METHANE EMISSION FROM RICE ECOSYSTEMS: 100 YEARS OF RESEARCH

S. K. RAJKISHORE1*, N. S. VIGNESH, P. DORAISAMY AND M. MAHESWARI1
1Agricultural Research Station, Tamil Nadu Agricultural University, Bhavanisagar - 638 451, INDIA
2Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore - 641 003, INDIA
e-mail: rajkishoresk@gmail.com

INTRODUCTION

Rice fields are an important source of atmospheric methane (CH4), contributing about 5-19 per cent of total global CH4 emissions (IPCC, 2007). Methane is a key greenhouse gas next to carbon dioxide, which is 25 times greater in global warming potential than CO2 on a 100-year horizon (IPCC, 2006). Despite the fact that 18th century Italian scientist Alessandro Volta first identified methane from marsh (Reay et al., 2010), the first research paper on methane emissions in rice fields by Harrison and Aiyer (1913) marks a great history in this field of research. These two pioneers kick started the research in the early 20th century and kindled the curiosity of several scientists to explore further. This literature survey has documented the list of some important researchers in the global arena who immensely contributed to the science behind methane emissions from rice farming (Table 1). Classical review papers in the domain of methane emission from rice fields has been published by scientists (Aulakh, 2001b; Dubey, 2005; Liesack et al., 2000). Nevertheless, the year 2013 commemorated the 100th year of the first published work by Harrison and Aiyer and this paper is a timely documentation to take stock of the situation so as to explore the research gaps besides honouring the contributions made by each and every researcher in this field. With this background, an attempt was made to review the existing literature base in order to summarize the highlights of the research outcome during these 100 years.

Methane production in rice soils

It is well documented in the book entitled “Green manure: Principles and practices” authored by Pieters (1927) that Harrison and Aiyer (1913) did pioneering work on the gases such as CH4 and CO2 that liberated in swamp rice soils as a result of anaerobic decomposition. Acharya (1935a,b) observed that in rice fields, organic matter is degraded to the gaseous end-products such as CO2 and CH4. Although the potential of rice ecosystem as a source of methane was well recognized in early part of the 20th century, the first field level quantification of CH4 emissions in rice fields were carried out during 1980’s in California by Cicerone and Shetter (1981), followed by extensive studies in several other countries including India. Despite these painstaking efforts to obtain reliable field data, the available database still lacks direct measurements in several agro-climatic regions. The first estimate of global methane emission (190 Tg CH4 year-1) from rice fields was reported by Koyama (1964) and it was revised over time by several researchers (see: Aulakh et al., 2001b). The initial estimates of global methane emission from rice paddies were overstated and literatures published in last two decades (IPCC, 1994; Reeburgh and Crill, 1996) reveal the average methane emission to be 100 Tg CH4 year-1. In general, the global estimates vary between 20 to 150 Tg CH4 year-1 (Houghton et al., 1997; Neue and Sass, 1998). Although techniques and models...
for quantifying CH₄ fluxes have improved considerably; large uncertainties remain even at the regional and national budgets. The methane emission in Indian rice fields is estimated as 3 Tg yr⁻¹ based on the measurements done upto 1990 (Mitra, 1991) besides the famous Methane Campaign 1991, Methane - Asia 1998 and other reports have estimated 3.64 + 1.26 Tg yr⁻¹ based on the flux data available upto 1999 (Gupta and Mitra, 1999; Gupta et al., 2002). Overall, the diversified conditions in rice crop management are not sufficiently characterized for accurate estimates (Wassmann et al., 1998). Hence, region-specific characterization of agronomic practices and natural factors (soil properties, weather patterns, etc.) are indispensable to work out reliable estimate of CH₄ budget. More recently, Batia et al. (2013) prepared a state-wise inventory of CH₄ emissions from agricultural soils of India for the base year 2007 using the IPCC national inventory preparation guidelines and reported that Indian rice fields emitted 3.37 million tons of CH₄.

Plethora of publications exists in the area of methane production in rice soils. Methane is produced as the terminal step in the anaerobic decomposition of organic matter in wetland soils (Sahrawat, 2004a). The key requirement for the production of methane is the flow of carbon and electrons to microbial (methanogens) populations that exist under reduced conditions in the strict absence of free oxygen (Sahrawat, 2004a). The CO₂ reduction pathway and/or decarboxylation (transmethylation) of acetic acid are the two notable pathways that produce CH₄ in flooded soils (Takai, 1970; Neue and Scharpenseel, 1984).

Decarboxylation of acetic acid

\[
\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2
\]

CO₂ reduction with H₂ derived from organic compound

\[
\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}
\]

Several factors such as temperature, soil pH and addition of organic materials influence the ratio between CH₄ and CO₂ produced (Aulakh et al., 2001b). As a whole, methane is produced in submerged soils after the sequential reduction of molecular oxygen, nitrate, iron (III), manganese (IV) and sulfate, which serves as electron acceptors for oxidation of organic matter to CO₂ (Ponnampuruma, 1972). The final products of reduction in flooded soils are Fe (II) from Fe (III), H₂S from SO₄²⁻ and CH₄ from CO₂. In rice soils, root exudates provide important C sources for CH₄ production. On an average, 30-60 per cent of photosynthesized C by plants is allocated to the roots and a substantial portion of this C is released or secreted by roots in the form of organic compounds in the rhizosphere (Marschner, 1995). The organic acids in root exudates supply energy to soil microbial communities including methanogens (Aulakh et al., 2001b) and thus facilitating in the production of a poten tent greenhouse gas.

Soil physical and chemical properties

Methane production in reduced soils is very sensitive to pH and its optimum range is reported to be 6.7-7.1 (Jakobsen et al., 1981; Bouwman, 1990) and it varies with soil type. For example, methanogenesis was found optimum in a pH range of 7.5-8.5 in four different Indian soils (Parashar et al., 1991). In general, flooding of soil causes the soil pH to stabilize between 6.5 and 7.2 (Ponnampuruma, 1972), which is the optimum range for CH₄ production. High pH in the water-soil interface may also inhibit CH₄ oxidation (King, 1992). Soil anaerobiosis is measured in terms of redox potential (Eh), ranging from about -100 to -200 mV has been reported to be needed for the initiation of CH₄ production in paddy soils (Takai, 1961; Cicerone et al., 1983; Lindau et al., 1991).

