Minireview

Methane Emission from Paddy Fields and its Mitigation Options on a Field Scale

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Rice is one of the most important cereals, especially in Asian countries. Methane (CH₄), one of the major greenhouse gases, is emitted from flooded paddy fields as a result of phenomena on various scales. This paper reviews studies on CH₄ emission from paddy fields, paying special attention to mitigation options from the viewpoint of their feasibility on a field scale. Field management of rice paddies is primarily carried out to obtain suitable rice yields, but it also has physical, chemical, and biological effects on CH₄ emission. Therefore, some management practices can be win-win options that sustain rice yield and mitigate CH₄ emission. For example, appropriate water management for rice growth and yield is also effective in decreasing CH₄ emission. Other practices, such as nitrogen fertilizer application and organic matter application can also have positive effects on rice yield and CH₄ emission. Recent microbial studies have been revealing the ecology of methanogens and methanotrophs in paddy soils. Further studies on a microbial scale will offer additional clues to the mitigation of CH₄ emission from paddy fields.

Key words: methane, global warming, paddy field, rice, field management

Introduction

Agriculture is essential for food and fiber production, but these activities impact the environment. Rice is one of the world's most important cereals; in 2000 it supplied 20% of the total calorie intake by humans worldwide⁵⁸). In Asia, an area of 136×10⁶ ha is harvested to produce 556 Tg (Mt) of rough rice, accounting for 88 and 90% of the world's total, respectively, in 2004³⁵).

In accordance with the availability of water, rice cultivation areas in 2001 could be divided into irrigated (57% of the total area in Asia), rainfed lowland (33%), upland (7%), and deepwater (3%)³⁵). Rice is cultivated sustainably in

flooded paddy fields because the reductive conditions cause substances harmful to rice growth to flow out. This is not the case in upland fields.

However, soil reductive conditions cause the emission of methane (CH₄), one of the major greenhouse gases (GHGs). Paddy fields will continue to be major sources of CH₄ because of the need to increase rice production and the harvested area to feed the increasing human population, especially in Asian countries (Fig. 1).

Global Warming

Contribution of GHGs

Global warming is a representative environmental problem that involves all living things on Earth. Carbon dioxide (CO₂), CH₄, and nitrous oxide (N₂O) are the major GHGs,

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Fig. 1. Decadal changes in human population (line) and rice harvested area (bar) in Asia and the world from 1961 to 2001 (data from FAO³⁵).

and radiative forcing of each of these accounts for approximately 60, 20, and 6%, respectively, of the total quantity of direct GHGs⁵⁷). Each GHG has its own lifetime against tropospheric OH loss, so time scale must be considered in the global warming potentials (GWPs) for different time horizons, i.e. 20, 100, or 500 years⁵⁷).

Before the Industrial Revolution in the 18th Century, atmospheric concentrations of the three GHGs had been stable because there was only natural exchange⁵⁶). Anthropogenic GHG emissions have been increasing since the Industrial Revolution, echoing the increasing pace of global agriculture and industrial development⁵⁷). Cole *et al.*²⁶) reported that CO₂, CH₄, and N₂O emissions from agriculture and agriculture-related land account for 34% of the annual increase in radiative forcing of these three GHGs. The IPCC⁵⁷) predicts that the atmospheric concentrations of the three GHGs over the next century will likely be driven by changes in both anthropogenic and natural sources. In taking a precautionary approach to global warming, we must mitigate anthropogenic GHG emissions.

Distribution of CH₄ sources

Methane, especially that emitted from agriculture and agriculture-related lands, is the second-most important GHG (Table 1). The global CH₄ emission from the most important sources is estimated at approximately 600 Tg CH₄/yr⁵⁷). Although the major sources have probably been identified, source strengths are still unclear because of the difficulty in assessing the global emission from biospheric sources, whose strengths are highly variable in space and time⁵⁷).

