Chapter 5
Wetlands: A Major Natural Source Responsible for Methane Emission

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Abstract Methane (CH_4), an important greenhouse gas (GHG), contributes ~33.0% to the total global GHGs emissions and accounts for 15–20% to the global warming. As the second most important human-generated GHG after $CO_{2,}$ CH_4 is strongly linked with various climate phenomena. Most of the wetlands from tropics to temperate have been reported to have significantly enhanced emissions of CH_4 during recent years. In wetland, microbial communities are a major determining factor in controlling the carbon cycle. The terrestrial wetlands are also among the key CH_4 emitters and play a major role to climate change. The role of wetland expansion in CH_4 emissions and its consequences on climate change and global warming might be a major concern for the future world. The methanogens and methanotrophs, two physiologically different microbial communities, seem to be crucial for future research investigations while comparing the CH_4 production and consumption in wetland ecosystems. Anthropogenic disturbances related to wetlands are likely to influence the altering of microbial community composition of methanogens and methanotrophs and consequently net CH_4 flux. The terrestrial wetlands have been reported to act as a source and sink for atmospheric CH_4. Therefore, recent concerns about CH_4 emission from terrestrial wetlands could be addressed properly because it is one of the major causes in contributing the status of CH_4 in the environment.

Keywords Methane · Wetlands · Climate change · Land use · Methanogens · Methanotrophs

1 Introduction

Methane (CH_4), a potent GHG, contributes about one third to the worldwide greenhouse gas emissions (Singh and Gupta 2016). It has 25 times more warming potential than CO_2 over a 100-year time scale (Bridgham et al. 2013; Fazli et al.

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2013; Forster et al. 2007), and little changes in its concentration could have a large consequences in the environment, climate and human being. Bridgham et al. (2013) reported that human alone contributes ~18% of total CH_4 which makes it second most important greenhouse gas after CO_2 (Singh and Strong 2016). The global warming contribution of CH_4 is 15–20% (Tiwari et al. 2015). CH_4 molecules that absorb the infrared radiation emitted from the earth become energized and start to emit heat in all directions (Fazli et al. 2013; Nema et al. 2012). The present concentration of CH_4 is 2.5 times higher than observed in ice cores dated to the period of AD 1000–1750 (Amstel 2012). Agriculture and fossil fuel together account for 230 Tg CH_4/year and are dominant natural source of methane emission, i.e. wetland is 174 (~100–231) Tg/year. Wetland emissions thus react to global warming and wetting. The anthropogenic CH_4 is produced by different sources and includes energy production, landfills, waste, cattle and milk production, agriculture and biomass burning, etc. (Amstel 2012; Bridgham et al. 2013; Denman et al. 2007; Wang et al. 2004).

The CH_4 emissions from the wetlands are the largest biogenic source of CH_4 budget, contributing to one third of total growing atmospheric emissions from various sources (Bhullar et al. 2014; Bridgham et al. 2013). CH_4, being the second most anthropogenic GHG after CO_2, is strongly associated with climate feedbacks. The degree to which wetlands expansion and CH_4 emissions will evolve and consequently driven climate feedbacks is thus a question of major concern. Besides, potential feedbacks between global change perturbations and CH_4 emissions from wetlands, climate change, CO_2 level and deposition of sulphate and nitrogen are also the major apprehensions of methane emission (Bridgham et al. 2006; Zhuang et al. 2006). In an estimation, the developing nations currently contribute approx. three-quarters of direct GHG emissions and seems to represent the fast-growing GHG emission sources in the coming decades (Boateng et al. 2017).

1.1 Wetlands and Methane Emissions

Wetlands occupy 3.8% of the Earth's land surface, amounting to 20–40% of global CH_4 emissions (Aselmann and Crutzen 1989; Ciais et al. 2013; Solomon et al. 2007). Despite of being a major source, wetlands are among the most prominent sources of unexplained spatial and temporal variability in global methane emission estimates (Bousquet et al. 2006). The main CH_4 emitting sites in wetlands are the littoral zones where helophytes form a channel for methane production via sediment–root–stem–atmosphere continuum (Bergstrom et al. 2007). Bergstrom et al. (2007) reported that the dense vegetation of emergent macrophytes in natural wetlands may account 90% of the methane emission. However, it was supposed that anthropogenic sources are to be the only driver responsible for the increasing atmospheric CH_4 burden from the late seventeenth century (Taylor et al. 2011). Paddy fields are one of the important sources of CH_4 (Fazli et al. 2013; Tyagi et al. 2010) and responsible for 15–20% of total anthropogenic CH_4 emission (Li et al. 2011; Xu et al. 2007) with an estimated 25–100 Tg CH_4/year (Xu et al. 2007).