As texture determines several physical and chemical properties of the soil, it could influence CH₄ emission indirectly. For instance, percolation rate, directly related to the soil texture, affects CH₄ production in paddy soils (Yagi et al., 1990). The temperature dependency of CH₄ production rates has been shown for several soils (Seiler et al., 1984; Parashar et al., 1991). Methane flux rates were dependent on soil temperature at 5 cm depth and emissions doubled as soil temperature increased from 20-25°C (Holzapfel-Pschorn et al., 1986). Studies in India showed that CH₄ fluxes increased as soil temperature increased to 35°C but emissions decreased above this temperature (Parashar et al., 1993).

Soil biology and biochemistry

A complex group of soil micro-flora is involved in the anaerobic degradation of organic matter and ultimately methane is produced (Dubey, 2001). The organic matter decomposed in anaerobic condition involves four stages: i) Production of simple sugars through hydrolysis of polymers by hydrolytic micro-flora, ii) acid production from simple organic compound by fermentative bacteria, iii) acetate production from metabolites of fermentations by homoacetogenic or syntrophic bacteria and iv) methanogenesis is the final stage of anaerobic degradation in which CH₄ is produced by methanogens from H₂/CO₂, acetate, simple methylated compounds or alcohols and CO₂ (Conrad, 1996; Yao and Conrad, 2001). Overall, the methane production is achieved by a complex microbial community consisting of hydrolytic, fermenting and methanogenic microorganisms (Conrad, 2007).

Methanogens

Methanogens exclusively produce methane in the strict absence of free oxygen and at redox potentials of less than -150mV (Wang et al., 1993). These microbes are strictly anaerobic unicellular organisms which were originally thought to be bacteria but later recognized as belonging to a separate phylogenetic domain, the archae (Garcia, 1990). Major share (about 80 per cent) of CH₄ that is produced by methanogens comes from acetate as a carbon substrate but other substrate like H₂/CO₂ and formats also contribute 10-30 per cent to CH₄ production (Chen et al., 1993). In general, the methanogens use NH₄⁺ as a nitrogen source, eventhough the ability to fix molecular nitrogen by employing nif gene is present in all the three orders (Methanobacteriales, Methanococcales and Methanomicrobiales) of methanogens (Palmer and Reeve, 1993).

The methanogens prosper at a pH of 6-8 with a temperature ranging 30-40°C (Vogels et al., 1988). Methane is usually produced by acetoclastic and hydrogenotrophic methanogenic archaea. In general, CH₄ production is first dominated by hydrogenotrophic methanogenesis, whereas the acetoclastic methanogenesis gains important in the later stages (Conrad, 2007). Rice soils exhibit a wide array of diversity in methanogenic archaea, including acetoclastic...
phenomenon when the water table fell below the sediment

(2013) observed the population of methanogens in the range

the season, even when the soil is drained. Recently, Rajkishore

involves the conversion of methyl group to CO₂ and sulfur oxidation - sulfate reduction. The methanotrophy

Methanosarcinales (Conrad, 2007).

Nevertheless, there is a demand to better understand more

phylogenetic marker functional marker genes, respectively.

methanogens by targeting 16S rRNA and

molecular techniques to study the populations of

improved. Substantial progress has been made by employing

microbial ecology of methanogens has been substantially

Methanobacteriales (Conrad

Methanosarcinaceae and Methanosetaeae as well as hydrogenotrophic Methanocellales, Methanomicrobiales and

Methanobacteriales (Conrad et al., 2012). Methanogens,

utilizing acetate as a C source, use hydrogen as their electron
donors. The consumption of H₂ by the methanogens is very

important in maintaining low enough H₂ partial pressures to

allow active growth of acetogenic bacteria that produce H₂,
yet are inhibited by its accumulation. This phenomenon of

“interspecies H₂ transfer” is important in anaerobic systems. It

is therefore observed that H₂ accumulation doesn’t occur

during active methanogenesis, but if methanogens are

inhibited by specific inhibitors, then H₂ accumulates. This

suggests that H₂ is an important and perhaps limiting energy

source for the methanogens.

Despite the fact that mechanisms of methanogenesis in rice

fields has been studied worldwide, data regarding

methanogenic population size in these soils is scanty (Dubey,

2005). The population of methanogens is usually enumerated

using Mah’s medium (Mah, 1980) and the colonies are

identified by their bluish florescence under UV light. It has

been documented that Garcia and co-authors in the year 1974

first reported the methanogenic populations in 28 rice fields of

Senegal (Garcia, 1990), followed by Rajagopal (1988) who

isolated and characterization of methanogens from Louisiana

rice fields and reported the presence of two

Methanobacterium-like strains and two Methanosarcina-like strains. Kudo et al. (1997) observed the presence of

Methanosaeta, Methanobacterium, Methanosaeta and


reviewed in detail the physiology, phylogeny, diversity,
habitats, ecological niches of methanogens and methanotrophs. His review has greatly contributed for better

understanding of the complexity of microbial ecology in the

rice ecosystem. Ma et al. (2011) reported abundance of

methanogens in rice soils (>10⁶ cells g⁻¹ dry soil) throughout

the season, even when the soil is drained. Recently, Rajkishore

(2013) observed the population of methanogens in the range of

6.7 to 20.6 x 10⁶ CFU g⁻¹ of dry soil in the rice fields of

Tamil Nadu, India. Overall, the depth of knowledge on the

microbial ecology of methanogens has been substantially

improved. Substantial progress has been made by employing

molecular techniques to study the populations of

methanogens by targeting 16S rRNA and

mcrA genes as phylogenetic marker functional marker genes, respectively.

