12 Understanding Methanogens, Methanotrophs, and Methane Emission in Rice Ecosystem

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Abstract

Rising concentration of methane (CH_4), nitrous oxide, carbon dioxide, and chlorofluorocarbons in the atmosphere result in global warming. These greenhouse gases (GHGs) trap the infrared radiations remitted from the Earth. The global mean temperature is rising more rapidly than ever due to presence of higher concentration of GHGs in the atmosphere. Anthropogenic activities such as fossil fuel burning, biomass combustion, industrialization, modern agricultural system, etc., are the key factors responsible for rising GHGs concentration. After carbon dioxide, CH_4 is the major GHG contributing to the global warming. CH_4

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is produced by methanogens by complex processes known as methanogenesis. Methanogens are strictly anaerobic bacteria and they can persist in extreme environmental conditions. Rice is the stable food for more than 50% of global population. Rice is generally cultivated in subtropical regions and it is reported that continuous flooded environment is better for higher production. Flooding condition of the rice creates favorable environment for methanogenic bacteria. Under anaerobic environment, methanogens consume soil organic matter as carbon source and emit CH_4 gas to atmosphere. CH_4 emission from rice soil is the net balances of two processes: production by methanogens and oxidation by methanotrophs. Methanotrophs are obligate aerobic bacteria which consume CH_4 as the source of carbon and help oxidation of CH_4 to carbon dioxide. In rice ecosystem, population of methanogenic and methanotrophic bacteria depends upon several biotic and abiotic factors which are discussed in this chapter.

Keywords

Rice · Methane · Methanogens · Methanotrophs · Mitigation · Global warming

12.1 Introduction

Methane (CH_4) is the simplest hydrocarbon greenhouse gas (GHG) produced by methanogens (archaea) under anaerobic environment (Liu et al. 2019a; Malyan et al. 2019b). CH_4 is colorless, odorless, non-toxic gas with tetrahedral structure. The density of CH_4 and air at standard temperature and pressure is 0.714 and 1.225 kg/m^3, respectively, and it is much lighter than the air. Methane, carbon dioxide, and nitrous oxides are the major greenhouse which emitted from agriculture soil including rice and play major role in global warming (2019a; IPCC 2014). Global atmospheric concentration of CH_4 was below 800 ppb before industrialization and its rose above 1850 ppb in 2019 (Fig. 12.1). Higher anthropogenic emission of CH_4 play significant role in rising atmospheric concentration. Rice field, biomass burning, fuel production industry, landfill, waste treatment, and livestock are the major anthropogenic sources of the CH_4 gas (Kumari et al. 2020; Kumar et al. 2020a; Mukherjee et al. 2018; Kumar et al. 2016a, b; Malyan et al. 2016a, b, c; Pathak et al. 2016) (Fig. 12.2). Saunois et al. (2016) reported that the CH_4 emission form rice cultivation emits about 115–243 Tg CH_4 year^{-1} and it is the leading contributor to anthropogenic emissions (Table 12.1).

Rice is the grain of the grass species *Oryza glaberrima* (African rice) and *Oryza sativa* (Asian rice). Rice is the stable food for more than half of the world population (Pramanik and Kim 2017) and its global production was 769.7 million tonnes in 2017 (FAO 2019). China, India, and Indonesia were the three biggest rice producing countries in the world and they account for 61% of the total production (Fig. 12.3). All the three greenhouse gases i.e. CH_4, CO_2 and N_2O emits from the rice field (Kumar et al. 2017; Malyan et al. 2019a; Kumar et al. 2020b). Standing water throughout the cropping period after root establishment is considered favorable

