, 319–322.
94. Nugroho, S. G., Lumbanraja, J., Suprpto, H., Sunyoto, Ardjasa, W. S., Haraguchi, H. and Kimura, M., *Soil Sci. Plant Nutr.*, 1994, **40**, 275–281.
95. Bergstrom, D. W., Tenuta, M. and Beauchamp, E. G., *Biol. Fertil. Soils*, 1994, **18**, 1–6.
96. Crill, P. M., Martikainen, P. J., Nykanen, H. and Silvola, J., *Soil Biol. Biochem.*, 1994, **26**, 1331–1339.
97. Hori, K., Inubushi, K., Matsumoto, S. and Wada, H., *Jpn. J. Soil Sci. Plant Nutr.*, 1990, **64**, 49–54.
98. Wang, Z. P., Delaune, R. D., Lindau, C. X. and Patrick, W. H. Jr., *Fert. Res.*, 1992, **33**, 115–121.
99. Lindau, C. W., Alford, D. P., Bollich, P. K. and Linscombe, S. D., *Plant Soil*, 1994, **158**, 299–301.
100. Adhya, T. K., Pattnaik, P., Satpathy, S. N., Kumaraswamy, S. and Sethunathan, N., *Soil. Biol. Biochem.*, 1998, **30**, 177–181.
101. Xu, H., Xing, G. X., Cai, Z. C. and Tsuruta, H., *Chin. J. Appl. Ecol.*, 1999, **10**, 186–188.
102. Keerthisinghe, D. G., Xin, J. L., Q, X. L. and Mosier, A. R., *Fert. Res.*, 1996, **45**, 31–36.
103. Rath, A. K., Swain, B., Ramakrishnan, B., Panda, D., Adhya, T. K., Rao, V. R. and Sethunathan, N., *Agric. Ecosys. Environ.*, 1999, **76**, 99–107.
104. Jones, B. G. and Sauberbeck, D. R., *Ecol. Bull.*, 1977, **25**, 366–373.
105. Smith, M. S. and Tiedje, J. M., *Soil Biol. Biochem.*, 1979, **11**, 261–267.
106. Xu, K. W., Wang, Z. P. and Chen, G. X., *Biol. Fertil. Soils*, 1997, **24**, 341–343.
107. Xu, H., Xing, G. X., Cai, Z. C. and Tsuruta, H., *Acta Pedolog. Sin.*, 2000, **37**, 499–505.
108. Parashar, D. C., Rai, J., Sharma, R. C. and Singh, N., *Indian J. Radio Space Phys.*, 1991, **20**, 12–17.
109. Hynes, R. K. and Knowles, R., *Can. J. Microbiol.*, 1984, **30**, 1397–1404.
110. Aulakh, M. S., Doran, J. W. and Mosier, A. R., *Adv. Soil Sci.*, 1992, **56**, 95–102.
111. Achtnich, C., Bak, F. and Conrad, R., *Biol. Fertil. Soils*, 1995, **19**, 65–72.
112. Bronson, K. F. and Mosier, A. R., *Biol. Fertil. Soils*, 1991, **11**, 116–120.
113. Lindau, C. W., *Soil Biol. Biochem.*, 1994, **26**, 353–359.
114. Watanabe, I. and Kimura, M., *Communications Soil Science Plant Analysis*, 1999, pp. 302449–302463.
115. Jaekel, U. and Schnell, S., *Soil Biol. Biochem.*, 2000, **32**, 1811–1814.
116. Lu, W. F., Chen, W., Duan, B. W., Guo, W. M., Lu, Y., Lantin, R. S., Wassmann, R. and Neue, H. U., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 65–73.
117. Wang, Z. Y., Xu, Y. C., Li, Z., Guo, Y. X., Wassmann, R., Neue, H. U., Lantin, R. S., Buendia, L. V., Ding, Y. P. and Wang, Z. Z., *Nutr. Cycl. Agroecosys.*, 2000, **58**, 55–63.
118. Mosier, A. R., Season, K. F., Freney, J. R. and Deegala, K. G., in *CH₄ and N₂O: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*, NIAES, 1994, pp. 197–207.
119. Shoji, S. and Kanno, H., *Fert. Res.*, 1994, **39**, 147–152.
120. Chen, X., Shen, S. M., Zhang, L., Wu, J. and Wang, X. Q., *Chin. J. Appl. Ecol.*, 1995, **6**, 104–105.
121. FAI (Fertilizer Association of India), *Fert. News*, 1977, **22**, 3–18.
122. Pillai, G. K., *Fert. News*, 1981, **26**, 3–9.
123. DeDatta, S. K. and Magnaye, C. P., *Soil Fert.*, 1969, **32**, 103–109.
124. Kimura, M., in *World Inventory of Soil Emission Potentials* (eds Batjes, N. H. and Bridges, E. M.), WISE Report 2, 1992, ISRIC, Wageningen.
125. Vyas, B. N., Godrej, N. B. and Mistry, K. B., *Fert. News*, 1991, **2**, 19–25.
126. Savant, N. K., Craswell, E. T. and Diamond, R. B., *Fert. News*, 1983, **28**, 27–35.

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