Nevertheless, there is a demand to better understand more

on the intrinsic ecology of the methanogens, besides learning

the ecological niches of its different species (Conrad, 2007).

Methanotrophs

Methanotrophy is the other part of the coupled reaction of

methanogenesis which is similar to nitrification - denitrification

and sulfur oxidation - sulfate reduction. The methanotrophy

involves the conversion of methyl group to CO₂, using either

oxygen or other compounds of higher oxidation status as

electron acceptors. The CH₄ emitted from rice fields to the

atmosphere is the balance of two opposite processes, i.e.,

CH₄ production and oxidation in the soils. The first evidence

for consumption of atmospheric CH₄ by wetland sediments

was reported by Harris et al. (1982) who observed this

phenomenon when the water table fell below the sediment

surface. In the global CH₄ cycle, substantial quantity of CH₄ is

consumed by biological processes and it is probably greater

than that of chemical oxidation, if the total cycle of CH₄

production and oxidation is considered, and not just the fate of

CH₄ after it is emitted into the atmosphere (King, 1992). The

only known biological sink for CH₄ is its oxidation in aerobic

soil layers by methanotrophs or methane-oxidizing bacteria

(MOB), which can contribute up to 15 per cent to the total

global CH₄ destruction (Singh, 2011).

Methanotrophs are strictly obligate aerobes that use

monocarbon organic compounds such as CH₄ and methanol

as a substrate (Pappen and Rennenberg, 1990). Since they require

molecular oxygen (Bedard and Knowles, 1989), methanotrophs are

active in oxic - anoxic interfaces where concentration

gradients of CH₄ and O₂ overlap. Therefore, a sizable fraction of

CH₄ produced in the reduced layers of soil or in micro-sites is

oxidized when it diffuses upward. Methanotrophs oxidize

CH₄ by employing methane monooxygenase (MMO) enzyme.

MMO catalyze the reaction to convert CH₄, O₂ and reducing
equivalents to methanol and H₂O. The MMO occurs in two

forms namely membrane bound particulate form (sMMO) and

soluble form. The sMMO is present in all types of

methanotrophs, whereas the soluble form is found in Type-II

and Type X methanotrophs (Mancinelli, 1995). In order to

enumerate methanotrophs, the pour plate technique is usually

performed using Noble Agar Medium and the plates are

incubated in the Macintosh jar assembly with provisions for

attaching a bladder containing methane. Further, o-dianisidine
dye test is performed for assessing the methanotrophs activities in

the presence of naphthalene crystals. Methanotrophs exhibit

methylene monooxygenase (MMAO) activity and hence, napthol

is produced and purple red colour colonies are observed

(Rajkishore, 2013). Recently Shulka et al. (2013) critically

reviewed the state of knowledge on soil methane oxidation

and methanotrophs besides highlighting the recent advances

made in this field.

Methanotrophs isolated and investigated so far uses molecular

oxogen as the terminal electron acceptor and therefore are

obligate aerobes, although there is evidence that certain, mostly

SO₄²⁻ reducing habitats exist in which anaerobic CH₄ oxidation

occurs. Although several attempts to isolate CH₄ oxidizing

anaerobes in pure culture have failed, sulfate dependent methane

oxidation (SDMO) has been accepted to exist in nature.

Coupled with the poor thermodynamic yield of SDMO, this has led to a notion that CH₄ oxidation under anaerobic

conditions is a co-metabolic activity and that the responsible

organisms do not conserve energy from the process.

Methanotrophs are highly sensitive to environmental

perturbations and hence, the factors that limit or even inhibit

the activities of MOB may have major effects on the global

CH₄ budget. Besides major limiting factors, i.e, CH₄ and oxygen,

nitrogen is one of the limiting factors for CH₄ oxidation and may

become an inhibiting or stimulating factor for growth of

methanotrophs (Singh, 2011). Inorganic N influences CH₄

oxidation due to shifts in the population structure and the

kinetics of methanotrophs (Dubey et al., 2002). This may

directly affect the threshold value for CH₄ oxidation (King,

1982). According to Hutsch et al. (1994) the NO₃⁻ N

fertilization did not affect the CH₄ consumption but NH₄⁺ N
fertilization completely ceased CH$_4$ oxidation. However, nitrite was found to inhibit CH$_4$ oxidation in the cultures of Methylomonas albus BG8 and M. trichosperum O83b (King and Schnell, 1994). Bodelier et al. (2000) reported stimulation of methanotrophs in the root zone of rice plants as a result of ammonium fertilization. Currently, there are many contradictory results reporting inhibition effects, stimulation effects or no effects of NH$_4^+$ - N based nitrogen fertilizers on MOB. So far, many mechanisms have been proposed for stimulation and inhibition effects on methane oxidation and methanotrophs, but none of them has yet been experimentally verified (Singh, 2011). More recently, Rajkishore (2013) has undertaken field experiments to verify such anomalies and reported a strong negative correlation of soil NH$_4^-$ N with methanotrophs population in rice soils.

**Sulphate reducers**

The total sulfur content in rice soils is rather low and hence sulfur is required to occur preferentially in the oxic-anoxic interfaces (Liesack et al., 2000). The sulfate-reducing bacteria isolated from rhizosphere soil and bulk soil suggested the presence of two different physiological types of sulfate reducers: The rhizosphere soil, ‘rich’ in substrate, as dominated by fast-growing incomplete oxidizers like Desulfotomaculum species, whereas the substrate-impoverished bulk soil mainly contained complete oxidizing, spore forming and slow growing Desulfotomaculum species (Wind et al., 1999). Sulphate reducers is enumerated by isolating the black colonies that appeared on Postgate’s medium (Postgate, 1981). In a review carried out by Mer and Roger (2001), intermittent drainage and utilisation of the sulphate forms of N-fertilisers reviewed by Mer and Roger (2001), intermittent drainage and utilisation of the sulphate forms of N-fertilisers are some of the recommendations to reduce CH$_4$ emission. Short drainage induce the formation of sulphate and ferric -anoxic interfaces (Liesack et al., 1999).