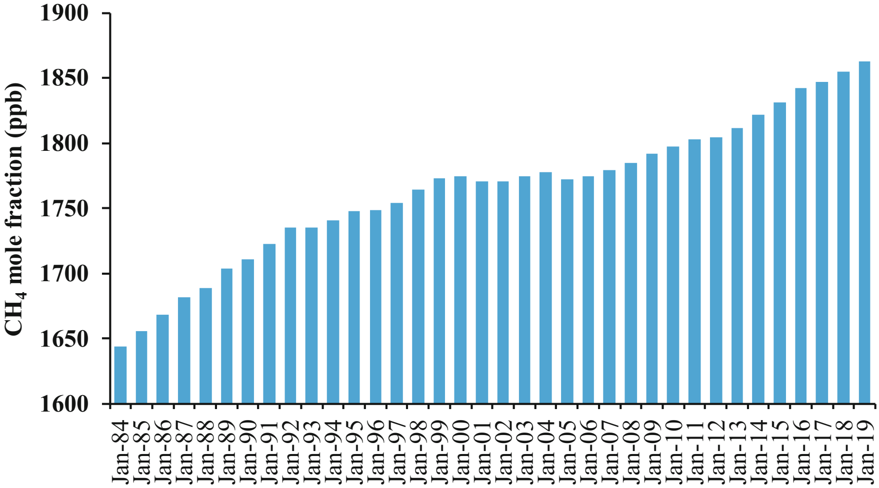

Fig. 12.1 Trend of CH_4 concentration in atmosphere (Source: Ed Dlugokencky, NOAA/ESRL online link https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/)

Fig. 12.2 Major sources of anthropogenic methane emission to atmosphere

condition for better rice production (Malyan 2017; Kumar and Malyan 2016; Malyan et al. 2016a; Gupta et al. 2015; Sethunathan et al. 2002). The standing water create anaerobic environment in the soil which stimulate the population of CH_4 producing bacteria (methanogens) (Mishra et al. 1997; Smartt

Table 12.1 Major anthropogenic contributor for global atmospheric methane emissions

S. No	Source	Anthropogenic emissions(in Tg (CH_4)/ year
01	Rice cultivation	115–243
02	Landfill	77–133
03	Ruminants	
04	Waste treatment	
05	Energy	
06	Biomass burning	15–53
07	Othe	

Source: (Saunois et al. 2016)

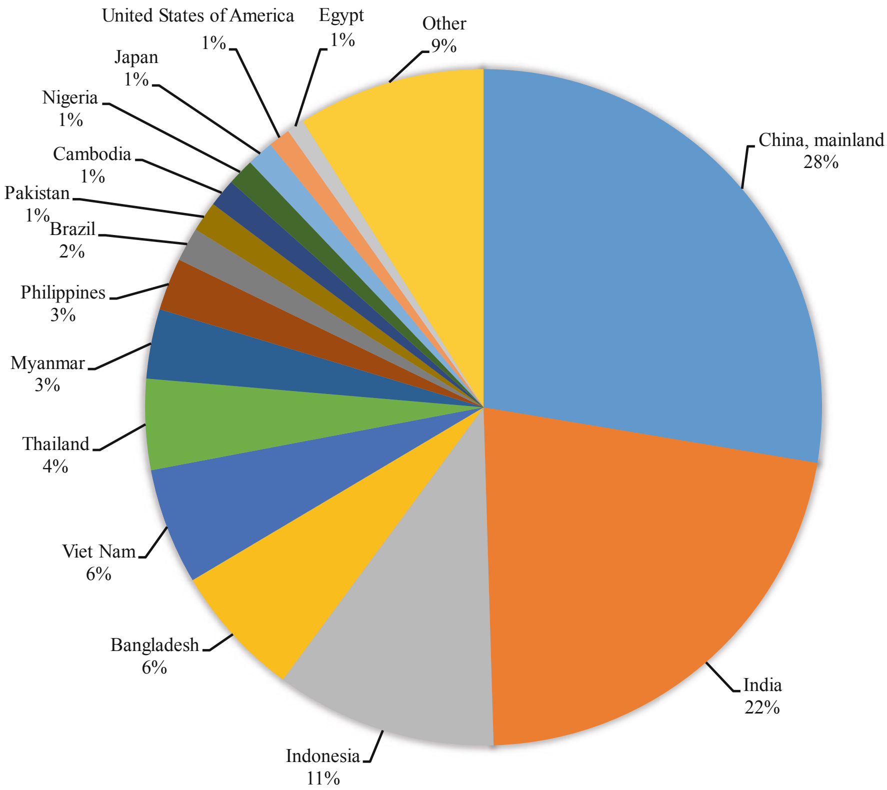

Fig. 12.3 Global rice production (2017) (Source: FAO 2019)