Methane sources are divided into biological and non-biological types. Biological sources consist of wetlands, termites, oceans, landfills, ruminants, and paddy fields. Non-

biological sources are biomass burning and fossil fuel origins such as hydrates, mining, and transport. Both types comprise anthropogenic and natural emissions. As calculated from Fung *et al.*³⁸) and Hein *et al.*⁴⁹), anthropogenic CH₄ emission accounts for 60–70% of total CH₄ emission.

CH₄ Emission from Paddy Fields

Estimation of total amount of CH₄ emission

Recent studies have estimated the CH₄ emission from paddy fields at 53 Tg CH₄/yr²¹), 25–54 Tg CH₄/yr⁹⁸), 33–49 Tg CH₄/yr¹⁰¹), or 25.1 Tg CH₄/yr¹⁴⁵), although studies performed before 1990 gave higher estimates^{7,25,50,118}). The recent estimates of paddy emission account for 4.2–9.0% of the total global CH₄ emission (600 Tg CH₄/yr). National-scale estimations have been made in rice-cultivating countries, such as China^{18,66,114,128,150}), India¹⁰⁶), Japan^{139,142}), Taiwan¹⁴⁸), Thailand¹⁴²), the Philippines^{100,101}), and the United States^{101,113}). Previously, Kumaraswamy *et al.*⁷⁴) reviewed CH₄ emission from paddy fields, and Le Mer and Roger⁷⁶) reviewed CH₄ production, oxidation, emission, and consumption in various soils.

Paddy fields also emit CO₂ and N₂O. Tsuruta *et al.*¹²⁴) evaluated the contributions of emissions of the three GHGs from Japanese paddy fields to the GWPs with a 100-year time horizon. The CH₄, CO₂, and N₂O emissions accounted for 78.2, 16.0, and 5.8% of the total CO₂-equivalent emission, respectively. Therefore, a decrease in CH₄ emission would be the best option for mitigating total GHG emissions from paddy fields.

Mechanism of CH₄ emission

In flooded paddy soils, after the trapped molecular O₂ has

Table 1. Estimates of the global CH₄ sources (Tg CH₄/yr) from different references

References: Base year:	Fung <i>et al.</i> ³⁸⁾ 1980s	Hein <i>et al.</i> ⁴⁹⁾ —	Lelieveld <i>et al.</i> ⁷⁵⁾ 1992	Houweling <i>et al.</i> ⁵³⁾ —	Mosier <i>et al.</i> ⁹⁸⁾ 1994	Olivier <i>et al.</i> ¹⁰⁵⁾ 1990
Natural sources						
Wetlands	115	237	225 ^b	145		
Termites	20	—	20	20		
Ocean	10	—	15	15		
Hydrates	5	—	10	—		
Anthropogenic sources						
Energy	75	97	110	89		109
Landfills	40	35	40	73		36
Ruminants	80	90 ^a	115	93	80	93 ^a
Waste treatment	—	^a	25	—	14	^a
Rice agriculture	100	88	^b	—	25–54	60
Biomass burning	55	40	40	40	34	23
Other	—	—	—	20	15	
Total source	500	587	600			

Data from IPCC⁵⁷⁾.

—: not estimated, blank: no aim to estimate originally.

^a Waste treatment included under ruminants.^b Rice agriculture included under wetlands.

quickly been consumed, sequential reduction of the following soil oxidants progresses in accordance with the thermodynamic theory: NO₃[−], Mn⁴⁺, Fe³⁺, SO₄^{2−}, and CO₂. Methane is the final product of the reductive process and is produced by methanogens. The major direct substrates for methanogenesis are H₂+CO₂, formate, acetate, methyl alcohol, and methylamine. The following two reactions are dominant in methanogenesis in the soil: the reduction of CO₂ using H₂ and the transmethylation of acetate^{117,121)}.

Carbon substrates for methanogenesis are supplied from applied organic matter, exudates and sloughed tissues of rice plants, and soil organic matter^{68,137)}. Part of the CH₄ produced is consumed by methanotrophs under oxidative conditions in the rhizosphere of rice plants and in a thin layer of soil interfacing with the surface water. Most of the CH₄ emitted is transported to the atmosphere through the aerenchyma of rice plants, but other pathways are ebullition and diffusion through surface water^{17,119)}. Moreover, a considerable amount of CH₄ trapped in the soil is emitted by direct diffusion during drainage⁹⁰⁾.