**Table 1:** Some important contributions across the globe in the field of methane emissions from rice ecosystems

<table>
<thead>
<tr>
<th>Country</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>Harrison and Alyer (1913); Acharya (1935a,b); Maitra (1991); Parashar et al. (1991); Adhya et al. (1994); Ramakrishnan et al. (1995); Banik et al. (1995); Deb Nath et al. (1996); Satpathy et al. (1997); Misha et al. (1997); Jain et al. (2000); Dubey (2001); Aulakh et al. (2000, 2001a,b); Gupta et al. (2002); Sahrawat (2004a,b,c); Dubey (2005); Purkait et al. (2007); Singh (2011).</td>
</tr>
<tr>
<td>Philippines</td>
<td>Ponnampremu (1972); Denier van der Gon et al. (1992); Denier van der Gon and Neue (1994); Neue et al. (1994a,b); Wassmann et al. (1993, 1996, 2000); Bronson et al. (1997)</td>
</tr>
<tr>
<td>Japan</td>
<td>Koyama (1964); Yagi and Minami (1990); Nouchi et al. (1990); Watanabe et al. (1995)</td>
</tr>
<tr>
<td>United States</td>
<td>Cicerone and Shetter (1981); Sass et al. (1991); Sass and Fisher (1994); Lindau et al. (1991); Lindau and Bollich (1993); Lindau (1994); Sigren et al. (1997)</td>
</tr>
<tr>
<td>Spain</td>
<td>Seiler et al. (1984)</td>
</tr>
<tr>
<td>China</td>
<td>Khalif and Rasmussen (1991); Chen et al. (1993); Wassmann et al. (1993); Lu et al. (2000)</td>
</tr>
<tr>
<td>Italy</td>
<td>Holzapfel-Pichorn et al. (1986); Schütz et al. (1989); Butterbach-Bahl et al. (1997)</td>
</tr>
<tr>
<td>Indonesia</td>
<td>Nugroho et al. (1994); Husin et al. (1995); Lumbanraja et al. (1997)</td>
</tr>
<tr>
<td>Thailand</td>
<td>Jermsawadtipong et al. (1994); Yagi et al. (1994)</td>
</tr>
<tr>
<td>Germany</td>
<td>Conrad and Rothfuss (1991); Conra (1996); Ratering and Conrad (1998); Conrad (2007); Conrad et al. (2012)</td>
</tr>
</tbody>
</table>

**Pathways of methane transport**

Methane is emitted from the rice soils to the atmosphere by three pathways (Fig. 1) viz. ebullition, diffusion and transport through the rice plant (Dubey, 2005). These pathways are briefly discussed below.

**Ebullition**

Ebullition (gas transport via gas bubbles) is a physical process through which methane escapes from the soil in the form of bubbles. Ebullition of CH$_4$ from sediments is a common and significant mechanism accounting for 49-70 per cent of the total flux in natural wetlands (Wassmann and Martius, 1997). However, in rice fields CH$_4$ ebullition occurs only during the initial growth stages of rice besides during cultural operations (Wassmann et al., 1996). Soil disturbance as a result of intercultural operations in the rice field could release soil entrapped CH$_4$ and enhance its emission through ebullition (Denier van der Gon et al., 1992). Furthermore, ebullition plays a major role in other scenarios where soil is unvegetated soil or plant aerenchyma is not yet well-developed (Byrenes et al., 1995) but it occurs only at surface layer and its rate is regulated by CH$_4$ concentration, temperature, soil porosity and plant aerenchyma (Li, 2000).

**Diffusion**

Diffusion of CH$_4$ across the overlying water of the rice field to the atmosphere is a function of surface-water concentration of CH$_4$, wind speed and CH$_4$ supply to the surface-water (Sebacher et al., 1983). The transport of CH$_4$ via diffusion through soil and water is very small. The contribution of diffusion to the total CH$_4$ emission during the rice growing season is often 1-2 per cent (Butterbach-Bahl et al., 1997). In general, the produced CH$_4$ is oxidized especially in the soil-water interface and some in the rhizosphere of the rice plant. Therefore, CH$_4$ diffusion contributes only a small amount to the total CH$_4$ flux from rice fields. Moreover, CH$_4$ diffusion through the soil is a very slow process because the ‘diffusion rate’ of gaseous CH$_4$ is very low in liquid phase (about 10$^4$ times slower than diffusion through the gas phase) and hence, it hardly contributes to the total CH$_4$ flux (Aulakh et al., 2001a).

**Rice plants acts as chimney**

Plant mediated transport is the primary mechanism (Wassmann et al., 2000) for the CH$_4$ emission from paddy
fields and contributes 90 per cent to the total CH₄ flux (Khosa et al., 2010 and Akinbile et al., 2012). As a morphological adaptation to flooding, hydrophilic and wetland plants including rice possess aerenchyma. This air-filled tissue is required to aerate the roots of hydrophilic and wetland plants and constitutes the major pathway for the flux of gases through plants into the roots (Aulakh et al., 2000).

Methane dissolves in the soil-water surrounding the roots and diffuses into the cell-wall water of the root epidermis cells and then diffuses through the cell-wall water of the root-cortex, depending upon the concentration gradient between the soil-water surrounding the roots and the lysigenous inter-cellular spaces in the roots. Methane is then gasified in the root cortex and transported to the shoots via lysigenous intercellular spaces and aerenchyma. Eventually, CH₄ is released primarily through the micropores in the leaf sheath of the lower leaf position and also through the stomata in the leaf blade (Nouchi et al., 1990). In the overall methane dynamics, rice plants act as: a) source of methanogenic substrate, b) conduit for CH₄ through well developed system of inter cellular air space (aerenchyma) and c) potential methane oxidizing micro-habitat in the rhizosphere by diffusing oxygen which favour the growth and multiplication of methanotrophs (Dubey, 2005).