et al. 2018; Malyan et al. 2016c; Ke et al. 2014; Conrad 2007). Neue (1993) quoted that CH_4 emission form rice field was first reported by Harrison and Aiyer in the year 1913. The emission of CH_4 is actually the net balance of two processes, the production by methanogens and its oxidation by methanotrophs (Malyan et al. 2016c). CH_4 emission from rice field is effected by several biotic (methanogens, methanotrophs, other microorganisms' population) and abiotic (soil pH, temperature, texture, organic carbon matter, water content, etc.) factors (Mona et al. 2021; Malyan et al. 2019b; Gupta et al. 2016a; Hussain et al. 2015; Bhatia et al. 2013; Liesack et al. 2000). In the present chapter, we focused on the microbial diversity, mechanism, and influencing factors for CH_4 emission from rice soils.

12.2 Methanogens and Methane Production in Rice Field

The process of CH_4 production by methanogens is known as methanogenesis, it takes place under anaerobic conditions (Serrano-Silva et al. 2014; Conrad 2007; Le Mer and Roger 2001). In the biogenic formation of CH_4 in rice ecosystem, the soil organic matter is consumed by methanogens as carbon source and they release CH_4 gas as by-product (Gupta et al. 2016b; Dubey et al. 2014; Le Mer and Roger 2001). Plants litter, roots, weed biomass, dead microorganisms, animal waste, and organic fertilizers are the main source of soil organic matter (Kimura et al. 2004). The soil organic matter is converted into acetate by three process: hydrolysis, acidogenesis, and acetogenesis (Dubey 2005). Methanogens prefer to consume acetate as substrate for the production of CH_4. Generally, methanogens are mesophilic and the optimum temperature for the CH_4 production is 25 °C (Dunfield et al. 1993). Some of the genera of methanogens are also found in extreme environmental conditions such as geothermal sediments, hot springs, and hypersaline sediments (Nazaries et al. 2013; Dubey 2005). The rate of CH_4 production in soil by methanogens depends upon several factors such as environmental conditions, substrate availability, and the presence of other competing microbial community (Serrano-Silva et al. 2014; Dubey 2005; Roy and Conrad 1999). Methanogens are divided into five categorized based on substrate utilization (Table 12.2). About 80% of the methanogens prefer to utilized acetate as the C source, while 10–30% of methanogens prefer formate and hydrogen/carbon dioxide as the C source (Conrad 2007).

Methane producing bacteria use NH_4^+ as N source, however, there are few methane producing microbes which are having N-fixing gene (nif): *Methanobacteriales, Methanococcales, and Methanomicrobiales* (Serrano-Silva et al. 2014; Dubey 2005). Methane producing Achaea needs unique coenzymes such as coenzyme (F_{420}), coenzyme M (CoM), coenzyme B (CoB), ferredoxin (Fd), methanofuran (MFR), and tetrahydromethanopterin (H_4MPT), to complete methanogenesis (Nazaries et al. 2013).

Table 12.2 Types of methanogens on the basis substrates consumption

Substrates	Product formed	Trophic group
$4H_2 + CO_2$	$CH_4 + 2H_2O$	Hydrogenotrophs
4HCOOH	$CH_4 + 3CO_2 + 2H_2O$	Formatotrophs
Acetate	$CH_4 + CO_2$	Actetotrophs
$4CH_3OH$	$3CH_4 + CO_2 + 2H_2O$	Methylotrophs
$CH_3CHOHCH_3 + CO_2$	$CH_4 + 4CH_3CHOHCH_3 + 2H_2O$	Alcoholotrophs

Source: Malyan et al. (2016c)

