Methane Emission from Flooded Rice fields

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Rice production has a significant effect on global warming and atmospheric chemistry through methane emission from flooded rice soils. Water regime, soil properties and the rice plant are major factors controlling the flux of methane in rice fields. Flooded rice soils provide an optimum environment for methane production and emission. This review deals with discussion of various factors affecting methane emission, estimation, mechanism and control of methane emission. A brief description is also given on the measurement of methane emission from paddy soil with and without rice straw applications, as well as with pot experiments to estimate the contribution of rice straw to the total methane emission during the growth period of rice plants.

Introduction

Tremendous progress has been made in understanding the interactions between global change and rice production through international and interdisciplinary research collaboration between IRRI, National Agricultural Research Systems, International Geosphere-Biosphere Programme (IGBP) and advanced research institutes of various countries. Role of agriculture in global warming has attracted public awareness and attention. Rice plants play an important role in the emission of methane flux into the atmosphere. Rice is the second most important crop in the world after wheat and about 550 million tonnes of rice is being produced from about 150 million ha annually. Already there is an increasing pressure on rice growing area, especially in Asia, where more than 90 per cent rice of the world is grown and consumed. Uncertainties become greater as rice cultivation has a significant effect on global warming through emission of greenhouse gases like methane and nitrous oxide. Up to 90 per cent of the methane released from the flooded rice soil to the atmosphere is emitted via the rice plant. The aerenchyma tissue and intracellular space of rice plants mediate the transport of methane from the soil to the atmosphere. At the same time the stalk of rice plants acts as chimney through which atmospheric oxygen is supplied to the roots for respiration. Oxygen diffusion from rice roots seems to constitute an important part of the oxidizing power of the roots. Due to the abundance of methane oxidizing bacteria present in the rhizosphere, the potential of rice cultivation for methane oxidation is very high.

Fllooded rice soils provide an optimum environment for methane production and emission especially in the tropics. Anaerobic decomposition of organic matter occurs due to low redox potential in the flooded soil. Variations in methane fluxes from rice paddies are caused by variation in soil properties, crop management and related growth of rice. The duration, pattern of flooding and saturation are important criteria for methane formation.

The potential for upland rice for methane production is insignificant since upland rice is never flooded for a prolonged period. Aerobic soils including upland rice soils, are important sites for microbial oxidation of atmospheric methane. Irrigated rice has the highest potential to produce methane because of flooding and consequent anoxic conditions prevailing there. The potential for methane production in rain-fed rice should widely vary in time and space since flood water regimes are primarily controlled by rainfall within the watershed.

In this review the authors have made an attempt to discuss production and emission of methane from flooded rice fields including estimation, mechanism, and factors affecting methane emission which help in adopting the right control measures. They have also compared some of their own data obtained from naturally flooded and irrigated rice fields in and around Bhubaneswar, Orissa.

Production and Emission of Methane

The major pathways of methane production in flooded soils are the reduction of CO₂ with fatty acids or alcohols as hydrogen donor and the transmethylation of acetic acid or methyl alcohol by methane producing...
bacteria (methanogens). In paddy fields the kinetics of the reduction process is strongly affected by the composition and texture of soil and its content of organic electron acceptors. The period between flooding of the soil and the onset of methanogenesis can be significantly different for the various soils.

Ramakrishnan et al., while studying methane production from two rice soils (alluvial and acid-sulphate), differing in physico-chemical characteristics, found that methane production in both soils were negligible under non-flooded conditions while the process was enhanced by submergence in alluvial soil. Adhya et al., while studying methane emission from flooded rice fields under irrigated conditions found that the amount of methane emission is about 20-times more in planted rice fields compared to directly sown rice fields. While studying the effect of rice varieties, the maximum efflux was noticed in the plots planted with Ratna followed by Annada and IR-36. A diurnal variation in methane emission was noticed from plots planted with Gayatri and Ratna rice varieties. Efflux was maximum at mid-day and minimum at midnight. In rain-fed low land areas, the methane efflux over a rice cropping season is less pronounced than in continuously submerged rice fields.