### Strategies for methane mitigation

Irrigated rice represents the most promising target for methane mitigation strategies (Aulakh et al., 2001b). Uprety et al. (2011) reviewed the methane emissions in rice fields and reported the future emission scenarios for India in the year 2030. Accordingly, the methane emissions are projected to reach 24.4 Tg, 21.3 Tg and 17.6 Tg for reference, medium mitigation and strong mitigation scenarios, respectively. The list of most reliable mitigation options without affecting rice yield has been presented in Table 2 and the details are discussed below.

#### Water management

Water regimes are the key determinants for the production and emission of CH₄ from rice fields. Mid-season drainage, intermittent irrigation or pre-harvest field drying could be effective in reducing CH₄ fluxes (Buendia et al., 1998). During the dry spells, an increase in soil Eh and a decrease in CH₄ flux are often observed resulting in markedly reduced total seasonal CH₄ emissions (22-88 per cent) compared to the continuously flooded treatment without reducing rice yields (Mishra et al., 1997; Jayashree et al., 1998; Jain et al., 2000). Compared with continuous flooding, intermittent irrigation and constant moisture (field with no standing water, but remained saturated) reduced methane emission rate by 25.4 and 58.4 per cent, respectively (Wang et al., 1999). Wassmann et al. (2000) reported that the distinct drainage periods within the season can drastically reduce CH₄ emissions to less than 30 kg CH₄ ha⁻¹ season⁻¹. Intermittent irrigation system reduces the water consumption in rice cultivation and mitigates methane emission (Yang and Chang, 2001). Since methanogens require highly reducing conditions, aerating the soils arrests the development of reducing conditions in the soils and enhances the methane oxidation, which ultimately decreases methane emissions. Thus, proper drainage during the growing season could be a promising mitigation strategy (Anand et al., 2005). During the Alternate Wetting and Drying (AWD) cycle, most of the methane gas oxidizes before reaching the soil – air interface resulting in lower methane flux (Purkait et al., 2007). High Eh values prevent CH₄ formation by methanogenic bacteria and hence reduce the CH₄ emissions during intermittent drainage (Hadi et al., 2010). Li et al. (2011) concluded that early aeration strongly reduces CH₄ emission.

<table>
<thead>
<tr>
<th>Strategies</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water management</td>
<td>Yagi and Minami (1990); Wassmann et al. (1993)</td>
</tr>
<tr>
<td>Midseason drainage</td>
<td>Li et al. (2011)</td>
</tr>
<tr>
<td>Early aeration</td>
<td>Buendia et al. (1998); Purkait et al. (2007); Hadi et al. (2010)</td>
</tr>
<tr>
<td>Intermittent wetting &amp; drying</td>
<td></td>
</tr>
<tr>
<td>Inorganic fertilization</td>
<td>Schutz et al. (1989)</td>
</tr>
<tr>
<td>Deep incorporation of urea</td>
<td>Kimura et al. (1992)</td>
</tr>
<tr>
<td>Foliar application of N fertilizers</td>
<td>Lindau (1994); Denier van der Gon and Neue (1994)</td>
</tr>
<tr>
<td>SO₄²⁻ containing fertilizers</td>
<td>Sahrawat et al. (2004c); Bharati et al. (2000)</td>
</tr>
<tr>
<td>Gypsum</td>
<td>Babu et al. (2006)</td>
</tr>
<tr>
<td>Nitrification inhibitors: nimin, nitrapyrin, wax coated calcium carbide, sodium azide, pyridine, aminopurine, ammonium thiosulphate, (DCD) and thiourea</td>
<td>Lueders and Friedrich (2002)</td>
</tr>
<tr>
<td>Muriate of potash</td>
<td>Chen et al. (2011); Uprety et al. (2011)</td>
</tr>
<tr>
<td>Addition of electron acceptors</td>
<td>Wang et al. (1993)</td>
</tr>
<tr>
<td>Organic fertilization</td>
<td>Lindau et al. (1995); Aulakh et al. (2000)</td>
</tr>
<tr>
<td>Composted manure, Biogas residues</td>
<td>Rajkishore et al. (2013); Jain et al. (2013); Gathorne-Hardy et al. (2013)</td>
</tr>
<tr>
<td>Dual cropping of Azolla</td>
<td>Aulakh et al. (2001b)</td>
</tr>
<tr>
<td>Cultivars</td>
<td></td>
</tr>
</tbody>
</table>
from rice paddy fields. Khosa et al. (2011) investigated the effects of six different water regimes on methane emissions and reported that irrigation to rice fields at 0.15 bar matric potential reduced seasonal methane flux by 60 per cent as compared to completely flooded conditions. To summarize, the water management practices like intermittent wetting & drying, early/mid-season aeration are some of the important strategies for methane reduction.

**Inorganic fertilization**

Fertilizers application may affect the production and emission of CH₄ by influencing

(i) the growth of the rice plant, (ii) the activity of methanogenic microbial communities and (iii) the amount and composition of root exudates of growing rice plants (Aulakh et al., 2001a). Numerous studies have revealed the impact of chemical fertilizers on CH₄ emissions (Schutz et al., 1989; Adhya et al., 2000; Sethunathan et al., 2000) and among the major nutrients, the effects of nitrogen fertilizers on methane emissions are still inconclusive (Aulakh et al., 2001b).