12.3 Methanotrophs and Methane Oxidation in Rice Soil

Methanotrophs are gram-negative aerobic bacteria which play significant role in controlling atmospheric CH_4 levels. Methanotrophs oxidize CH_4 to CO_2 via methanemonooxygenase (MMO) enzyme (Dubey 2005; Hanson and Hanson 1996). Rice cultivation is a main anthropogenic source of CH_4 emission at global level. The population of methanotrophs in rice is diverse and it depends upon the prevailing biotic and abiotic factors at that particular time (Conrad 2007; Liesack et al. 2000). The commonly reported methanotrophs from rice fields include *Methylobcater, Methylomonas, Methylocystis, Methylococcus, Methylosinus, Methylocaldum, Methylocystis, Methylomicrobium*, etc. (Chen and Murrell 2010; Mancinelli 1995; Trotsenko and Khmelenina 2005). All the identified methanotrophs are broadly categorized in two major groups based on their assimilating compounds (Fig. 12.4): type I and type II (Fazli et al. 2013). The methanotrophic bacteria which are phylogenetically identified as γ-proteobacteria assimilate one carbon compounds via the ribulose monophosphate cycle are known as type I methanotrophs (Fazli et al. 2013). The methantrophic bacteria which are phylogenetically identified as α-proteobacteria assimilate C1 intermediates via serine pathways are known as type II methanotrophs (Fazli et al. 2013). In rice field, the population of methanotrophs in rhizosphere is much higher than the bulk soil (Dubey 2005; Gilbert and Frenzel 1995). The concentration of oxygen and CH_4 affect the niches of type I and type II methanotrophs in rice. The aerenchyma assists the transportation of oxygen from atmosphere to rhizospheric zone. The more the arenchyma size more oxygen sinks towards rhizospheric zone which deplete the anaerobic condition and enhance the aerobic environment in rice-rhizosphere. In aerobic environment the dominance of methanotrophs type I was observed

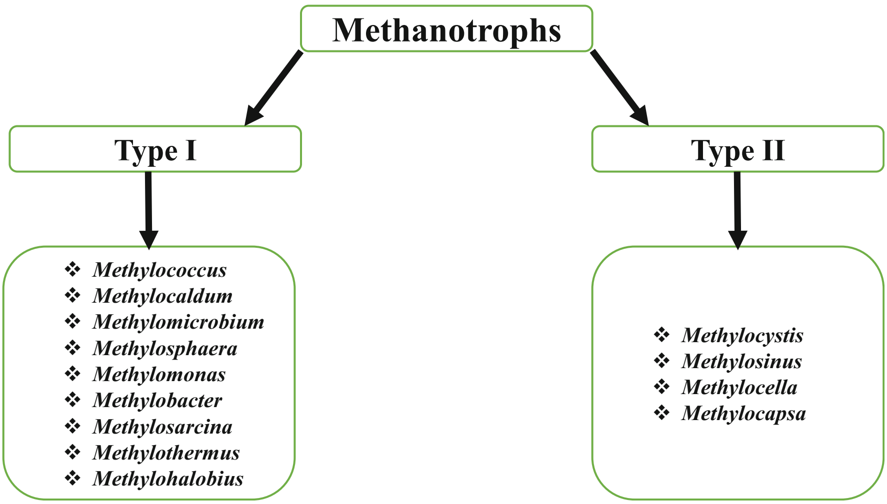

Fig. 12.4 Major groups of methanotrophs (Source: Conrad 2007)

(Bhattacharyya et al. 2019). Methanotrophs type I are active in the environment with low CH_4 and high oxygen concentration (Mayumi et al. 2010). The population of methanotroph type II organisms is found in anaerobic environment such as bulk soil in rice ecosystem. Therefore, in continuous flooded bulk soil, methanotrophs type II organisms are more active while in intermitted rice ecosystem methanotrophs type I organisms are more active.