Soil redox potential (Eh) is the most useful indicator for measuring soil redox conditions, although there are other indicators such as, the terminal electron-accepting processes and oxidative capacity⁴⁰⁾. Soil Eh is a comprehensive measure of soil chemical and biological redox processes¹³¹⁾. With the development of reductive conditions, soil Eh de-

creases from positive (600 mV) to negative (< −200 mV). Generally, CH₄ production begins at approximately −150 mV, and is stimulated at less than −200 mV^{84,130)}.

Methanogens and methanotrophs

The significance of soil microorganisms, including methanogens and methanotrophs, as controllers of atmospheric trace gases has been well documented²⁷⁾. Methanogens phylogenetically belong to the domain *Archaea*. In paddy soils, the following seven genera have been isolated or evidenced: *Methanobacterium*, *Methanobrevibacter*, *Methanoculleus*, *Methanogenium*, *Methanosaeta*, *Methanosarcina*, and *Methanospirillum*^{5,6,36,63,64,71,87,108)}. The population of methanogens varies among soils. In Senegal, the population in 29 paddy soils ranged between 10² and 10⁷ g^{−1} dry-soil⁴¹⁾. In an Italian paddy soil, acetotrophs numbered 10⁴ g^{−1} dry soil and the hydrogenotroph population was 10⁶ g^{−1} dry soil⁸⁶⁾. Asakawa and Hayano⁵⁾ reported that the populations of hydrogenotrophs, methylotrophs, and acetotrophs were 10³–10⁴, 10⁴–10⁵, and 10⁴–10⁵ g^{−1} dry soil, respectively, in Japanese paddy fields. Moreover, several reports have revealed that the population and community structure of methanogens remain more or less constant regardless of the type of field management^{5,36,86)}.

The CH₄-oxidizing bacteria are divided into methanotrophs and autotrophic ammonium-oxidizing bacteria. Methan-

otrophs isolated from paddy soils belong to the genera *Methylocystis*¹²²⁾ and *Methylosinus*^{15,77)}. The population of methanotrophs is reported to be 10^4 g⁻¹ dry soil in Japanese paddy soils¹³⁶⁾ and 10^6 g⁻¹ dry soil in Italian paddy soils¹⁰⁾. The methanotroph population increased with the growth of rice plants in an Italian paddy soil^{34,42)}. On the other hand, Takeda *et al.*¹²³⁾ reported that the population was 10^5 – 10^6 g⁻¹ dry-soil in Japanese paddy soil, and that it did not change with irrigation or the kind of fertilizer applied.

Different scales of factors controlling CH₄ emission

Yagi¹³⁹⁾ categorized the factors controlling CH₄ emission into four scales (Fig. 2). From the microbial to global scales, these factors are soil properties, rice plant activity, field management, and climate. The most important objective of studies on CH₄ emission from paddy fields is the mitigation of global warming. Of course, it is also essential to balance mitigation options with rice production.

Emitted CH₄ affects global warming on the largest scale, but the microbiological processes of CH₄ production and oxidation occur on the smallest scale. In terms of environmental factors, temperature^{33,37,153)} and water regime^{92,110)}

principally determine the potential for CH₄ emission. On the microbial and plant scales, the amount of CH₄ emitted is determined by the population and activity of microorganisms^{1,34,44,48,86)}, the physical conditions and chemical properties of the soil^{125,126,135,151,152)}, the biomass and activity of rice plants^{22,28)}, and the kinds and amounts of substrates^{68,137)}.