However, Sass et al., while studying methane production and emission in two rice fields of different soil types at Beaumont, Texas (USA) during a period from shortly after permanent field flooding until field draining prior to harvest, found that integrated methane emission over 75 d was 4.5-15.9 g/m², which is strongly related to the above ground biomass. Data from laboratory incubation of soil samples revealed that methane production by soil bacteria was highest near the soil surface in the rice row and decreased with depth and distance from the plant. The seasonally integrated methane emission was 42 per cent of total methane production in both fields. Sass et al., had compared methane emission data sets obtained over a four-year period from three different soil types at the same station with variable physical and chemical properties of the soil. The authors found a direct correlation between the seasonal methane emission with the extent of sand in the soil. With an increase in soil content from 18.8 per cent to 32.5 per cent, seasonal methane emission ranged from 15.1 g/m² to 36.3 g/m². Holzapfel, pscron et al., had measured methane emission rates from rice fields in Vercelli, Italy, in 1983, during a complete vegetation period by using a static box system. The rate of methane emission ranged between a few milli grams to 51 mg CH₄/m³/h, showing a seasonal variation with maximum emission rates between tillering and flowering stages. The methane release rates were more in the late afternoon and less in the early morning. Methane was exclusively emitted into the atmosphere by gas bubbles (ebullition) during the first six weeks after flooding without vegetation. Almost 80 per cent of the observed methane release from the paddy fields into the atmosphere was by diffusion through the stems of the rice plants. Khalil et al., while studying methane emissions from rice fields in China, found that the emission rate was 4-10 times higher than those of the US and Europe. Average emission rates during the growing season were 0.0-600 mg/m²/h from rice fields at Tzu in the Szechuan Province of China, showing that the rice fields are major contributor of methane emitted to the atmosphere. Schutz et al., had determined the seasonal change of the rates of production and emission of methane from an Italian rice paddy in 1983 and 1986. The contribution of plant-mediated transport, ebullition and diffusion through the flooding water to the total emission was quantified by cutting the plants and trapping emerging gas bubbles with funnels. Both production and emission of methane increased during the season reaching a maximum in August. At its maximum ~ 300 mg CH₄/m³/h were produced. Only ~ 6 per cent of it were emitted via plant-mediated transport. Radiotracer experiments showed that 30-50 per cent of methane was produced from H₂/CO₂ system and from the acetates present in soil.

