Methane in rice agriculture: A review

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This review gives an account of mechanisms of methane production and emission from flooded paddy fields. Future methane emission scenarios show that methane emissions in 2030 in India are projected to reach 24.4 Tg (reference scenario), 21.3 Tg (medium mitigation scenario) and 17.6 Tg (strong mitigation scenario). Morpho-physiological parameters (leaf number, tiller number and plant biomass) are reported to influence methane emissions. Use of nitrification inhibitors (prilled urea and nimin) are reported to be suitable methane mitigation options.

Keywords: Methane, Mitigation options, Rice agriculture

Introduction

Methane (CH$_4$), first discovered by Allessandro Volta (1778) in Italy, is the most abundant organic trace gas in atmosphere. It has a strong infrared absorbance with re-emitted radiations contributing to destruction of ozone layer. Atmospheric CH$_4$ has almost tripled since industrial period and has increased from a pre-industrial value of 715 ppb to 1774 ppb in 2005. CH$_4$ in atmosphere is eventually oxidized, producing CO$_2$ and H$_2$O. Atmospheric concentration of CO$_2$ increased from 278 ppm in 1750 to 365 ppm in 1998. CH$_4$ is 25 times more effective as an agent of global warming than CO$_2$. Total CH$_4$ released to atmosphere is reported to be 566 Tg CH$_4$ per year (1 Teragram, Tg = 10$^{12}$ g). Rice fields were first identified as sources of atmospheric CH$_4$ in 1960s. Estimated global emissions of CH$_4$ from rice fields during 2000 were 25.6 Tg y$^{-1}$. According to latest summary by IPCC, rice fields emit 60±40 Tg CH$_4$ y$^{-1}$. Recent CH$_4$ (conc. 70-90%) increase in atmosphere has come from biological sources, especially agro-ecosystems. Rate of CH$_4$ emission from rice is comparatively higher than other wetland species Sphagnum sp, Carex saxatilis, Eriophorum scheuchzeri, Oryza sativa L. (cv. Manohar Sali) and O. sativa L. (cv. 93812), 13.6 mg CH$_4$ m$^{-2}$ h$^{-1}$.

Major sources of CH$_4$ are geological deposits as natural gas fields. CH$_4$ is generated by anaerobic fermentation of organic matter including manure, waste water sludge, and municipal solid waste.

Paddy fields are important anthropogenic sources of atmospheric CH$_4$. With emission of 50-100 million t CH$_4$/y, rice agriculture is a big source of atmospheric CH$_4$. Degradation of organic matter (rice straw) in wetland rice soil samples showed CO$_2$ and CH$_4$ as major gaseous end products of degradation. CH$_4$ emissions from paddy field arise due to anaerobic decomposition of organic materials in flooded soil and CH$_4$ escapes to atmosphere mainly by diffusive transport through paddy plants. Of total global paddy growing area (150 Mha), upland paddy fields (15%) are not flooded and do not emit CH$_4$. Global CH$_4$ emitted from paddy fields is 60±40 Tg y$^{-1}$. Flooded a field in wetland rice cuts off O$_2$ supply from atmosphere, resulting in anaerobic fermentation and release of CH$_4$ from submerged soils to atmosphere through roots and stems of rice plants. Live stocks

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produce 37% of anthropogenic CH₄. Cattle contribute about 16% of total atmospheric CH₄ emissions²¹. Garg et al²² reported that agriculture and waste related emissions contribute above 65% of Indian CH₄ emissions. Future CH₄ emissions in 2030 are projected to reach 24.4 Tg (reference scenarios), 21.3 Tg (medium mitigation scenario) and 17.6 Tg (strong mitigation scenario).

Whittenburry et al²³ demonstrated presence of methanotrophs, which use CH₄ as their sole carbon and energy source for growth. Although methanotrophic bacteria have not been cultured outside host, tissues containing bacteria have been shown to use¹⁴C methane under aerobic condition²⁴. Methane emission in tissues are inhibited by acetylene, specific inhibitor of methane mono oxygenase²⁵. Major pathways of CH₄ production in flooded soil are reduction of CO₂ with H₂ from fatty acids or alcohols as hydrogen donor and transmethylation of acetic acid or methanol by CH₄ producing bacteria²⁶. In paddy fields, kinetics of reduction processes is strongly affected by composition and texture of soil and its content of inorganic electron acceptors. Patrick²⁷ demonstrated that redox potential of a soil must be below -150 mV in order to have CH₄ production.