On the other hand, from the farmer's viewpoint, field management on a field scale is the sole way to produce rice and increase the rice yield. Such field management also has physical, chemical, and biological effects on CH₄ emission. A statistical analysis by Yan *et al.*¹⁴⁶⁾ showed that the average CH₄ flux during the growing period was significantly affected by water management, organic matter application, content of soil organic carbon, soil pH, preseason water status, and climate. Therefore, ecological problems on different scales and from different viewpoints—i.e. CH₄ emission (global warming) and rice production—need to be considered simultaneously.

Irrigated paddy fields were estimated to account for 70–80% of CH₄ emission from the global rice area, whereas rainfed (about 15%) and deepwater (about 10%) fields had

Fig. 2. The factors controlling CH₄ emissions from paddy fields on different scales (modified from Yagi¹³⁹⁾).

much lower shares¹³³. As evaluated by Wassmann *et al.*¹³⁴, irrigated rice offers the most options for modifying field management to mitigate CH₄ emission. On the other hand, mitigation options for rainfed and deepwater fields are very limited in both number and potential gains¹³⁴. Therefore, it is certain that irrigated paddy fields are the most promising targets for applying mitigation options.

Effects of Field Management on CH₄ Emission from Paddy Fields

A combination of appropriate field management techniques is used to obtain suitable rice yields and these techniques have various effects on CH₄ emission. Wassmann *et al.*¹³² reported that local variation in field management among Asian countries overrode the impacts of soil- and climate-related factors on CH₄ emission. Yagi¹⁴⁰ listed the mitigation options for CH₄ emission and evaluated them from the viewpoints of rice productivity and economics (Table 2). Generally, farmers aim to a greater or lesser extent for economic rice production. Although the consideration of environmental issues on various scales has some economic advantages in a few developed countries, the en-

vironmental viewpoint is never comparable to the economic one under the present condition.

Water management

Water management, such as midseason drainage and intermittent irrigation is commonly used in irrigated paddy fields in Japan, to control surplus tillering and to supply rice roots with molecular O₂ for preventing sulfide toxicity⁶⁵. Various countries have adopted similar management practices, but they cannot be applied to rainfed and deepwater fields. Although there remains some vagueness in timing and span, appropriate water management increases rice yield.

Water management is also one of the most effective options in decreasing CH₄ emission, because it prevents the development of soil reductive conditions. On a rainfed lowland field, CH₄ emission was about 4–10 times higher than that on an irrigated shallow field¹¹⁰. One or multiple drainage systems have been reported to decrease CH₄ emission compared to continuous flooding under field and lysimeter conditions^{102,141,156} and microcosm and pot conditions^{88,92,109}. Moreover, many researchers have reported that midseason drainage and/or intermittent irriga-

Table 2. Evaluation of mitigation options for CH₄ emission

Field management	Mitigation efficiency	Problem for application						
		Applicability		Economy		Effects on		Other effects
		Irrigated	Rainfed	Cost	Labor	Yield	Fertility	
Water management								
Midseason drainage	□	○	●	~	↑	+	~	May promote N ₂ O
Short flooding	□	○	●	~	~	–	–	May promote N ₂ O
High percolation	□	○	●	↑	↑	+	~	May promote nitrate leaching
Soil amendments								
Sulfate fertilizer	□	○	○	↑	~	△	–	May cause H ₂ S injury
Oxidants	□	○	○	↑	↑	△	–	
Soil dressing	○	○	○	↑	↑	–	–	
Organic matter								
Composting	□	○	○	↑	↑	+	+	
Aerobic decomp.	□	○	○	~	↑	~	~	
Burning	○	○	○	~	↑	~	~	Atmospheric pollution
Others								
Deep tillage	○	○	○	↑	↑	–	–	
No tillage	?	○	○	~	↓	–	~	
Rotation	○	○	△	~	↑	–	–	
Cultivar	○	○	○	~	~	~	~	Require long time

Modified from Yagi¹⁴⁰.

□: very effective, ○: Effective/applicable, △: case by case, ●: not applicable, ?: no information, ↑: increase, ↓: decrease, ~: about equal to previous situation, +: positive, –: negative.