**Effect of Soil Amendment on Methane Emission**

Yagi et al., while measuring methane emission rates from four Japanese paddy fields throughout the cultivation period in 1988 by using the closed chamber method, observed a large seasonal variation of methane flux. Drainage and application of mineral fertilizers reduced methane emission substantially. The highest methane emission rate was observed in a paddy with peat soil (44.8 g CH₄/m³) followed by grey soil (8.0-27.0 g CH₄/m³). Methane emission rates were increased by 1.8 to 3.5-fold with the application of rice straw at a rate of 6-9 tonnes/ha. Methane emission was slightly increased by the application of compost. The authors had also correlated annual methane emission rates from individual plots with the contents of readily mineralizable carbon (RMC) in paddy soils collected before flooding, suggesting that RMC was one of the most important factors affecting methane emission from flooded soils.
Two field experiments had been conducted by Cicerone et al. in California rice paddies, one with a single treatment of a research plot and the other with varied treatments like addition of rice straw and the presence or absence of vegetation in a typical commercial rice field. In the first experiment, only 11 g and CH₄/m² was emitted during the entire growing season. In the second experiment, the total emission varied from 1.2 to 58.2 g CH₄/m². Addition of organic matter greatly influenced methane emission, whereas vegetation influenced the mode and timing of release. The amount of methane emission, was not greatly affected by the application of nitrogenous fertiliser. During the period of largest emission, ¹³C values of methane were measured to be -55.7 ± 1.8 per cent in plots supplemented with organic matter. Lindau et al. had conducted field experiments to measure methane fluxes over the first and subsequent cropping seasons from a flooded Louisiana rice field by the application of urea at a rate of 100 kg N/ha with rice plants, urea without rice plants and unfertilised plants. Methane gas samples in the morning and afternoon hours were collected by using a closed chamber technique. The plots having urea without plants, unfertilised plants and plants with urea treatments released approximately 50, 240 and 340 kg of CH₄/ha over the main crop-growing season (77 d). On the other hand, methane emission from the subsequent cropping (73 d) were perceptively higher, i.e., 220, 520 and 1490 kg/ha under similar conditions. Pot experiments had been conducted by Inubushi et al. with the acrylic chamber method during August to October. Methane emission from paddy soils to the atmosphere through the rice plants was found to be 0.16-23 mg/m²/h. The emissions through rice were maximum at the heading stage and in late afternoon. Methane emissions were enhanced by 2-10 folds with the application of rice and wheat straw to the soil. The order of the rates of methane emission was: grey soil > grey low land soil > brown low land soil. Sugimoto et al. had carried out soil incubation experiments of paddy soil collected from Nonosu, Japan for ten weeks to measure the concentration and isotopic compositions of methane produced in the incubated system. The δ¹³C value of biogenic methane was highly variable ranging from -60 to -33 per cent corresponding to changes in its formation pathways. The value was estimated to be -43 to -30 per cent after acetate depletion while from the CO₂/H₂ reduction it was estimated to be -77 to -60 per cent. Sugimoto et al. also reported that the δ¹³C value of methane was a useful indicator for the assessment of the contribution of each process to methane production in sulfate-depleted fresh water areas. Nouchi et al. had measured the methane flux and methane concentration in the soil-water system and the biomass of rice once per week throughout the entire growing season in 1992 at Tsukuba, Japan. The total methane emission over the growing season varied from 3.2 g CH₄/m²y without the addition of rice straw and 49.7 g CH₄/m²y with rice straw application or with microbial amendment. The annual methane emission due to the ebullition of gas bubbles from the un-vegetated plot with the application of rice straw was estimated to be almost the same as that from the vegetated site with the application of rice straw. Tomori and Mamoto had measured the emission rates of methane from paddy soil using pots with and without rice straw to estimate the contribution of rice straw to the total methane emission during the growth period of rice plants. Methane derived from the rice straw was calculated to be 44 per cent of the total emission. Kimura et al. while investigating the effects of application of rice straw and percolation rate on the leaching amounts of methane in a soil column experiment, found that the amount of methane in the leachate increased with an increase in the application level of rice straw (0.3-1.0 × 10⁻³ kg/ha). Watanabe et al. had conducted pot experiments to estimate the increase in methane emission rates from paddy fields by the contribution of organic constituents in rice straw. The removal of lipids and lipids with water soluble polysaccharides from rice straw increased the total methane emission by 36 and 46 per cent, during the first 48 d period after transplantation, respectively. The removal of hemicellulose decreased the total methane emission by 23 per cent during the same period compared with the treatment applied with the original rice straw. Yong-Kwang et al., while measuring methane flux from a rice paddy in Korea, studied the effects of water management and rice straw application on methane emission. Methane emission was the lowest in NPK plot under intermittent irrigation and highest in NPK with rice straw application under flooding. Ramakrishnan et al. have reported that the addition of molybdate partially accelerated the production of methane in acid-sulphate soil but retarded it in alluvial soil.

Cicerone et al., while measuring the methane emissions from a California rice paddy field during the entire 1982 growing season, reported that the methane emissions were highest in the last 2-3 weeks before harvest.
Over the 100 d season, the average daily emission was about 0.25 g CH₄/m². The same authors had found a poor correlation between soil temperature at 10 cm soil depth with the measured fluxes. Conrad et al.¹⁹ while estimating methane flux from stable soil cores of a flooded rice field in Italy under aerobic and anaerobic incubation conditions, found that the difference between aerobic and anaerobic methane fluxes was due to the oxidation of methane in the oxic soil surface layer. Methane was oxidized at an extent of about 80 per cent during its passage through the soil surface layer. The methane concentration in the active surface layer limited methane oxidation. The authors had also reported that the addition of ammonium ion to the water layer on top of the soil core increased the aerobic methane fluxes due to the inhibition of methane oxidation in the soil surface layer. Nouchi et al.²⁰ had conducted pot (soil and hydroponic) culture experiments to examine the formation of methane in flooded soil and emission through rice plants. Methane concentration in surface water above soil was extremely low as compared to that in water embedded in the soil. Its concentration in an un-vegetated soil was thrice that of the vegetated soil. The emission rate was 20-times higher in vegetated than in un-vegetated pots. There was a linear relationship between methane emission rate from rice plants and methane concentration in the culture solution. Nene²¹ had described the role of major rice systems, soil processes upon flooding and agronomic practices in the process of methane emission. They had estimated that methane from rice fields accounted for ~ 20 per cent of global methane emission.