Methods of CH₄ Estimation

Wassmann et al²⁸ suggested closed chambers with following systems for estimation of CH₄ emission in rice field: 1) Closed chambers (1 m x 1 m x 1.2 m) distributed in field; 2) A pneumatic system for automatic opening and closing of chambers; 3) A sampling system for automatic opening and closing of chambers; and 4) An analytical system (GC plus integrator) linked to a data acquisition device. Measurements are conducted continuously in a 2-h cycle of operation comprising one emission measurement with a 24-min closing interval for each box. Methane emerging through water column is collected in small Plexiglas chambers (40 cm x 20 cm x 20 cm) placed in position for 24 h between plants in sunlight. Total amount of CH₄ entrapped in soil is computed as

\[
CH₄ = \frac{(C_{bag} - C_{amb}) \times V_{bag} + C_{core} \times V_{core}}{DV_{soil}}
\]

where \(C_{bag} = \text{CH}_₄ \text{ concentration in sample bag (mg/1)}\); \(C_{amb} = \text{CH}_₄ \text{ concentration in ambient air (mg/1)}\); \(V_{bag} = \text{gas volume in sample bag (1)}\); \(C_{core} = \text{CH}_₄ \text{ concentration in core head space (mg/1)}\); \(V_{core} = \text{gas volume in core head space (1)}\); \(DV_{soil} = \text{dry weight of soil (mg)}\).

Dissolved CH₄ in soil solution is computed as

\[
\text{Dissolved CH}_₄ = \frac{C_{vac} (V_{vac} + \alpha V_{soil}) - C_{amb} \times V_{vac}}{V_{soil}}
\]

where \(C_{vac} = \text{CH}_₄ \text{ concentration in vacutainer head space (after equilibration) (mg/1)}\); \(V_{vac} = \text{volume of vacutainer head space (1)}\); \(\alpha = \text{water/ air partition coefficient (0.03 at 25°C)}\); \(V_{soil} = \text{volume of soil solution (1)}\); and \(C_{amb} = \text{CH}_₄ \text{ concentration in ambient air (mg/1)}\).

Dissolved CH₄ estimation method was slightly modified³⁹ according to Indian conditions as

\[
\text{Flux (mg m}^² \text{ h}^{-1}) = \frac{c_{CH₄} x 16 x 1000 x 60}{22400 x A x t}
\]

where \(BV = [(H-h) \times L \times W - \text{biomass volume inside box}], H = \text{Box height (cm)}, h = \text{Water level above channel (cm)}, L = \text{Box length (cm)}, W = \text{Box width (cm)}, BP = \text{Barometric pressure (mm Hg)}, T = \text{Inside temperature of the box at the time of sampling (°C)}, c_{CH₄} = \text{Change in methane concentration (ppmv) from 0 min sampling to t min sampling}, A = \text{Paddy area covered by box (m}²\).

Two types of chambers (open and dynamic chambers, closed and static chambers and controlled environment closed chambers) are used. In open chamber technique, boxes used for collecting samples are flushed with ambient air at a constant flow rate. Continuous air flow in this type of chamber prevents increase in
temperature and humidity unlike in closed chambers. Uniform mixing can be achieved by maintaining high flow rates and appropriate chamber design. Relatively short measuring periods are recommended for this technique. In dynamic type of chamber, soil flux (F) of CH₄ is determined as F = Q/A ρ dc, where Q is air flow rate through chamber, A is soil area covered by chamber, ρ is density of CH₄ at temperature and pressure recorded inside chamber and dc is difference in concentration of CH₄ between chamber outlet and inlet. Sebacher & Harriss³⁰ employed this technique in wetland studies.

Closed or static chamber method is most widely used technique of CH₄ flux measurement, due to long lifetime, low solubility in water and low interaction with common chamber materials. CH₄ mixing ratios in air enclosed by chamber are recorded as a function of time. Use of a fan helps in avoiding development of a vertical CH₄ gradient and flux is calculated. Contribution of plants to emission of CH₄ from aquatic and wetland soils was analyzed by enclosing plant in a plastic bag and monitoring temporal increase of CH₄ mixing ratios inside bag volume. Disadvantage of this method lies in separation of paddy field from environment may cause an alteration in emission rate. Closed chamber method is also associated with a large amount of uncertainty when it is used to calculate fluxes from large area because chamber covers only 1 m² area while large spatial variation exists in CH₄ emission.