Fig. 3. Seasonal changes in soil Eh (upper lines) and CH₄ flux (lower lines) with different water management, continuous flooding and Eh control in an Andosol field with rice straw application (Minamikawa *et al.*⁹¹). The upper and lower limits of Eh control are 100 and -150 mV, respectively. Vertical bars indicate the standard error. An arrow indicates the final drainage.

tion decrease CH₄ emission without decreasing rice grain yield^{16,112,127,143}.

However, the drainage timing and span of the conventional water management depend on the farmer's empirical knowledge and customary practices, which may lead to careless CH₄ emission. Recently, to positively decrease CH₄ emission, water management based on soil Eh (Eh control) has been proposed⁸⁸. Eh control maintains soil Eh between predetermined lower and upper limits by drainage and flooding. Field experiments have demonstrated that Eh control decreases CH₄ emission by 64% compared to continuous flooding without decreasing rice grain yield⁹¹ (Fig. 3).

Appropriate water management for sound rice growth is also effective in decreasing CH₄ emission. This means that appropriate water management will be a win-win option for increasing rice yield and decreasing CH₄ emission. At present, optimizing water management in irrigated paddy fields is the best way to mitigate CH₄ emissions from the global rice area. We cannot do better than adopt appropriate water management in consideration of N₂O emission during drainage^{16,19,102,144}. There is room to improve water management and achieve an optimal balance between rice yield and GHG emissions.

Soil amendment

Soil amendment is now essential to intensive cultivation. Nitrogen is an element that is fundamental to crops and strongly affects growth and yield. However, the application of large amounts of nitrogen to paddy fields can cause over-luxuriant growth, spindly growth, lodging of rice plants, and N₂O emission^{19,54}. There have been many reports on the ef-

fects of the type, rate, and method of nitrogen application on CH₄ emission. However, there is little information on the effect of slow- (controlled-) release nitrogen fertilizer.

Sulfate-containing fertilizers are known to decrease CH₄ emission because of the competition between sulfate-reducing bacteria and methanogens for the substrates, hydrogen and acetate^{51,52}. Many researchers have demonstrated the CH₄-decreasing effect of ammonium sulfate [(NH₄)₂SO₄] under field conditions^{16,30,67,80,81,82,90,117,149} and pot and incubation conditions^{9,129}. The application of gypsum (CaSO₄) also decreased CH₄ emission^{29,30}. Minamikawa *et al.*⁹⁰ reported that increases in the application rate of ammonium sulfate from 45 to 135 kg N/ha (compared to a conventional rate of 90 kg N/ha) decreased CH₄ emission and increased rice yield under field conditions (Table 3). Ammonium sulfate is a physiological acid fertilizer and in 2002 accounted for only 2.5% of the total amount of nitrogen fertilizers consumed globally³⁵. Although ammonium sulfate can induce

Table 3. Total CH₄ emission and rice yield at different application rates of ammonium sulfate

Application rate (kg N/ha)	CH ₄ emission (g CH ₄ /m ²)	Grain yield (g DW/m ²)	Straw yield (g DW/m ²)
135	2.67 b	682 a	775 a
90	6.73 a	646 a	693 b
45	7.86 a	514 b	494 c
0	Not determined	389 c	394 d

Data from Minamikawa *et al.*⁹⁰.

The same letters in each column are not significantly different at $p=0.05$ by Tukey's HSD test.

rice root rot from H₂S production, its use is a win-win option.