Until recently, it was believed that methanotrophs cannot consume carbon-carbon bond compounds such as acetate as the sole source of energy and therefore methanotrophs were consider as obligate methylotrophic (Conrad 2007). However, Dedysh et al. (2005) reported that *Methylocella* spp. of methanotrophs use acetate as carbon and energy source and they prefer acetate compound over CH_4. Hence, the presence of available carbon source also effects the population of methanotrophs in rice ecosystem. The population of aerobic methanotrophs is measured generally by most probable number (MPN) counts method (Singh and Pandey 2013). Generally, MPN count per gram soil ranges from 10^4 to 10^7 (Conrad 2007) but the aerobic methanotrophs population in the rhizosphere zone is much higher than this order. In the flooded environment methanotrophic bacteria became inactive due to lack to oxygen.

12.4 Methane Oxidation in Rice Ecosystem

Methane oxidation in rice ecosystem is a biological process carried out by aerobic and anaerobic methanotrophs. CH_4/methanol serves as an energy source for the growth of methanotrophs (Hanson and Hanson 1996; Semrau et al. 2010). Aerobic methanotrophs are obligate (use only CH_4 as C and energy source) and facultative (utilize multi-carbon substrates) in nature (Dedysh and Dunfield 2011) having mesophilic characteristics (optimum growth range 20 °C–40 °C) and neutrophilic characteristics (optimum growth range pH 6–8) (Whittenbury et al. 1970). Oxygen availability plays important role for aerobic methanotrophy (Bodegom et al. 2001). Aerobic methanotrophs can be low-affinity methanotrophs (oxidize high CH_4 concentrations($>$100 ppm)) and high-affinity methanotrophs (oxidize low CH_4 concentrations (1.8 ppm) (Malyan et al. 2016c; Alam and Jia 2012).

The aerobic methane oxidation is completed through the sequential conversion of methane into carbon dioxide utilizing different enzymes. Firstly, CH_4 is converted into methyl aldehyde (CH_3CHO) by methane monooxygenase enzymes. The CH_3CHO is subsequently converted into formaldehyde by methanol dehydrogenase and formaldehyde is further converted into formate by the activity of formaldehyde dehydrogenase and this formate finally converts into carbon dioxide through dehydrogenase activity. Methane monooxygenase is of two types, i.e. particulate or membrane-bound form (pMMO) and soluble cytoplasmic form (sMMO) (Semrau et al. 2010) and serves as the process initiation catalysts and rate limiting enzyme. MMOs is multi-substrate enzyme that can oxidize propylene (PP) (Inubushi et al. 2002) and is inhibited by acetylene (C_2H_2) (Hanson and Hanson 1996). MMO can also be inhibited by $NH4^+$ due to competitive nature of ammonia with methane

(Dunfield and Knowles 1995) as MMO is also able to convert ammonia into nitrite through hydroxylamine intermediate which are further toxic to methanotrophs and lead to inhibition of methane oxidation ability in rice soil (Eller and Frenzel 2000).

The anaerobic methane oxidation is completed by Achaea, sulfate-reducing bacteria and starts by physical association of anaerobic methanotrophs (Serrano-Silva et al. 2014; Chowdhary and Dick 2013; Nazaries et al. 2013). The sulfate reducing bacteria oxidize CH_4 to CO_2 and sulfate acts as an electron acceptor. Nitrite is also one of the electron acceptors in rice flooded soil as sulfate (Beal et al. 2009) and Fe and Mn in marine environment for anaerobic methane oxidation (Malyan et al. 2016c).

Nitrogen fertilization through synthetic fertilizers and organic fertilizers increases the $NH^{+}{}_{4}$ and $NO^{-}{}_{3}$ concentration in rice soils which inhibits the CH_4 oxidation. This inhibition promotes the chance of carbon reduction in form of CH_4 emission (Fagodiya et al. 2017). The ammonium-based fertilization stimulates growth and activity of methanotrophs in the rice-rhizosphere (Bodelier et al. 2000a, b). Nitrate inhibit only in very high concentrations due to osmotic effects (Bodelier and Laanbroek 2004a). Krüger and Frenzel (2003) reported that with decrease in mineral nitrogen in rice field, methane oxidation decreased up to zero. Bodelier and Laanbroek (2004b) concluded that mineral nitrogen can function as limiting factors for growth of methanotrophic bacteria and ultimately regulated methane oxidation.