Quantification of CH₄ fluxes due to gas bubble ebullition is performed by placing gas collecting traps or devices over sediment-water or soil water interface. Flux rate is computed by determination of CH₄ concentration of gas volume. Diffusive flux of CH₄ across water/ atmosphere boundary layer is determined by using a static chamber and then covering emission site with a fine mesh screen that impedes CH₄ bubble emission. Application of models like stagnant film model is also reported to be used for determining diffusion flux. Automated chamber covers a soil area of 0.5 m² and has a motor driven lid that remains operational throughout a range of weather conditions. Containers in automated system are filled by pumping gas from closed chamber via a multilayer rotary valve.

Comparing flux data obtained with closed chamber with models or micro-meteorological techniques (gradient or eddy correlation method) is a way to reduce associated uncertainties. Gradient and eddy correlation techniques are some of the alternative non-destructive techniques that need highly sensitive and high frequency CH₄ responders. However, these methods have not given any consideration to location effects. To overcome this problem, Mukherjee & Sarkar have developed a flux footprint method, where footprints of scalar CH₄ concentration in atmospheric surface layer are estimated on the basis of an Eulerian advection-diffusion equation.

Some models of this category include – Atmospheric Tracer Model, Regression Model, Process Based models and Trajectory Models. Atmospheric Turbulent and Diffusion Laboratory (ATDL) is an improved type of box model, which has been reported to be useful in measuring integrated regional CH₄ emission from rice fields. An IR Laser source for measuring CH₄ concentration along a relatively long path in real time is being used. Akagi et al have put forward a protocol to calculate CH₄ emission rate using data obtained by laser source. In this system, emission is independent of diffusion rate. However, fulfillment of some environmental and meteorological conditions limit its efficiency.

Research
First field measurement of CH₄ emission from rice paddy field was conducted in California, followed by extensive studies in Spain, Italy, China, Indonesia, Japan, Australia, Korea and Philippines. In India, CH₄ emission measurement was started from 1991 onwards. CH₄ emission factor for Indian paddy cultivation areas with less than 0.7% soil organic carbon (SOC) estimated for irrigated continuously flooded (17.48±4 g m⁻²), rainfed drought prone (6.95±1.86 g m⁻²), rainfed flood prone and deepwater (19±6 g m⁻²), irrigated intermittently flooded single aeration (6.62±1.89 g m⁻²) and irrigated multiple aeration paddy water régimes (2.01±1.49 g m⁻²). State wise study indicated national methane budget estimate of 4.09±1.19 Tg y⁻¹ and trend from 1979 to 2006 was from 3.62±1 to 4.09±1.19 Tg y⁻¹. Higher emitting states were West Bengal, Bihar, Mahdya Pradesh and Uttar Pradesh amounting 53.9% of total CH₄ emission with rainfed flood prone paddy water regime as major contributor. CH₄ emissions were enhanced by 1.5 times due to increase in SOC, by 1.8 times due to paddy cultivars, 1.5 times due to age of seedlings, 1.4 times due to seasons and 1.8 times in Kharif or monsoon season.

Studies demonstrated that difference in CH₄ emission rate between two rice varieties (Ranjit & Mahsuri) grown under different agro-ecosystems were
mainly due to higher shoot and root biomass accumulation in Ranjit compared to Mahsuri. Larger root biomass provides more surface area for diffusion of CH₄ from adjacent reduced soil to roots while larger above ground biomass as stems signifies conduit effect of rice plants. CH₄ emission over entire crop growing seasons showed significant positive correlation with leaf area index (LAI) of crop in both cultivars. Nodal development provides major path way of CH₄ release to atmosphere, which may be the reason for higher CH₄ emission in the variety with profuse vegetative growth. Arenchyma tissue of rice plant serves as a conduit to transport CH₄ from anoxic soil to atmosphere. Most of the methanogenic bacteria are mesophilic with temperature optima of 30-40°C. Higher temperature was recorded during Sali/monsoon rice growing season as compared to Ahu/premonsoon season, which stimulate organic matter degradation, thus favoring CH₄ production as well as limiting accumulation of intermediate metabolites.