Urea [(NH₂)₂CO] is the most consumed nitrogen fertilizer in the world, accounting for 47.4% of the total as of 2002³⁵⁾. The incorporation of urea into the soil at a depth of 20 cm decreased CH₄ emission to half of that with surface application¹¹⁸⁾. Compared to the effects of ammonium sulfate, the effects of urea on CH₄ emission are very complex, bringing conflicting results among different fields and soils. Many researchers have reported that CH₄ emission increased with increases in the rate of application of urea and/or was higher than no application under field conditions^{28,78,79)} and pot and incubation conditions^{9,31,85,129,147)}. This result was attributed to an increase in soil pH caused by the hydrolysis of urea¹²⁹⁾, an increase in rice biomass⁹⁾, and the inhibition of methanotrophs by ammonium^{27a,31,73)}. On the other hand, contrasting results have been reported^{12,13,19,69,89,156)}. Bodelier *et al.*^{12,13)} reported that ammonium stimulated the oxidation of CH₄ and methanotrophs in a microcosm experiment. Cai and Mosier²⁰⁾ found that if the initial CH₄ concentration in the headspace was sufficiently high under soil incubation conditions, then adding ammonium chloride (NH₄Cl) first inhibited but eventually stimulated the oxidation of CH₄. Therefore, the effect of ammonium on CH₄ oxidation may vary among experimental conditions. Schimel¹¹⁶⁾ arranged the effects of ammonium on CH₄ oxidation into the following three-scale phenomenon: stimulation with increases in rice biomass on a plant/ecosystem scale; inhibition with population growth of methanotrophs on a microbial-community scale; and stimulation with competition for methane monooxygenase on a biochemical scale. It was concluded that the set of effect that dominates the total CH₄ emission may vary among systems¹¹⁶⁾.

The application of agricultural chemicals affects the activity of microorganisms, as reported by Mohanty *et al.*⁹⁶⁾ and Satpathy *et al.*¹¹⁵⁾. However, such chemicals are highly specialized, and their residues in rice plants and soil are minimal or zero if withholding periods for residues are observed. Therefore, the effects of these chemicals on microorganisms are more or less inevitable, and there would be little room to change the rate and kind of chemicals with regard to the emission of CH₄.

Soil oxidants are added to degraded paddy fields to avoid the autumn decline (akiochi) of rice growth. Oxidants delay the development of soil reductive conditions. There have been several reports on the effects of Fe-containing materials on decreases in CH₄ emission^{39,61,107,155)}. Addition of Fe-containing slag increased the soil Eh and pH^{103,155)}. Yoshiba

*et al.*¹⁵⁵⁾ also reported CH₄-decreasing effects of Mn⁴⁺ and SO₄²⁻. Although excessive use of oxidants would damage the physiology of rice plants, these substances could be used as a mitigation option.

Organic matter management

The application of organic matter conserves soil fertility for sustainable rice production. In Japan, it is recommended that organic matter be applied together with a chemical fertilizer. Because of the slow release of organic nitrogen during decomposition, the use of organic matter prevents temporal and spatial variations in rice yield. However, the organic matter supplies substrates for the development of soil reductive conditions and CH₄ production. The kind, rate, timing, and degree of maturation affect the magnitude of CH₄ emission.

In paddy fields, rice straw is a reasonable type of organic matter to apply in terms of the carbon cycle. Many studies have reported that rice straw increases CH₄ emission^{16,24,29,62,104,118,141,147)}. In Japanese paddy fields, because of aerobic decomposition during the fallow period, the application of straw in the previous autumn or winter decreased CH₄ emission compared to just before transplanting (spring)^{43,85)}. Moreover, several researchers reported that there was no difference in CH₄ emission between winter application (application two-month prior) and no application^{55,91)}. Composting of rice straw is also effective in decreasing CH₄ emission because of aerobic decomposition outside the field^{24,141)}. Burned straw also decreases CH₄ emissions from fields¹⁴⁾, but CO₂ emissions are increased by the burning.

There have been reports on other kinds of organic matter, such as wheat straw¹⁵⁶⁾, *Sesbania rostrata*^{16,30,62,104,110)}, *Azolla caroliniana* Wild¹¹⁾ and manures from cow, pig, and horse^{2,24,104,120,127)}. Organic matter is sooner or later decomposed to CO₂ or CH₄, and preferably it should be emitted as CO₂ with the lowest GWP by composting, maturation, and aerobic decomposition. The amount of animal manure is likely to increase with increases in the human population, thus increasing GHG emissions. Further studies are needed on the effective treatment of animal manure in ways that do not enhance GHG emissions.