A very significant variation in CH_4 emission across different types of wetland could be due to the variations in time, space and the factors operating within the wetland ecosystem (Kirschke et al. 2009; Melton et al. 2013). The main processes controlling the seasonal and inter-annual variations in wetland CH_4 emission includes carbon availability, rate of decomposition, wetland inundation and temperature (Yvon-Durocher et al. 2014). Other controls are the presence of macrophytes (Laanbroek 2010), organic C decomposition rates (Miyajima et al. 1997), and pH (Singh et al. 2000), etc. Methane emitted from natural wetlands is a significant component of atmospheric methane budget. Biogeochemistry and atmospheric inversion models estimate the total wetland emissions to be 100–230 Tg CH_4 /year, under the present climate condition (Denman et al. 2007; Tang et al. 2010). Although wetlands occupy only 2–6% of Earth's land surface (Whiting and Chanton 2001), they significantly contribute a larger proportion of the total carbon stored in terrestrial reservoir (Schlesinger 1991). Zhang et al. (2017) reported that the climate change-induced enhancement in boreal wetland and tropical CH_4 emissions would be the dominate anthropogenic CH_4 emissions source by 38–56% at the end of the twenty-first century. The various reports suggested that climate mitigation policies must be in legislation to balance the wetland CH_4 feedbacks to maintain average global warming below 2 °C (Zhang et al. 2017). The wetland may play a crucial role in atmospheric methane concentration in coming decades because of the huge stocks of organic carbon and mineral stored under anaerobic conditions in both boreal and tropical regions. In an estimate, carbon storage in histosols (wetland soil type composed of mainly organic materials) ranges from 3% to 68% of the total soil organic carbon reservoir (Post et al. 1982). The combination of elevated water tables, high productivity and lower decomposition rate has led to significant carbon storage in histosols (Gorham 1991) and contributes global methane balance.

2 Overview of the Methane Emissions and Methane-Producing Bacteria

The bacterial clusters involved in the emission and reduction are crucial in the methane flux of soil. The study explores that solutions are required to be developed to decrease the emission rate or encourage consumption of CH_4 by methanotrophic bacteria to minimize its concentration from flooded soils, particularly to the rice fields.

The methanogens and methanotrophs are actively involved in the biogeochemical cycling of CH_4 in soil (Fazli et al. 2013). The methanogenic bacteria are accountable for releasing CH_4. They are obligate anaerobes and active in flooded, swampy areas (Pazinato et al. 2010). However, the methanotrophs are aerobic microorganisms, ubiquitous in nature and mostly active in oxic soil. Methanogens and methanotrophs have been reported from several environmental conditions likely sludge digesters (Hwang et al. 2008), lakes (Antony et al. 2012), peatland (Godin et al. 2012), freshwater and marine sediments (Newby et al. 2004) and rice soil (Fazli et al. 2013; Wang et al. 2010).

2.1 Methanogens

The methanogens are obligate anaerobes (Garcia 1990) that belong to kingdom Euryarchaeota of Archaea domain (Ferry 2010). Borrel et al. (2011) reported that methanogenic group consists 31 genera under the phylum Euryarchaeota based on 16S rRNA sequence analysis (Rosenzweig and Ragsdale 2011). Methanogens produce CH_4 through diverse metabolic pathways termed as methanogenesis (Singh 2009). The methanogenesis includes acetoclastic methanogenesis and hydrogenotrophic methanogenesis pathway to release CH_4, i.e. the conversion of acetate to CH_4 and CO_2 and H_2 and CO_2 to CH_4, respectively (Conrad et al. 2006; Dubey 2005). In fact, methanogens are engaged in the biodegradation of organic compounds anaerobically in wetlands and rice fields (Rosenzweig and Ragsdale 2011). The 16S rRNA analyses showed that methanogenic archaea can be classified under three important groups, i.e. group I contains of *Methanobacterium* and *Methanobrevibacter*, group II comprises *Methanococcus* and group III includes *Methanospirillum* and *Methanosarcina*. They multiply in anaerobic environments, for example, swampy areas, sediments, flooded water, the digestive tract, etc. (Dubey 2005). Most of the methanogens thrive in mesophilic conditions and actively function from 20 to 400 °C temperature range (Dubey 2005). The methanogens have also been reported from extreme environmental conditions such as deep hydrothermal vents sustaining at temperatures >100 °C. Methanogenic Archaea generally takes acetate (contributing up to 80% of total CH_4 production) as carbon source. In addition, H_2/CO_2 and formats also contribute 10–30% in CH_4 release (Dubey 2005).