Gogoi et al. observed that highest CH₄ fluxes were recorded at maximum tillering and panicle initiation stages of rice crop. Regression analysis conducted for rate of CH₄ flux and plant growth parameters for all the varieties indicated that there is a significant positive relationship with leaf number, tiller number and leaf area index. Ziska et al. demonstrated that elevated CO₂ brought significant increase in dissolved soil CH₄ relative to ambient control. CO₂ concentration appears to stimulate CH₄ emission primarily by increasing supply of carbon either through root exudates or root autolysis products. However, anatomical changes that occur due to elevated CO₂ influence transfer pathway.

Nouchi et al. showed that dissolved CH₄ absorbed by roots can be gasified quickly in root cortex and transported in gaseous state to shoots through aerenchyma and lysigenous intercellular space. This results in a steep gradient of CH₄ concentration in medullary cavities, where very high concentration of CH₄ can be detected. Air space of medullary cavity is linked to lysigenous air space through aerenchyma tissues involved in CH₄ transport. High methane emitting cultivars recorded significantly greater size of medullary cavity compared with medium and low emitting ones. CH₄ concentrations in medullary cavities of rice plants are reported to be about 2900 times higher than that of ambient air. Thus, CH₄ emission among rice cultivars may be associated with anatomical features of medullary cavity. A positive correlation between CH₄ flux and size of medullary cavity was observed. Before shoot elongation, 50% of CH₄ is released from leaf blades. Stomata of leaf sheaths are suggested to be main site of CH₄ release. Similar mechanism may operate in leaf blade also, which may explain close relationship among CH₄ emission, leaf area and stomatal frequency. Allen et al. recorded that highest CH₄ efflux coincides with increased transpiration rate, indicating that soil water flow to roots deliver more dissolved CH₄ to rice plant during periods of rapid transpiration.

Das & Baruah, experimenting with two rice varieties (Ranjit & Agni), recorded low CH₄ flux soon after transplanting and attributed it to the outcome of limited respirable soil carbohydrate resulting in minimal methanogenesis. Higher CH₄ flux was recorded in Agni may be due to larger root system as compared to Ranjit. Higher grain yield and superior yield related parameters along with lesser vegetative growth of Ranjit indicate higher photosynthetic partitioning towards panicles and developing grains and low CH₄ emission. In Agni, photosynthetic carbon could not be allocated efficiently to developing grain during reproductive stage, with major portion of photosynthates being translocated towards vegetative parts, including roots and thus available for methanogenesis which explains larger emissions of CH₄.

Major sources of substrate for methanogens are derived from root exudates; plant parts derived from rice plants and incorporated organic matters. Therefore, rate of production and emission of CH₄ largely depend on growth characteristics and photosynthetic efficiency of rice plant, which in turn influence supply of substrate to methanogens for CH₄ production and its subsequent release into environment. CH₄ emission and photosynthetic characteristic of rice are reported to be closely related (Fig. 1). Average (30-60%) of net photosynthetic carbon is allocated to the root and as much as 40-90% of this fraction enters the soil in the form of rhizo deposition. Lu et al. (2002) reported that about 1-5% of the photo assimilated carbon was incorporated into soil within 3-5 h after assimilation, part of photosynthesized carbon was transported to the rhizosphere, transformed to CH₄, and emitted to the atmosphere. Rhizo-deposition was shown to be the main origin of CH₄ evolved from rice fields.

Das & Baruah in two rice cultivars recorded a significant positive correlation between CH₄ emission and root growth, in terms of length and dry weight of rice cultivars. Greater root growth provides greater surface area for diffusion of CH₄ into roots and greater air space, which might be the reason for enhancement of CH₄ emission.
emission from cultivar ‘Disang’. After panicle initiation, photosynthetic rate was higher in cultivar ‘Luit’ compared to ‘Disang’. Despite higher photosynthetic rate, ‘Luit’ recorded lower CH$_4$ emission during this period. The trend may be associated with the pattern of photosynthates translocation towards developing panicle. An inverse relationship is reported between rice plant’s capacity to store photosynthetically fixed carbon and seasonally emitted CH$_4$, and on an average, 11± 4\% of carbon, not allocated to rice grains, was emitted as CH$_4$.