Measurement of Methane (CH₄)

Chanton et al.²² had demonstrated the importance of vegetation in supporting methane production and emission within flooded rice fields. The amount of subsoil methane was more in vegetated plots than plots free of vegetation. Cecereone et al.²³ while examining the role of rice paddy in methane evolution, found that methane was escaping primarily through the plants by molecular diffusion. Much more methane was released through nitrogen fertilised plants in comparison to unfertilised plants. Frenzel et al.²⁴ had demonstrated that the photosynthetically produced oxygen did not increase methane oxidation in the rhizosphere. However, when the microorganism was incubated in an atmosphere of nitrogen, the methane emission rates increased. They indicated that transport of oxygen from the atmosphere to the rhizosphere was important for methane oxidation. Methane release into the atmosphere was only 10-20 per cent of the methane production as determined in cores taken from the microcosms. The same authors reported that about 80-90 per cent of the methane produced was oxidized in the rhizosphere. Minami et al.²⁵ while estimating methane emission from paddy fields in Japan, observed that the redox potential is the most important factor for the production of methane in paddy soils. Soil temperature is known to be an important factor in affecting the activity soil micro-organisms. Yamane and Sato²⁶ in 1961, found that methane formation attained a maximum at 40°C and minimum at 20°C in alluvial paddy soils. Holzapfel-pschron and Seiler²⁷ and Schutz et al.²⁸ had reported that the methane emission rate doubled as the temperature rose from 20°C to 25°C.

Lindau et al.²⁹ had measured methane emission and dissolved methane concentration from a flooded Louisiana rice field. Urea, ammonium sulphate and potassium nitrate were applied at a rate of 0, 60 and 120 kg N/ha before flooding and methane fluxes were measured twice a week until harvest. Dissolved methane concentration in vertical flood water-soil profiles was measured during the early, middle and late growing seasons. The evolution of methane during the 93 d sampling period was 60, 70, 80 and 110 kg/ha from the control, ammonium sulphate, potassium nitrate, and urea applied fields respectively. Methane emission from plots treated with 120 kg N/ha were 90, 100, and 220 kg/ha for potassium nitrate, ammonium sulphate, and urea treatments, respectively. Methane emission rate was reduced to 55 and 59 per cent due to high ammonium sulphate and potassium nitrate application in comparison to fluxes measured from the fields with higher urea application. During the growing season, dissolved concentration of methane in water increased and higher values (245 mmol) were recorded in unplanted plots nearly three weeks before harvest. The same authors had also reported that the methane evolution rate was inhibited by the addition of calcium sulphate to flooded rice.

Matthews et al.³⁰ had presented high resolution global data based on the geographical and seasonal distribution of rice cultivation and associated methane emission. Methane emission was found to be proportional to the area and duration of each harvest so that the seasonal, zonal, and country patterns of annual methane emission mimicked the distribution of rice-harvest areas. Sass et al.³¹ had reported that rice field methane emission depended on planting date, solar radiation, temperature, and straw amendment. The earliest planted straw-amended rice field had the highest methane emission.
Neue et al.\textsuperscript{31} reported that water regime, soil properties, and rice plants are the major factors in the production and flux of methane in rice fields. Irrigated rice cultivation is the major source of global methane emissions from rice fields. The assured supply and control of water, the intensive soil preparation and the resultant improved growth of rice favour methane production, emission, and transport of methane into the atmosphere.

**Related Work Done at RRL, Bhubaneswar**

In a national campaign on measurement of methane emission from rice fields under different agro-climatic zones of India in 1991, it was found that maximum methane is emitted from naturally flooded fields with traditional genotype and field management practices.\textsuperscript{12,31} The average emission from such fields spread over the states of West Bengal, Bihar, Orissa, Assam, other north-eastern states, and deep water rice fields of the east coast was found to be 20.83 g/m\textsuperscript{2} integrated over the whole kharif season while the range varied from 35 to 10 g/m\textsuperscript{2}. Measurements carried out in an actual farmer's field in the suburbs of Bhubaneswar in 1991 kharif season showed that the efflux varied from 3.18 to 15.24 mg/m\textsuperscript{2}/ha with a mean of 8.853 mg/m\textsuperscript{2}/ha. When integrated over the whole season, the flux was found to be 13.05 g/m\textsuperscript{2}. Similar measurements at rice farms of the Orissa University of Agriculture and Technology during the kharif season of 1996 showed\textsuperscript{14} the integrated flux to be 7.39 g/m\textsuperscript{2} for the season while the range varied from 0.12 to 19.55 mg/m\textsuperscript{2}/ha with a mean of 3.30 mg/m\textsuperscript{2}/ha. From these results it can be concluded that the kharif season with natural flooding over a long period produces more methane as compared to dry land and intermittent flooding. The traditional rice varieties and cultivars used by actual farmers produce more biomass which, in turn, contributes to higher soil carbon responsible for higher methane generation under anaerobic conditions. The farmers at times apply organic manure before field preparation which again contributes to organic carbon in the soil. Thus our observations supplement the reported findings.