Others

There is a little information available on the effect of tillage on CH₄ emission. In Japan, no/minimum tillage is carried out mainly to reduce the cost and energy consumption in machinery use. It is expected that no/minimum tillage will increase soil resistance and prevent both wet injury and

the development of soil reductive conditions. Moreover, no/minimum tillage may be effective in soil carbon sequestration^{32,45}). There have been several reports that no/minimum tillage decreased CH₄ emission compared to conventional tillage^{23,46,59,85,95}). On the other hand, several researchers reported the enhancement of CH₄ emission with no tillage^{46,112}). This conflicting result can be explained partly by differences in soil characteristics, such as the water requirement in depth⁵⁹) and a high content of Fe³⁺⁴⁶). With no tillage, no straw is applied to the topsoil, and the redox conditions are relatively high^{85,95}). Surface-applied rice straw caused the surface soil to be reductive, and CH₄ emission occurred near the surface^{46,47}). Although most reports agreed with the decreasing effect of no tillage on CH₄ emission in the short term, it is necessary to consider the long-term effects because of the accumulation of rice residues on and in the soil and the changes in soil physical properties.

Rice cultivars are selected to obtain higher yields and better quality. Rice plants play several important roles in CH₄ emission, and their large biomass cannot help increasing the emission. Previous reports compared, in addition to CH₄ emission, the following characteristics of several cultivars; rice growth and yield^{8,67,93,127}), plant conductance of CH₄ transport¹⁵⁴), and concentration of dissolved organic carbon in the soil⁸³). However, the development of new cultivars is far removed from farmers. It may be a possible option in the future.

There have been a few reports on the effects of crop rotation⁷²), direct seeding^{70,97,127}), and planting density^{90,138}). Their effects on CH₄ emission depend on changes in the soil redox conditions and the physiology of rice plants. There have already been studies on most of the conventional field management techniques used for rice production, but there is room to propose other techniques that positively decrease CH₄ emission.

Contributions of Microbial Studies to the Mitigation of CH₄ Emission

Present mitigation options are mostly those on a field scale, which are relatively feasible for farmers. These options basically affect the ecology of microorganisms, but insights into microbial ecology are often apt to be disregarded in field-scale mitigation. How do microbial studies contribute to the mitigation of CH₄ emission?

Variations in CH₄ emission from paddy fields are attributable mostly to variations in methanotrophic activity^{111,118}), indicating that methanotrophs are suitable organisms for controlling CH₄ emission¹). Therefore, stimulation of the

populations and/or activity of methanotrophs can decrease CH₄ emission. Anaerobic CH₄ oxidation occurs in ecosystems other than paddy soils^{3,60}). Although there have been no reports of the isolation of bacteria that affect anaerobic CH₄ oxidation⁷⁴), the possibility of anaerobic CH₄ oxidation in paddy fields has been suggested by Miura *et al.*⁹⁴) and Murase and Kimura⁹⁹).

Amann *et al.*⁴) reported that probably less than 1% of bacterial species have ever been isolated. The microorganisms that have been isolated are not necessarily those that are the only, or the most active, ones in the soil⁷⁶). As suggested by Kumaraswamy *et al.*⁷⁴) and Schimel¹¹⁶), further microbial studies will enable us to predict ecosystem behavior and the ecological significance of diversity and community structure.

Conclusions

This paper reviewed the effect of field management on the emission of CH₄ on a field scale, which is the basis used for rice production by farmers. The most important objective of studies on CH₄ emission from paddy fields is the mitigation of global warming. Methane emission is controlled by factors on various scales, and there is no sole solution to the balancing of rice production with CH₄ emission and global warming. In a transient situation, we can establish win-win options to both sustain rice yield and mitigate CH₄ emission, e.g. water management and nitrogen fertilizer application. Combination, ramification, and specialization of field management replying to the demand on site will urge to study GHG emissions from paddy fields. Further studies to unravel such phenomena, especially on a microbial scale, will offer us knowledge that can be used to solve the problem on a large scale.

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