Higher values of yield parameters were recorded in cultivar ‘Luit’, indicating higher photosynthate partitioning towards panicles and developing grains. On the other hand, translocation of higher amount of photosynthates towards vegetative parts during reproductive phase resulted into larger root and shoot growth in cultivar ‘Disang’.

High yielding cultivars with low photosynthate-carbon translocation towards root would result in lower CH$_4$ emission. Therefore, screening of existing rice cultivars, and initiation of breeding programme for new cultivars with low photosynthate partitioning to root could offer an important CH$_4$ mitigation option. Development of new plant type of rice with balance source and sink capacity may be important in mitigating CH$_4$ emissions from paddy field. Gogoi et al$^{19}$ observed that mean flux value of CH$_4$ at panicle stage was higher than tillering stage and related it to increasing availability of substrate for methanogenic bacteria in the form of root exudates. Higher flux value at panicle initiation stage was found to be significantly correlated with higher root vigor in terms of biomass.

Factors

Several factors (water regime, organic fertilizer application, soil type & texture, pH, redox potential, temperature) and agricultural practices (direct seeding, transplanting) determine emission of CH$_4$ from rice fields$^{72}$. Application of rice straw to paddy fields significantly increased CH$_4$ emissions than compost prepared with rice straw and chemical fertilizers. CH$_4$ reaches to a maximum value at 35°C in waterlogged alluvial soil. Critical pH for CH$_4$ emission is between 6.4 and 7.8. As plants grow CH$_4$ emissions increases due to increase in root surface area and in the number of tillers.
that in turn increase efficiency of CH$_4$ transport from soil to atmosphere. Increased soil temperature leads to increased CH$_4$ emissions. Methanotropic bacteria also increase with increasing temperature and oxidize more CH$_4$.

Mitigation of CH$_4$

Crop Diversifications

Cumulative CH$_4$ emission from tropical rice ecosystem can be lowered by growing suitable upland crops to reduce period of submergence during an annual cropping cycle.$^{72}$ Datta et al.$^4$ reported highest CH$_4$ flux from rice-rice rotation while rice-potato-sesame is the most suitable cropping system with respect to greenhouse gas emission. Crop diversification in a low land rice ecosystem might be considered as a feasible option to reduce total CH$_4$ emission.

Water Management

Studies$^{75-78}$ showed that when water is allowed to evaporate during growing season and an intermittent flooding schedule is adopted, CH$_4$ emissions are greatly reduced compared to the conditions when fields are inundated during entire growing season. Higher water levels result in lower soil temperature, resulting in lower CH$_4$ emissions. Mid season drainage (a common irrigation practice adopted in major rice growing regions of China and Japan) and intermittent irrigation (common in Northwest India) reduces CH$_4$ emissions significantly.$^{79,80}$ Intermittently flooded paddy field with high water percolation rate is reported to emit low CH$_4$ during a cropping season.$^{81}$ Nelson et al.$^{82}$ found that due to one midseason drying, net revenue drops less than 5% while greenhouse gas emission drops by almost 75 million tonnes of CO$_2$ equivalent. Field drainage not only retards CH$_4$ production but also promotes CH$_4$ oxidation. Towprayoon et al.$^{83}$ demonstrated that drainage during flowering period reduce CH$_4$ emission. Adhya et al.$^{84}$ reported that intermittent irrigation reduced CH$_4$ emissions (15%) as compared to continuous flooding. Increasing length of mid season aeration and addition of sulphate fertilizer is reported to reduce CH$_4$ emissions significantly.$^{85}$ If continuously flooded fields were drained at least once during growing season, CH$_4$ emissions would be reduced by 4.1 Tg y$^{-1}$. Yan et al.$^8$ also reported that off season rice straw application would result in further reduction of CH$_4$ emission by 4.1 Tg y$^{-1}$ and if both these mitigation options are adopted, global CH$_4$ emission from rice paddies could be reduced by 7.6 Tg y$^{-1}$. Out of four different drainage systems (continuous flooding, tillering stage drainage, mid season drainage and multiple drainage) mid season drainage (36.7% less CH$_4$ efflux compared to continuously flooded) and multiple drainage (41% less CH$_4$ efflux compared to continuous flooding) were found to be highly effective in mitigating CH$_4$ efflux from paddy fields.$^{86}$ International Rice Research Institute (IRRI), Philippines has developed an alternate wetting and drying (AWD)$^{79}$ mitigation technology for CH$_4$, which improved use of mitigation water and increased rice productivity. It can reduce CH$_4$ emission by 50% as compared to rice produced under continuous flooding.