2.1.1 Methanogens in Paddy Soil

The paddy rhizosphere is a vital habitat for methanogens (Ma and Lu 2011) due to the decay of paddy roots and the liberation of H_2 and CO_2, which provides nutritional support to microbes (Watanabe et al. 2010). Das et al. (2011) and Datta et al. (2013) reported that higher populations of acetoclastic methanogens are found in Indian rice soil than hydrogenotrophic methanogens. The pathway of methanogenesis in rice fields has been investigated globally. But the detailed information about methanogenic population in paddy soil is limited. First of all, Rajagopal et al. (1988) isolated and characterized the methanogenic *Archaea* from Louisiana paddy soils and elucidated about the presence of strains similar to *Methanobacterium* and *Methanosarcina*. Joulian et al. (1997) showed the existence of methanogenic bacterial population in the paddy soils of the Philippines, France and the United States. In addition, Reichardt et al. (1997) reported that the root extracts of adult paddy plants were rich in methanogenic bacteria. Four genera *Methanobacterium*, *Methanosarcina*, *Methanobrevibacter* and *Methanoculleus* were isolated from Italian paddy fields (Fetzer et al. 1993). Asakawa et al. (1995) reported that only couple of strains (*Methanobrevibacter arboriphilus* and *Methanosarcina mazei*) have been identified in rice fields. Similarly, Adachi (1999) reported *Methanobrevibacter* and *Methanobacterium* spp. from Japanese paddy soil.

2.1.2 Methanogenesis

The CH_4 is released in the anoxic layers of rice soil by methanogenic breakdown of organic substances (Dubey 2005). The anoxic conversion of organic matter takes mainly four steps: (1) action of hydrolytic organisms on polymers, (2) action of fermentative bacteria on organic compound for acid formation, (3) action of syntrophic bacteria or homoacetogenic on fermentations metabolites for acetate formation and (4) liberation of CH_4 from H_2/CO_2, acetate, etc. Emancipation of CH_4 from the organic matter also involves various important coenzymes, some of which are solely found in methanogenic archaea. At least nine methanogen-specific enzymes are used in the mechanism of CH_4 removal from H_2 and CO_2 (Dubey 2005).

2.1.3 Factors Affecting Methane Production

Methanogens are influenced by variety of natural as well as anthropogenic factors. It has been reported that acetoclastic methanogenesis is accountable above two third of the CH_4 liberation and remaining portion of CH_4 is emitted by hydrogenotrophic methanogens (Das and Adhya 2012). Moreover, at elevated temperatures (40–50 °C), the phenomenon methanogenesis is shown by hydrogenotrophic methanogenic archaea. In addition, the expanding CO_2 level favours hydrogenotrophic methanogenesis in the environment (Das and Adhya 2012). For instance, Wang et al. (2010) reported the following methanogenic archaea in a Chinese rice field: Methanomicrobiales, Methanosaetaceae, Zoige cluster I (*ZC-I*), Methanosarcinaceae and Methanocellales.

Wang et al. (2010) also stated that the types of methanogenic structure found in rice field are different due to soil type, sampling location, moisture content and temperature (Das and Adhya 2012). Sugano et al. (2005) demonstrated that before the mid-season drainage, the methanogenic communities included rice cluster I, Methanomicrobiales and Methanosarcinales, but after this period, the Methanomicrobiales were perceived. Methanomicrobiales and rice cluster I are the archaea accountable for breakdown of paddy straw under flooded environment. The water management can also influence the methanogens community composition by changing the moisture content of soil; subsequently it is an important aspect for CH_4 emissions (Yao et al. 2006; Zhao et al. 2011). The alternate wetting and drying of the soil could modify the population, community structure and transcriptional functions of methanogens (Watanabe et al. 2010). Since, methanogens are more active under flooding environments as compared to dry soil (Watanabe et al. 2009). Thus, draining the soil reduces CH_4 production from rice field (Khosa et al. 2011; Zhang et al. 2011). In addition, drainage might also augment the nitrous oxide (N_2O) liberation (Johnson-Beebout et al. 2009; Zhao et al. 2011) due to denitrification of nitrate in anoxic and flooded situation (Fangueiro et al. 2010; Malla et al. 2005). Therefore, the issue needs more specific research to reduce the production of CH_4 along with of N_2O release. Ghosh et al. (2003) suggested that the use of nitrification inhibitors likely dicyandiamide might have a reducing impact on CH_4 and N_2O emission. Malla et al. (2005) also reported that dicyandiamide plays a significant role as a sink for CH_4. Similarly, Smith et al. (1997) showed that addition of dicyandiamide after urea application could decrease N_2O production up to 82%. The polymer-coated fertilizers are also potent to reduce N_2O release (Akiyama et al. 2010). It has been showed that at low C:N ratio in soil improves N_2O emission. As a result, C:N balance could shrink the emission, though the threshold ratio needs to be explored. The addition of fertilizers can modify the methanogens found in soil. The N fertilizer stimulates the denitrifying bacteria, which are more competent than methanogenic archaea for growth nutrients. Consequently, N fertilizers suppress CH_4 production, for example, $(NH_4)_2SO_4$ reduces CH_4 emission than urea application (Ghosh et al. 2003).