**Nitrogen**

Although the impact of rate, type and method of N application has been investigated in several field studies, the available data are mostly unclear (Cheng-Fang et al., 2012). Reviewing wide range of literatures on this topic suggests that the published results can be classified into the ones that reported positive effects and other set of research data with negative effects of nitrogen on methane emissions. Several researchers have reported that nitrogen fertilizers inhibited the methane emissions. Schutz et al. (1989) reported that the application of 100 and 200 kg urea - N ha⁻¹ to rice fields over a 3 year period reduced CH₄ emissions by 18 per cent as compared to control plots. They reported that the application modes differed in their impact with highest CH₄ flux from “surface applied urea” followed by “raked into soil” (5 cm depth) and “incorporated” (20 cm depth). Lindau (1994) reported the decrease in CH₄ emission rate with ammonium nitrate application due to competitive inhibition of nitrate reduction in favour of methane production. Cai et al., (1997) showed that CH₄ emissions decreased by 42 and 60 per cent in the ammonium sulphate treatments and 7 and 14 per cent in the urea treatments at rates of 100 and 300 kg N ha⁻¹, respectively, compared to the control. They noticed both depressive and stimulative effects of urea application as a consequence of changes in NH₄⁺ concentration. The negative effect of ammonium-based fertilizer is mainly attributed to the stimulation on CH₄ oxidation via enhancing the growth/activity of methanotrophs (Bodelier and Laanbroek, 2004).

In contrast, Lindau et al. (1991) observed that the surface-applied urea at the rates of 0, 100, 200 and 300 kg ha⁻¹ evolved total CH₄ emissions of 210, 300, 310 and 370 kg ha⁻¹, respectively and these results revealed that the urea had a stimulatory effect on methane emission. Lindau and Bollich (1993) also showed enhanced CH₄ emission with surface-applied urea as a result of hydrolysis to ammonium. Urea application enhances CH₄ fluxes possibly by increasing soil pH following urea hydrolysis and subsequent drop in redox potential, stimulates methanogenic activities (Wang et al., 1993). Addition of ammonium to flooded rice soils has been reported to inhibit CH₄ oxidation (Conrad and Rothfuss, 1991; Wassmann et al., 1993). Lu (1998) demonstrated that NH₄-N application promoted higher and faster development of dissolved CH₄ concentration and CH₄ emission in flooded rice. The positive effect of nitrogen mainly results from the stimulation of CH₄ production and vascular transport capacity via enhancing methanogenic growth/activity and rice growth (Xu et al., 2004).

Numerous studies have demonstrated that the application of nitrogen may directly or indirectly influence all of the processes in CH₄ production, oxidation and transport from the soil to the atmosphere and therefore, the effects of N application on CH₄ emission at the ecosystem level is the net consequence of these processes (Cai et al., 2007). Ma et al., (2007) observed that urea decreased CH₄ emission relative to the control when applied at a rate of 200 kg N ha⁻¹ but the effect lessened if the application rate was further increased to a rate of 270 kg ha⁻¹. They showed that effects of urea application on CH₄ emissions depend on its integrated effects on CH₄ production and oxidation. Since effects of urea application on CH₄ production, oxidation and transport can be negative and positive and take place simultaneously, it is not surprising that the reported effects of urea application on CH₄ emissions from rice fields are contradictory. According to Xie et al. (2010), the application of ammonium based fertilizers at widely applied rates usually inhibits CH₄ emission as compared to no N addition. Ammonium based fertilizer at the rate of 150 kg N ha⁻¹ greatly inhibited as compared to fields without N application. However, the inhibitory effect was not observed by further increasing N application to 250 kg N ha⁻¹. Out of the ten cases, seven cases recorded the methane reduction by 14 per cent whereas remaining three cases registered an enhancement of methane emission by 47 per cent. However, they reported that all of these inhibitory or stimulatory effects were not statistically significant. Hence, they concluded that further studies are very much necessary (Xie et al., 2010). Cheng-Fang et al. (2012) recorded that the application of nitrogen fertilizer significantly increased CH₄ emissions by 13 – 66 per cent and attributed that nitrogen promoted the rice growth and in turn, provided additional C sources to methanogenic communities. Further experiments with more nitrogen application rates and simultaneous measurements of CH₄ production, oxidation and emission are necessary to help elucidate the underlying mechanisms (Ma et al., 2007) and to bring out a clear relationship between them.

**Amendments/inputs**

Application of nitrification inhibitors such as nimin, nitrapyrin, wax coated calcium carbide, sodium azide, pyridine, aminopurine, ammonium thiosulphate, dicyandiamide (DCD) and thiourea are found to reduce CH₄ emission (Bharati et al., 2000a). Furthermore, herbicide butachlor (N-butoxymethyl-2-chloro-2´,6´ -diethyl acetanilide) inhibits CH₄ emission by causing a drop in soil redox potential (Eh) as well as accumulation of Fe⁺² (Mohanty et al., 2001). Other agri-inputs such as carbamate insecticide, carbofuran also retard CH₄ emission through enhanced CH₄ oxidation (Sethunathan et al., 2000). Lueders and Friedrich (2002) indicated reduced CH₄ emissions by addition of electron acceptors to stimulate microbes competitive to methanogens.
METHANE EMISSION FROM RICE ECOSYSTEMS

System of cultivation
Combining individual mitigation options to packages of technologies can effectively reduce emissions (Aulakh et al., 2001b). Jayadeva et al. (2009) investigated the effect of three systems of rice cultivation viz., Transplanting, System of rice intensification (SRI) and Aerobic on methane emissions and concluded that normal transplanting contribute for higher emission. SRI practices aim to provide rice plants with better growing environments and has immense potential to boost the yield besides several added advantages such as higher nutrient use efficiency and reduced water requirements (Barison and Uphoff, 2011; Chowdhury et al., 2014). More recently, Rajkishore et al., (2013) demonstrated the unique advantage of SRI over conventional systems of rice cultivation in reducing the overall methane emission by 30 per cent. They also pointed out that the practice of cono-weeding employed with SRI by itself contributes 19 to 63 per cent of the reduction in the methane emissions. More interestingly, the findings of Gathorne-Hardy et al. (2013) suggest that the net effects of SRI practice on reducing global warming potential were positive in that the small increases in N\textsubscript{2}O did not offset the larger diminishment of CH\textsubscript{4}. Furthermore, direct seeding of pre-germinated rice instead of transplanting rice seedlings has also shown to reduce methane emissions due to shorter flooding periods and decreased soil disturbances (Metra-Corton et al., 2000).