Biological Mitigation

Selection and cultivation of rice cultivars, which transport maximum portion of their photosynthates to panicle growth and grain development rather than growing varieties that use their photosynthates for development of vegetative parts (root, leaf sheath, culm etc.), is an effective biological mitigation option for CH$_4$. Addition of nitrate as chemical fertilizer to flooded soil suppresses CH$_4$ production due to changes in redox potential of soil. Emission of CH$_4$ was found lowest in plots treated with mixture of prilled urea and Nimin, a nitrification inhibitor, which inhibits autorophic oxidation of NH$_4^+$ to NO$_2^-$.$^{87}$ Lindau et al.$^{88}$ also reported that some nitrification inhibitors can mitigate CH$_4$ emissions from rice fields. Application of nitrification inhibitors, nitrapyrin and wax coated calcium carbide, retarded CH$_4$ emission significantly$^{89}$ in dry seeded flooded rice. Decrease in CH$_4$ emission in plots treated with wax coated calcium carbide was attributed to slow release of acetylene, a known inhibitor of methanogenesis.$^{90}$ Application of green manure in combination with prilled urea further enhanced CH$_4$ emission significantly over that in treatments with prilled urea and green manure alone.$^{91-93}$ Application of dicyandiamide (DCD) is reported to inhibit CH$_4$ flux from flooded rice as compared to that of urea alone.$^{84}$ However, repeat applications of DCD with fertilizer N to flooded rice soils might not be effective in controlling CH$_4$ production under field condition due to the enhanced degradation of DCD following its repeated application and also due to the inhibition of CH$_4$ oxidizing bacterial populations and noticeable stimulation of heterotrophic bacterial populations.$^{84}$ Influence of six nitrification inhibitors on CH$_4$ production in an alluvial soil under...
flooded condition followed the order of sodium azide > DCD > pyridine > aminopurine > ammonium thiosulfate > thiourea. Use of nitrification inhibitors (Nimin or placement of urea supergranules) in flooded rice fields can be considered as suitable options for mitigating CH\textsubscript{4} emission from rice fields without affecting grain yield.

Several benzene-ring compounds and N-containing compounds also suppress methanogenesis. Chemicals inhibiting CH\textsubscript{4} production as well as CH\textsubscript{4} oxidation include DDT and acetylene. Application of (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} as N fertilizer also affect CH\textsubscript{4} emissions. Application of a commercial formulation of herbicide butachlor (N-butoxymethyl-2-chloro-2′,6′-diethyl acetanilide) to an alluvial soil planted with direct-seeded flooded rice significantly inhibited both crop mediated emission (= 20%) and ebullition fluxes of CH\textsubscript{4} (= 81%) by causing a drop in soil redox potential (E\textsubscript{h}) as well as accumulation of Fe\textsuperscript{2+}. Thus, butachlor, even at very low concentrations, can affect CH\textsubscript{4} production and its oxidation, thereby influencing biogeochemical cycle of CH\textsubscript{4} in flooded rice soils. Application of herbicide as well as CH\textsubscript{4} emission through enhanced CH\textsubscript{4} oxidation. Hexachlorocyclohexane was also found to inhibit CH\textsubscript{4} emission.

Kimura et al. suggested that foliar applications of N fertilizers could suppress CH\textsubscript{4} fluxes from flooded paddy soils. Fertilizers with an ammonical form of N (NH\textsubscript{4}+ - N) inhibit CH\textsubscript{4} uptake in terrestrial ecosystems. In principle, three different causes have been suggested for inhibitory effect of nitrogenous fertilizers, especially NH\textsubscript{4}+ - N fertilizers, on CH\textsubscript{4} oxidation: i) An immediate inhibition of methanotrophic enzyme system; ii) Secondary inhibition through NO\textsubscript{2} production from methanotrophic NH\textsubscript{4}+ oxidation; and iii) Dynamic alteration of microbial communities of soil.