12.5 Factors Affecting Methane Emission in Rice Ecosystems

12.5.1 Soil Temperature

For the best activity of mesophilic microorganism usually temperature range of 20–35 °C is considered as ideal. The microbial community of CH_4 oxidation bacteria is highly sensitive to temperature change (He et al. 2012). He et al. (2012) conducted sediment incubation study with three temperatures (4 °C, 10 °C, and 21 °C) to identify methanotrophs activity and CH_4 oxidation. The CH_4 oxidation at 21 °C was highest (37.4μmol g^{-1} day^{-1}) in the uppermost sediment layer (0–1 cm) (He et al. 2012). The rate of CH_4 oxidation increased with increasing temperature from 5 °C to 20 °C were also reported by Whalen et al. (1990). But some of the contrasting findings were also reported by Bender and Conrad (1995), they observed the maximum CH_4 oxidation at 0 °C.

12.5.2 Soil Organic Matter

Soil organic matter affect the cumulative microbial community and the functions of the ecosystem (Tveit et al. 2013). Several findings reported that addition of organic matter such as straw, farm yard manure, residues of other crops, etc., increases the CH_4 emissions (Gupta et al. 2016b; Hussain et al. 2015; Bhatia et al. 2013a). In fact, there are few studies which reported that the addition of organic matter in the form of biochar help in CH_4 mitigation in rice (Purakayastha et al. 2019; Panwar et al. 2019; Xiao et al. 2018; Pandey et al. 2014). In one recent study, Wu et al. (2019b) reported that biochar application increased the CH_4 oxidation potential of methanotrophic bacteria. Nitrate and ammonium promoted the methanotrophs type II and type I respectively, which enhanced the CH_4 oxidation potential for prolonged duration on biochar application (Wu et al. 2019b; Feng et al. 2012).

12.5.3 Soil Texture

Soil texture directly influences the population of microbes. Soil porosity changes with the soil texture and its effects the CH_4 oxidation process (Shukla et al. 2013). Soil with greater porosity (such as sandy) is the favorable environment for CH_4 oxidation by methanotrophs type I.

12.5.4 Application of Fertilizers

Fertilizer type, method, and dose are the critical component affecting for microbial community dynamics in rice soil. Fertilizer applied to soil is not completely utilized by crop (Ranjan and Yadav 2019). The activity of methanotrophs is affected by the type of fertilizer applied. The period of ammonium ion in the soil affect the CH_4 oxidation. In short term, ammonium ion has no effect on CH_4 oxidation potential of methanotrophs. Ammonium ions in long term act as inhibitors of CH_4 oxidation potential of methanotrophs in rice soil (Shukla et al. 2013; Banger et al. 2012). Role of ammonium ions is different in different CH_4 environmental conditions. Un-saturated soil such as in upland rice have low soil CH_4 and under such environment increased in ammonium ions deceased the rate of CH_4 oxidations (Shukla et al. 2013; Hütsch et al. 1994; Steudler et al. 1989). The role of ammonium ions in rice soils was not conclusive as different studies concluded positive as well as negative control (Shukla et al. 2013; Bodelier et al. 2000a, b) especially in case of flooded and non-flooded rice soils (Table 12.3).

12.6 Mitigation of Methane Emission from Rice Ecosystem

Methane emission from rice soil can be mitigated by modifying water content, fertilizer application, tillage practice, by selecting suitable rice cultivars, organic matter management, etc. (Malyan et al. 2020; Samoy-Pascual et al. 2019; Setyanto et al. 2018; Tariq et al. 2017). Some of the significant tools of CH_4 mitigation from rice are discussed below:

Table 12.3 Factors affecting methane emission from rice field

S. No	Factors	References
01	Soil temperature	(Centeno et al. 2017; Gaihre et al. 2016; He et al. 2012; Schütz et al. 1990)
02	Soil organic matter	(Dhanuja et al. 2019; Wu et al. 2019a; Bhattacharyya and Barman 2018)
03	Soil texture	(Singh et al. 2018)
04	Rice cultivar	(Malyan et al. 2019b; Zheng et al. 2018)
05	Fertilizers	(Kong et al. 2019; Liu et al. 2019b; Sun et al. 2019; Buragohain et al. 2018; Hussain et al. 2015)
06	Method of transplanting	(Li et al. 2019; Wang et al. 2018a; Simmonds et al. 2015;)
07	Water management	(Fertitta-Roberts et al. 2019; Jiang et al. 2019)