Elevation in GHGs, especially CO_2, is a serious concern. The increased concentration of CO_2 in atmosphere can simultaneously decrease the methanogenic activity, reducing the CH_4 oxidation in paddy fields (Das and Adhya 2012). To overcome the situation, water management could be a suppressing tool for CH_4 production (Epule et al. 2011; Tyagi et al. 2010; Zhao et al. 2011). Temperature of the soil also plays an important role in CH_4 production (Khalil et al. 1998; Yang and Chang 1998). Yang and Chang (1998) reported the enhanced emission of CH_4 emission at temperature 4 to −37 °C. Nozhevnikova et al. (2007) also reported CH_4 formation at temperature 15–20 °C in anaerobic soil.

2.2 Methanotrophs

Methanotrophs include aerobic and anaerobic CH_4-oxidizing important bacterial groups. The methanotrophs have been categorized into couple of groups: type I (*Gammaproteobacteria* which takes CH_4 adapting the RuMP pathway) and type II (*Alphaproteobacteria* which oxidize CH_4 via the serine pathway) (Rosenzweig and Ragsdale 2011). However, Hanson and Hanson (1996) added 'type X' group of methanotrophic cluster, likely *Methylococcus* and *Methylocaldum* (Bowman 2006). Moreover, the type X can be considered as a subdivision of type I. Irrespective of few resemblances, the type X (having low levels of enzymes of the serine pathway) showed differences with other members of type I methanotrophs. But, information regarding the group is still lacking (Semrau et al. 2010). Methanotrophs oxidize the CH_4 produced by methanogens in soil and the rhizospheric region of plants (e.g. rice) (Bodelier et al. 2005; Conrad et al. 2006) and use CH_4 as sole carbon and energy source. Moreover, the CH_4 consumers have a major role in regulation of CH_4

production from submerged soils, such as rice fields and natural wetlands (Hoffmann et al. 2002).

2.2.1 Methanotrophy in Paddy Soil

Type I and II of methanotrophs are natural inhabitants of paddy fields and thrive in different niches based on oxygen and CH_4 availability (Mayumi et al. 2010). Type I CH_4 oxidizers grow in environments with high oxygen and low CH_4 intensity as compared to type II methanotrophs which sustain well in poorer oxic soils (Mayumi et al. 2010). In flooded condition, the interchange of oxygen from outer environment to the root might develop an oxygen-rich environment in the root and rhizosphere which support the high growth and activity of methanotroph type II than type I (Wu et al. 2009). In the case of drained soil, the type I methanotrophs are prevalent in place of type II (Mayumi et al. 2010). Additionally, a positive correlation has been shown between methanotrophs and the age of paddy plants due to elevation in plant biomass, decrease in soil moisture content and NH_4^+-N concentration in tropical rice fields (Yue et al. 2007).