Potassium Fertilizer Application Technology

Muriate of Potash (MOP) significantly reduced emission of CH\textsubscript{4} from a flooded alluvial soil planted to rice. Potassium application prevented a drop in redox potential and reduced contents of active reducing substances and Fe\textsuperscript{2+} contents in rhizosphere soil. Apart from producing higher biomass and grain yield, potassium amendments can effectively reduce CH\textsubscript{4} emission from flooded soil.

Incorporation of Green Manure

Dual cropping of Azolla in conjunction with urea considerably reduced CH\textsubscript{4} efflux without affecting rice yields and can be used as a practical mitigation option for minimizing CH\textsubscript{4} flux from flooded paddy. Application of vetch (Astragalus sinicus L.) as green manure and amendment can be an effective measure for sustaining rice productivity without increasing CH\textsubscript{4} emission compared to NPK fertilization in Korean mono-rice cultivation systems. Use of composted livestock manure in rice cultivation mitigates CH\textsubscript{4} emissions and re-utilizes livestock waste.

Addition of Electron Acceptors

Lueders & Friedrich demonstrated that CH\textsubscript{4} emissions from paddy fields may be reduced by addition of electron acceptors to stimulate microbial populations competitive to methanogens. These alternative electron acceptors promote respiratory processes other than methanogenesis. Lakshmanan et al. demonstrated that application of mycorrhiza and methanotrophs significantly reduced CH\textsubscript{4} emission from flooded paddy fields by decreasing methanogens and anaerobic population of rice field soil as low as 5.8x10\textsuperscript{3} CFU\textsubscript{g}\textsuperscript{-1} and 1094x10\textsuperscript{3} CFU\textsubscript{g}\textsuperscript{-1} respectively.

Time of Transplanting

In rainfed rice cultivation, late transplanting with comparatively aged seedlings could lead to a considerable reduction in CH\textsubscript{4} emission without being detrimental to yield. With more integrated approach to rice paddy irrigation and fertilizer application, substantial reduction in CH\textsubscript{4} emission is possible: i) Rice varieties grown in drier condition will bring a significant reduction in CH\textsubscript{4} emission without any loss in yield; ii) Greater potential for improved varieties of rice will be able to produce a larger crop per area of rice paddy reducing CH\textsubscript{4} emission without any drop in rice production; and iii) Addition of compounds such as ammonium sulphate, which favor activity of other microbial groups over that of methanogens, has proved successful in reducing CH\textsubscript{4} production from rice fields.

Suggested Technologies for Future

Following technologies are suggested for CH\textsubscript{4} mitigation: i) Optimizing irrigation patterns by additional drainage periods in field or an early timing of mid season drainage accounted for 7-80% of CH\textsubscript{4} emissions of respective baseline practice; ii) Reduction in CH\textsubscript{4} emission by compost (58-63%), biogas residues (10-16%) and direct wet seeding (16-22%) have been suggested as best CH\textsubscript{4} mitigation technologies; and iii) In baseline practices using prilled urea as sole N source, use of...
ammonium sulphate could reduce CH$_4$ emission by 10-67%. In all rice ecosystems, CH$_4$ can be reduced by fallow incorporation (11%) and mulching (11%) of rice straw as well as addition of phosphogypsum (9-73%).

Conclusions

Since agriculture sector is dominant source of CH$_4$ emission in India, involving Indian farmers in the whole process is a big challenge. Technologies available for mitigation are at different stages of development and a lot of research work is required to make these technologies commercially viable and usable. International agencies can play an important facilitator role for appropriate technology development, demonstration and subsequent increased penetration. Important plant physiological parameters (leaf number, tiller number and plant biomass) can help rice breeders to develop new low CH$_4$ emitting genetic lines of rice and developing site specific technology packages, ascertaining synergies with productivity and accounting for methane emission.

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References

20 Kesheng S & Zhen L. Effect of rice cultivars and fertilizer management on methane emission in a rice paddy in Beijing, Nutr Cycl Agroecosys., 49 (1997) 139-146.


30 Sebacher D I & Harriss R C, A continuous sampling and analysis system for monitoring methane fluxes from soil and water surfaces to the atmosphere, Presented at 73rd Annual Meeting of Air Pollution Control Assn in Montreal, 22-27 June 1980.


40 Ulden Van A P, Simple estimates for vertical diffusion from sources near the ground, Atmos Environ, 12 (1978) 2125-2129.