12.6.1 Irrigation Management

Methane is produced by methanogenic bacteria in anaerobic environment when soil redox potential is less than −150 mV (Khosa et al. 2011). Water is one of the important natural resource, which needs immediate attention to enhance the water use efficiency under changing environment (Pathak et al. 2014). At the same time water management also reduces the methane emission from the rice soil. Irrigation significantly affects the field pore space and soil oxygen concentration. Water management practices such as intermittent drainage, midseason drainage, alternate wetting and drying, controlled irrigation, etc. have been documented globally for reducing CH_4 emissions as compared to continuous flooding (Table 12.4). Intermitted drainage enhanced the oxygen diffusion in the soil and therefore rose the soil redox potential which result in CH_4 emissions reduction (Haque et al. 2017). Kim et al. (2014) and Kudo et al. (2014) stated that intermitted drainage reduced cumulative CH_4 emission by 43.52% and 47%, respectively, as compared to continuous flooding (Table 12.4). Haque et al. (2017) also reported 54–58% reduction in CH_4 emissions as compared to continuous flooding (Table 12.4). Alternate wetting and drying (AWD) is novel water and environment saving technology. AWD reduced CH_4 emissions (Table 12.4) with decreasing the economical yield. In AWD, irrigation water is given after the standing water disappearance in the crop. The number of days between irrigation and non-flooding varied from 1 to 10 days in AWD and it depended upon soil type, environmental conditions, and crop growth. Samoy-Pascual et al. (2019) observed that AWD can minimize cumulative CH_4 emissions by 20–73% as compared to traditional flooding system in Philippines (Table 12.4). Oo et al. (2018) conducted field experiment at Tamil Nadu Rice Research Institute, India, and reported that AWD can reduce 24–41% CH_4 emission as compared to traditional irrigation method (Table 12.4). In recent studies, 26% and 49% CH_4 mitigation by AWD were also demonstrated by Tran et al. (2018) and Chidthaisong et al. (2018), respectively (Table 12.4). Tariq et al. (2017) stated that early drainage is also effective irrigation methodology for CH_4 reduction as compared to continuous flooding (Table 12.4).

Table 12.4 Methane mitigation through several water management practices as compared to continuous flooding in rice

References	Practice name	Mitigation (%)	Remarks
Samoy-Pascual et al. (2019)	Alternate wetting & drying (AWD)	20–73	Experiment was carried out at Philippine Rice research institute, Philippines
Wu et al. (2019a)	Midseason drying-flooding	52.26	Study was conducted at Taoyuan, China
Setyanto et al. (2018)	AWD	35	Study was carried out in Central Java, Indonesia
Oo et al. (2018)	AWD	24–41	Study was conducted at Tamil Nadu Rice research institute, India
Tran et al. (2018)	AWD	26	Study was conducted at Huong Tra district, Central Vietnam
Chidthaisong et al. (2018)	AWD	49	Experiment was carried out in Prachin Buri, Thailand
Haque et al. (2017)	Intermitted drainage	54–58	Experiment was conducted in Gyeongsang National University, Jinju, South Korea
Tariq et al. (2017)	Early drainage	89–92	Experiment was carried out at University of Copenhagen, Denmark
Peyron et al. (2016)	Dry seeding with delay flooding	59	Experiment was carried out at Italian Rice research Center, Castello d'Agogna, Italy
Kudo et al. (2014)	Intermittent drainage	47	Study was conducted at Kanagawa, Japan
Kim et al. (2014)	Intermittent drainage	43.52	Study was conducted at Suwon, Korea
Li et al. (2014)	Midseason aeration	12–27	Study was conducted at Jurong city of China
Ma et al. (2013)	Midseason drainage	37–51	Study was conducted at Jiangxi Province, China