2.2.2 Factors Affecting Methanotrophs Activity

Methanotrophic activity is affected by various factors such as type of plants species, variety of the plants, pattern of crop rotation and other environmental constrains (Min et al. 2002; Xuan et al. 2011). The specific cultivar of rice has influenced the CH_4 consuming activity and methanotrophs level in paddy roots and rhizosphere as reported by Win et al. (2011). However, another study reported that paddies have no significant impact on methanotrophs population (Wu et al. 2009). The community composition of soil methanotrophs can be affected by type and crop rotation pattern including *Verrucomicrobia* (Xuan et al. 2011) which might be due to the production of different root exudates affecting the soil microbial community (Doornbos et al. 2012). Wu et al. (2009) reported that type I methanotrophs are sensitive to environmental factors. However, type II methanotrophs showed more stability (Vishwakarma and Dubey 2010). The pH of the medium significantly alters the community of methanotrophs and CH_4 production in soil. The optimum condition of CH_4 oxidation may be between pH level 6 and 8 in paddy soil (Min et al. 2002), which ultimately assists in the alleviation of methane. Paddy soil having pH <6 needs to be adjusted for better crop productivity. Results suggested that addition of crop residues, lime, pyrite and other organic amendments may improve the population of methanotrophs in rice fields and crop productivity (Li et al. 2011; Singh et al. 2010). Amendment of N fertilizer (urea) may inhibit the methanotroph population; however, the addition of N and K together (e.g. potassium chloride) or the combination of N, P, K and crop residues stimulates the growth of methanotroph abundance (Zheng et al. 2008).

3 Mechanistic Pathways of Methane Emission

For a better understanding of the processes which involved in the process of CH_4 emission from paddies, a brief introduction of plant and soil chemistry is essential. Carbon is the basic prerequisite for methanogenic growth generated from three basic sources: the death of crop root tissue, decay of both fresh organic matter and humus and carbohydrate exudates (Wassmann et al. 2000). The methanogens can produce CH_4 either from the H_2 or CO_2 (Wassmann et al. 2000) as follows:

$$CO_2 + 4H_2 = CH_4 + 2H_2O$$

Or

$$CH_3COO^- + H^+ = CO_2 + CH_4$$

Summary line

$$2(CH_2O) = CO_2 + CH_4$$

Schütz et al. (1989) explained CH_4 emission from paddies via three pathways including diffusion (<1%), ebullition (10%) and plant-mediated transport (90%) from rice plant itself. The rice plants have an efficient gas exchange system between the anaerobic soil and the troposphere which can change the exchange pathway according to soil condition and CH_4 concentration (Holzapfel-Pschorn et al. 1986; Wassmann et al. 2000). In rice growing in the temperate region, the main route of CH_4 (>90%) emission is plant transport (Dubey 2005), while in the tropics, CH_4 evolution takes place by the process of ebullition (transportation of gas in the form of bubbles) particularly in the early months of the season and high organic input (Dubey 2005). The process of ebullition of CH_4 flux is also commonly observed in natural wetlands (Dubey 2005) and found to be significant in the case of high fertilization (Sass et al. 2000). Dubey (2005) also reported that in the case of unvegetated plant and plant with undeveloped aerenchyma, ebullition plays a key role in CH_4 emission (Dubey 2005). However, CH_4 emission restricted to the surface layer and the rate of emission is regulated by the concentration of CH_4, porosity of the soil, temperature of the soil and plant aerenchyma (Li 2000). Methane diffusion through the soil is a very slow process as the rate of diffusion of CH_4 is extremely low in liquid phase (~104 times slower than diffusion through the gas phase) and thus hardly contributes to the total CH_4 flux (Aulakh et al. 2000). The CH_4 diffusion phenomenon across the flooded soil and overlying water of the paddy field to the atmosphere is a function of wind speed, surface water concentration of CH_4 and CH_4 supply to the surface water (Dubey 2005).

4 Adaptive Measures Controlling CH_4 Emission

From the centuries, European wetlands have been continuously drained for agricultural and other industrial needs. In estimation, more than 50% of all the peatlands in Europe were lost due to anthropogenic interference (Nivet and Frazier 2004; Jerman et al. 2009). However, with the increasing importance of the wetland functions, utilization and approaches towards wetland conservation have now been changed from Europe to all over the world. The major restoration strategies along these include cessation of agricultural practices, protection, conservation and re-establishment of wetland and its hydrology (Rosenthal 2003). The malpractices of wetland exploitation in agriculture in Europe have reversed to land subsidence and sequestered atmospheric CO_2 as peat accretes (He et al. 2015).

Wetlands are the biggest non-anthropogenic resource of atmospheric CH_4 and key global carbon reservoir. Therefore, characterizing the belowground wetland microbial communities which participate in carbon dynamics might be a broad area of research to understand the microbial importance and their responses to changing land and climate. Wetlands cover 5–8% of the total land area of the Earth (Jerman et al. 2009) and support various ecosystem services, viz. wildlife habitat, flood control, water purification, etc. Wetland, as a major terrestrial carbon reservoir, covers 20–30% of the global soil carbon pool (Jerman et al. 2009) and plays an important role in global carbon cycling. However, wetlands are continuously shrinking due to agricultural, urbanization, population growth and industrial insurgency (Jerman et al. 2009), releasing stored carbon into the atmosphere and enhancing global climate change. In addition to reversing land subsidence, the high primary production and low rate of decomposition in restored wetlands may result in a net atmospheric CO_2 sequestration, allowing them to act as 'carbon farms'.