Plant Cultivars
Methane emission is greatly influenced by genetic characteristics as a result of difference in the development of aerenchyma tissues. In addition, the high yielding cultivars with low photosynthetic carbon translocation towards root would also result in reduced CH\textsubscript{4} emission. Wang et al. (2000) reported that the use of cultivar Zhongzhou (modern japonica) reduced methane emissions by approximately 50 percent when compared with Jingyou (japonica hybrid) and Zhonghua (tall japonica). Recently, Bhullar et al. (2013) introduced agar-sealing technique, a novel method for studying the plant-mediated methane transport capability of wetlands species. This method was reported to be effective in preventing methane exchange from soil surface and hence it could serve as a useful tool for screening large sets of plant species/cultivars for their methane transport capabilities. Thus, screening of existing ruling varieties and initiation of breeding programme for new cultivars with low photosynthetic partitioning to root besides limited development of aerenchyma tissues could offer a promising option for CH\textsubscript{4} mitigation (Uprety et al., 2011).

Organic amendments
The organic amendments constitute an important component in integrated nutrient management, but pose problems of increased CH\textsubscript{4} emissions. The amount of methane formed in paddy soils is positively correlated with soil organic carbon and water soluble organic carbon provided other factors such as bacterial population and oxidizing capacity of the soil. Organic matter addition increases methane emission by 3-5 times. Delwiche and Cicerone (1993) reported that without the addition of organic matter, methane production was cumulatively low. Lauren and Duxbury (1993) observed that the application of Sesbania green manure to flooded rice increased methane emission and higher soil carbon levels elevated methane fluxes. Application of rice straw at the rate of 6 - 9 t ha\textsuperscript{-1} to the paddy fields increase the CH\textsubscript{4} emission rates 1.8 to 3.5 fold (Yagi and Minami, 1990). The increase in the application level of rice straw increases the cumulative amount of CH\textsubscript{4} emission (Watanabe et al., 1995). Compost application has a pronounced effect on increase of organic carbon (13 to 25%) and slightly increases CH\textsubscript{4} emission (Gotoh et al., 1984). Application of biogas spent slurry as a manure results in lowering of methane emission compared to application of FYM (Depnath et al., 1996). Use of biogas slurry therefore could be a practical mitigation option for minimizing methane flux from flooded rice fields.

Incorporation of green manures increases methane emission (Neue et al., 1994). Green manures like Sesbania aculeata, Tephrosia purpurea and Sesbania rostrata enhanced methane emission (Udayasoorian, 1995). Growing of Azolla for biological nitrogen fixation modify the chemical properties of soil by lowering the Eh value and NH\textsubscript{4}\textsuperscript{+}-N. Hence Azolla in rice fields enhance methane emission and reduces biological methane oxidation and porosity of rice soil (Ying et al., 2000).

On the other hand, bundle of literature suggest that azolla and cyanobacteria was found to reduce methane emissions (Bharati et al., 2000; Prasanna et al., 2002). Wang et al. (1993) reported that dual cropping of Azolla registered a higher redox potential leading to low CH\textsubscript{4} flux. Azolla and cyanobacteria facilitate high dissolved oxygen (DO) in the floodwater (Lakshmanan et al., 1994; Bharati et al., 2000) and this might retard CH\textsubscript{4} emission from rice field by promoting CH\textsubscript{4} oxidation at the soil water interface (Hanson and Hanson, 1996). Overall, the applications of compost and biogas slurry as alternate to fresh organic source/farm yard manure are considered as one of the effective means for CH\textsubscript{4} mitigation besides improving the fertility of soils (Yagi and Minami, 1990; Neue et al., 1994; Wassmann et al., 1993).

Methane measurements
Gas samples are usually collected from the rice fields using static closed chamber technique (Minami and Yagi, 1988; Jain et al., 1999) and estimated at the laboratory by employing Gas-Chromatograph (GC). The recommendations for fabricating fool-proof gas chambers are given by several researchers (Mosier, 1989; IAEA, 1992; Adhya et al., 1994; Dennead, 2008). Guidelines for measuring methane emissions are also stipulated by clean development mechanism (CDM) for the registered methane reducing project in rice fields that need to be qualified for carbon trading. On the other hand, automated chamber measurement for CH₄ estimation was first reported by Schutz et al. (1989a). In this automated device, the manual sampling of air samples from the inner volume of the gas collector chambers is replaced by a gas flow system providing sample transfer to the GC. However, the automated devices are costly and its use is confined to sites where a laboratory is in close vicinity of the experimental field. Despite such demerits, automated systems are an appropriate technique to achieve reliable and extensive data sets (Aulakh et al., 2001b). Although plethora of literature is serving as a guideline for estimation of methane emission at field level, inaccurate dataset as a consequence of improper standardization, lack of calibration during GC operation, besides extrapolation with limited replications has severely affected the quality of measured values. Hence, refinement in the existing protocol and publications with detailed step by step standard procedures to avoid anomaly is the need of the hour. Indirect measurement of methane is also carried out by measuring the dissolved CH₄ in soil solution and it is a good indicator for the emission potential during periods with predominant ebullition such as the early stages of rice growth (Wassmann et al., 1996).