12.6.2 Rice Cultivar

Selection of appropriate cultivar is most important for achieving the goal of sustainable agricultural. There is variation in the rate of CH_4 production, oxidation, and transportation among different rice cultivar (Aulakh et al. 2000; Hussain et al. 2015). Generally cumulative CH_4 emissions of long duration cultivar are higher than the short or medium duration rice cultivar (Malyan et al. 2019b). Soil redox potential affects the activity of both CH_4 production by methanogens and oxidation by methanotrophic bacteria. Size of aerenchyma varied among the rice cultivar and it affects the rate of methane emission and uptake through methanogens and methanotrophs under prevailing anaerobic/aerobic environment in rice soil (Nishiuchi et al. 2012).

12.6.3 Methane Mitigation Through Azolla

Azolla is nitrogen fixation aquatic fern and its importance for CH_4 emission reduction is explored in several studies globally (Table 12.5). Biologically nitrogen fixation, control of weed, and source of organic matter are other significant role of *Azolla* in rice ecosystem (Singh et al. 2016). Bharati et al. (2000) and Malyan et al. (2019b) reported that *Azolla* application in rice with optimum dose of nitrogen fertilizer reduced CH_4 emissions in the range of 15–42% (Table 12.5). *Azolla* is photosynthetic fern and it liberates oxygen in flooded water and it results in higher dissolved oxygen concentration in flooded water. The higher dissolved oxygen suppress the activity of methanogens bacteria and enhances the CH_4 oxidation simultaneously which result in CH_4 emissions reduction. Yang et al. (2019); Xu et al. (2017), and Liu et al. (2017) demonstrated the CH_4reduction by *Azolla* in China (Table 12.5).

12.6.4 Other Interventions for Methane Mitigation in Rice

Industrial by-products such as fly ash, phosphogypsum, steel slag have been reported to reducing the methane emission from rice fields (Kumar et al. 2020a). Steel slag is having high content of iron oxides and free (Fe^{3+}) form. Fe^{3+} contributes in mitigation of methane from rice soil as it competes with H_2/acetate for electrons during the degradation of soil organic matter (Wang et al. 2018b; Alpana et al. 2017; Wang et al. 2015). Silica present in steel slag supports aerenchyma enlargement and make more diffusion of oxygen towards the rhizosphere and hence reducing the anaerobic condition, further reducing methanogenesis and enhancing rhizospheric methane oxidation (Ali et al. 2012b, 2015). The phosphogypsum increases the sulfur-reducing bacteria in paddy soil as sulfate is the important constituent in it. These sulfur-reducing bacteria will compete with methanogens for organic matters, thus reducing the methane emission (Sun et al. 2018; Ozuolmez et al. 2015; Ali et al. 2007). The intermittent-irrigation, alternate drying and wetting, direct seeded rice, single aeration, etc. are the important agronomic practices to manage the methanogens and methanotrophs population for mitigating methane emission (Kumar et al. 2016a; Bhatia et al. 2013).

Table 12.5 Methane mitigation by *Azolla* as compared to full dose of chemical nitrogen fertilizers

Country (references)	Mitigation (%) as compared to dose chemically N dose
India (Bharati et al. 2000; Malyan et al. 2019b)	15–42
China (Liu et al. 2017; Xu et al. 2017; Yang et al. 2019)	11–33
Japan (Kimani et al. 2018)	34
Bangladesh (Ali et al. 2012a)	11–13

12.7 Conclusion

Methane is one of the major greenhouse gases emitted from the rice fields and play a significant role in global warming. Methanogens are basically responsible for methane production, while methanotrophs are responsible for methane oxidation. Enhancing methane oxidations or reducing productions are the two important aspects to curtail the methane emission from the rice soils. The population of methanogens is highly influenced by various factors such as organic matter, population of the substrate competitor microbes, pH, temperature, plant rhizosphere environment, rice cultivar, irrigation, etc. Thus, these managements are highly important to control the methane emission from rice fields. Besides this, applications of some industrial by-products are also found suitable for methane mitigation from rice fields.

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