**Mechanism of Methane Emission**

Nouchi et al.\textsuperscript{35} had suggested the mechanisms of methane transport from the rhizosphere into the atmosphere through rice plants. The membrane emission rate was measured from a shoot whose roots had been kept in a culture solution with a high concentration of methane or exposed to methane in the gas phase by using a cylindrical chamber. They found that methane was mostly released from the culm, which is an aggregation of leaf sheaths, but not from the leaf blade. Rice roots could absorb methane in the gas phase without water uptake. They also reported that methane dissolved in the soil water surrounding the roots diffuses into the cell wall water of the root cells, gasifies in the root cortex and finally released mostly through the micro pores in the leaf sheaths. Conrad et al.\textsuperscript{36} while studying the mechanism of controlling methane emission from wetland rice fields, reported that methane production involved a complex anaerobic microbial community which degraded organic matter via various intermediates to methane. The rice aerenchyma is the predominant route for the escape of methane from the soil into the atmosphere and tap bubbles which constitute methane reservoirs in the submerged soil.

Vogel et al.\textsuperscript{37} had demonstrated the two metabolic pathways of biological methane formation using carbon-isotope techniques: (i) Carbon dioxide reduction that utilizes hydrogen gas, fatty acids or alcohols as a hydrogen donor and (ii) transmethylation of acetic acid or methyl alcohol which does not involve carbon dioxide as an intermediate. These are illustrated in the following equations:

\[
\begin{align*}
\text{CHO}_2 + 4\text{H}_2 & \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \\
\text{CH}_3\text{COO}^- + \text{H}^+ & \rightarrow \text{CH}_4 + \text{CO}_2.
\end{align*}
\]

Jakobson et al.\textsuperscript{38} while studying the effects of sulfides on methane formation in soils and sediments, found that methane produced as the terminal step of the anaerobic breakdown of organic matter in paddy soils is exclusively produced by methanogenic bacteria which can metabolise only in the strict absence of free oxygen and at redox potentials of less than -150 mV.

**Control of Methane Emission**

Lombardi et al.\textsuperscript{39} had measured methane oxidation rates in the rhizosphere using methyl fluoride inhibition technique. The absolute rate of methane oxidation was highest during warmer months. Methane oxidation percentages decreased and methane emission rates increased as the plants developed towards their flowering stage. At high summertime, methane emission and rhizospheric methane oxidation rates were found to be similar in magnitude. Lindau et al.\textsuperscript{40} had conducted field experiments to determine the mitigating effects of selected nitrifying inhibitors and sulfate containing compounds on methane emission from flooded rice. Methane emission over the 77 d sampling period were approximately 230, 240, 260, 290, 310 and 360 kg
CH₄/ha from calcium carbide, sodium sulfate rate-II, sodium sulfate rate-I, ammonium sulfate dicyandiamine and urea control treatments respectively. The methane reduction rate ranged from 14 to 35 per cent compared to the control depending on the treatment. The authors reported that methane emissions from the flooded rice fields were reduced effectively by selected inhibitors and sulfate containing compounds. VanderGon et al. while monitoring methane emission from Philippine rice paddies by using a closed chamber technique during the 1991 and 1992 wet season, found that methane emission from plots amended with 6.6 tonnes/ha gypsum was reduced by 55-70 per cent compared to non-amended plots. This was most likely due to inhibition of methanogenesis by sulphate reducing bacteria.

Conclusions
Flooded rice fields are the primary source of methane produced from agricultural sector. The flux is highly dependent on soil composition, redox potential prevailing in the subsoil surface, environmental parameters like temperature, paddy variety, and field management practices. Actual measurements done by the authors under a nationally coordinated programme, actual farmer’s field as well as in a professionally managed farm, corroborate the already reported results in literature. Abatement practices like application of sulphur containing fertilizers, intermittent draining of standing water so as to aerate the soil might bring down the flux to a reasonable extent.

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