Climate and land use changes directly affect ecosystem processes by influencing the plant community composition (Sutton-Grier and Megonigal 2011), nutrient availability, organic carbon concentration and nutrient cycling in wetlands (Mitsch et al. 2013; Petruzzella et al. 2013; Singh et al. 2018). In addition, transport of oxygen in the root tissue may alter the accessibility of oxygen in the sediment, resulting into methanogenesis suppression or CH_4 oxidation (Sutton- Grier and Megonigal 2011).

Recent concern of global warming has developed interest in the role of terrestrial ecosystems in minimizing CH_4 levels (Chan and Parkin 2000). Terrestrial systems function as net sources or sinks for atmospheric CH_4. Methane flux measured at the soil/atmosphere interface is the result of CH_4 oxidation and methanogenesis (Knowles 1993). A negative CH_4 flux (consumption of CH_4 by soil) occurs when the magnitude of the CH_4 uptake is larger than the process of methanogenesis and generally found in arable land, when conditions are predominately aerobic (Hansen et al. 1993). A positive CH_4 flux indicates net CH_4 production and occurs when the magnitude of the methanogenic process is larger than CH_4 uptake and predominates in anaerobic condition such as paddies and wetlands (flooded or water saturated)

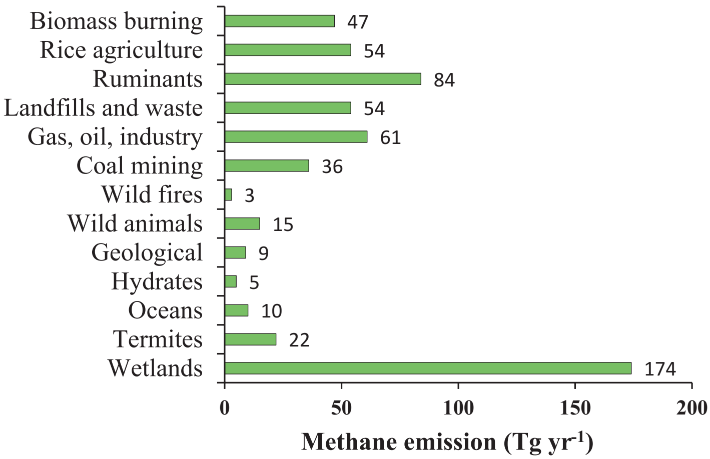

Fig. 5.1 Natural and anthropogenic sources of CH_4. (Modified from Amstel 2012)

(Lauren and Duxbury 1993). The process of CH_4 flux is supported by soil, wetland systems and mixture of anaerobic and aerobic sites. The natural sources of CH_4 include wetlands, oceans, hydrates, geological sources, termites, animals, wildfires, etc. (Fig. 5.1).

5 Conclusions and Future Prospects

This manuscript emphasizes the aspects of methanogenesis and CH_4 oxidation in different wetlands and the environment. The CH_4 has been recognized as one of the most important GHG in the atmosphere. Because of the strict anaerobic environment for CH_4 generation, natural wetlands are considered as the main sources of biogenic CH_4. Off all the wetland, tropical wetlands are the largest natural contributor of global CH_4 budget. Continuous increase in atmospheric CH_4 and other GHG level are predicted to raise global temperature with several implications. The assessment of climatic changes by CH_4 and other GHG can be assessed only by measuring the quantity of the production, oxidation and emission of CH_4 from all the natural and anthropogenic sources and characterizing their responses on the plants and animals. The available database on CH_4 flux to the atmosphere is insufficient in relation to the large variety of climatological and edaphological factors that would allow to extrapolate data at a global scale and to design more precise models on the impact of the global climatic change leading to a better forecast of future state of affairs. The increasing demands of rice due to population load could lead to further expansion of the areas used for rice cultivation and, therefore, would add to higher CH_4 level. As a result, rice cultivation would put a massive load on future global warming. Therefore, the research should not be focused only on rice cultivation but also in the development of technologies for better analysis of CH_4 production and its oxidation. Besides, it is imperative to develop possible mitigation approaches to diminish and/or suppress emissions of this hydrocarbon in a sustainable manner.

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