**Elevated CO₂ concentrations**

Ample number of literatures have reported that elevated CO₂ concentrations ([CO₂]) enhanced the methane emissions by 49 to 60 per cent @ 650 μmol mol⁻¹ (Ziska et al., 1998), 38 to 51 per cent @ 550 μmol mol⁻¹ (Inubushi et al., 2003), 58 per cent @ 700 μmol mol⁻¹ (Cheng et al., 2006) and 26 per cent @ 580 μmol mol⁻¹ (Tokida et al., 2010) over the ambient [CO₂]. These facts are further supported by a recent meta-analysis report (van Groenigen et al., 2011) which indicated that [CO₂] between 463 to 780 μmol mol⁻¹ stimulated CH₄ emissions on an average by 43.4 per cent. CH₄ is the dominant terminal degradation product of soil organic materials in submerged rice fields (Kruger et al., 2001), therefore, increased C input to the soil in response to elevated [CO₂] leads likely to enhanced CH₄ production (Ziska et al., 1998; Li et al., 2004). The positive correlations between CH₄ emissions and above-ground or root biomass suggests that greater assimilation of carbon under high [CO₂] leads to higher rates of rhizo-deposition (root exudation and autolysis products), which is an important source of substrates for CH₄ production (Inubushi et al., 2003; Xu et al., 2004; Tokida et al., 2010). In addition, the dissolved organic carbon (DOC) may also contribute for CH₄ flux (Mukherjee and Ray, 2013). The findings of Bhattacharyya et al. (2013) also revealed that the stimulatory effect on CH₄ emissions under elevated [CO₂] was associated with the increased amount of soil labile C, C rich root exudates, lowered Eh, higher Fe(+2) concentration and increased activities of methanogens and extracellular enzymes. More recently, Rajkishore (2013) exposed the rice plants to elevated [CO₂] under Open Top Chamber (OTCs) conditions and indicated that methane emissions were significantly higher under [CO₂] of 750 μmol mol⁻¹ by 33 to 54 per cent over the ambient [CO₂] of 380 μmol mol⁻¹. These facts suggest that alarming increase in the atmospheric [CO₂] may further increase the methane emission from rice fields.

**Future perspectives**

The state of knowledge reflects that current information is insufficient for the development of technology for reduction in methane emission at regional levels. There is a need to combine the available individual mitigation options into a wholesome package that can effectively reduce emissions. Insights into comparative genomics and proteomics of methanogens, methanotrophs and sulphate reducers will contribute to the deciphering their population structure and existing mechanisms of methane emission. Technology for improving the biological oxidation of methane by rhizosphere engineering with methanotrophs in rice fields need to be developed. Further, knowledge on soil microbial community associated with the ruling rice cultivars is essential for recommending mitigation strategies. Despite of the fact that numerous studies have been carried out to understand the influence of nitrogen fertilizers on methane emission, the available information is incomplete and this warrants more attention in this area. Studies to understand the effect of ammonium based nitrogen fertilizers on methanotrophic community structure is an important area to focus. In addition, new advancements such as nano-fertilizers need to be investigated for its methane emission potential. System of Rice Intensification (SRI) has been reported to reduce significant amount of methane emission and hence, protocol for development of methodology to include SRI for carbon trading need to be evolved which may benefit farming community. Simulation models to estimate CH₄ emissions for a range of climate and agricultural management practices need to be improved. Methane mitigation strategies evolved so far demands fine tuning in the context of exponential increase in the atmospheric [CO₂] and its positive effect on methane emission. The research priorities listed above might be selective in that it reflects the interests of the authors of this review.

**ACKNOWLEDGEMENT**

The authors sincerely acknowledge the hard work of Werner Liesack, Milkha S. Aulakh, S.K. Dubey for publishing review papers in different dimensions in the domain of methane emission from rice fields and their contributions served as a guiding reference to undertake this documentation on significant contributions made in this 100 years (1913-2013).

**REFERENCES**


S. K. RAJKISHORE et al.,


INSTRUCTION TO AUTHORS

The Ecoscan

An International Biannual Journal of Environmental Science

THE JOURNAL

The Ecoscan is an international quarterly journal of environmental sciences with international editorial board. The journal is online and details can be seen (downloaded from the site. www.thebioscan.in). For any query e-mail at m_psinha@yahoo.com & dr.mp.sinha@gmail.com can be used.

AIM & SCOPE

The journal aims to publish original peerly reviewed/refereed research papers/reviews on all aspects of environmental sciences.

SUBMISSION OF MANUSCRIPT

Only original research papers are considered for publication. The authors may be asked to declare that the manuscript has not been submitted to any other journal for consideration at the same time. Two hard copies of manuscript and one soft copy, complete in all respects should be submitted. The soft copy can also be sent by e-mail as an attachment file for quick processing of the paper.

FORMAT OF MANUSCRIPT

All manuscripts must be written in English and should be typed double-spaced with wide margins on all sides of good quality A4 paper.

First page of the paper should be headed with the title page, (in capital, font size 16), the names of the authors (in capitals, font size 12) and full address of the institution where the work was carried out including e-mail address. A short running title should be given at the end of the title page and 3-5 key words or phrases for indexing.

The main portion of the paper should be divided into Abstract, Introduction, Materials and Methods, Results, Discussion (or result and discussion together), Acknowledgements (if any) References and legends.

Abstract should be limited to 200 words and convey the main points of the paper-outline, results and conclusion or the significance of the results.

Introduction should give the reasons for doing the work. Detailed review of the literature is not necessary. The introduction should preferably conclude with a final paragraph stating concisely and clearly the aims and objectives of your investigation.

Materials and Methods should include a brief technical description of the methodology adopted while a detailed description is required if the methods are new.

Results should contain observations on experiment done illustrated by tables and figures. Use well known statistical tests in preference to obscure ones.

Discussion must not recapitulate results but should relate the author’s experiments to other work on the subject and give their conclusions.

All tables and figures must be cited sequentially in the text. Figures should be abbreviated to Fig., except in the beginning of a sentence when the word Figure should be written out in full.

The figures should be drawn on a good quality tracing/white paper with black ink with the legends provided on a separate sheet. Photographs should be black and white on a glossy sheet with sufficient contrast.

References should be kept to a minimum and listed in alphabetical order. Personal communication and unpublished data should not be included in the reference list. Unpublished papers accepted for publication may be included in the list by designating the journal followed by “in press” in parentheses in the reference list. The list of reference at the end of the text should be in the following format.


References in the text should be quoted by the author’s name and year in parenthesis and presented in year order. When there are more than two authors the reference should be quoted as: first author followed by et al., throughout the text. Where more than one paper with the same senior author has appeared in on year the references should