Chapter

Methane Cycling in Paddy Field: A Global Warming Issue

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Abstract

Paddy fields are major sources of CH_4 emission and a vital source of global warming. Thus, it is important to understand the CH_4 cycling in paddy field. The CH_4 chemistry, mechanisms of production and emission from paddy fields are also significantly important to understand. This paper discusses about the CH_4 cycling, how CH_4 emission effect on the global warming, and the mechanisms of CH_4 exchange between rice paddy field and atmosphere, factors effecting the CH_4 production, oxidation, transportation and calculation. Also try to suggest the CH_4 mitigation options of paddy fields. The mitigation of CH_4 emission can be achieved by water management, selection of rice cultivar and fertilization. Controlled irrigation can also reduce CH_4 production compared to flood irrigation. Cultivation of high-yielding and more heat-tolerant rice cultivars will be promising approach to reduce CH_4 emissions and slow down the global warming.

Keywords: paddy soil, methane cycling, atmosphere, mitigation, climate

1. Introduction

Methane (CH_4) is a key greenhouse gas (GHG), which has global warming potential 25-times higher than that of carbon dioxide (CO_2) over a 100-year period [1, 2]. Atmospheric CH_4 mixing ratio has increased approximately threefold since the pre-industrial era [3, 4]. The latest analysis of the World Data Centre for Greenhouse Gases (WDCGG) observations, the year-averaged CH_4 mixing ratio is 1853 ± 2 ppb in 2016. Atmospheric CH_4 mixing ratio has increased by 6.8 ppb y^{-1} over the last decade [5]. Paddy field is the dominant anthropogenic source of CH_4 [6–10], accounting for approximately 10% of global CH_4 emissions [11]. Emissions of CH_4 from paddy soils are concentrated in irrigated areas; irrigated paddy soils account for 60% of the total rice harvesting area worldwide, but produce 78% of CH_4 emissions in rice-producing areas [12]. Globally, around the tropics, sub-tropics and parts of the temperate boreal regions contribute most of the CH_4 emissions from paddy rice fields because these regions have a large area of paddy field compared with other regions. This includes areas like Central and Latin America, Africa and Southeast Asia [13]. Southeast Asia emits approximately 10 Mg CH_4 km^{-2} and it contributes 90% to the global rice CH_4 emissions chart [14]. Africa and South America contribute 3.5% and 4.7% to the global Paddy rice CH_4 budget respectively.

Rice is a vital crop in the world and it is grown on more than 167.25 million hectares of land globally [15]. In Asia, China, India, Indonesia, Bangladesh, and Vietnam are the major dominant rice-producing countries. So, the areas of high rice production are equally the area of high CH_4 emissions due to rice cultivation [14, 16].

Considering the large CH_4 emission from paddy fields, it is important to understand the CH_4 chemistry, mechanisms of CH_4 production and emission. Moreover, the reduction of CH_4 emission from rice paddy fields has become increasingly important. Therefore, the main objectives of this research are to discuss CH_4 cycling in the paddy soil and global warming, the basic understandings of methane chemistry, production, oxidation, transportation, calculation, the mechanisms of CH_4 exchange between rice paddy field and atmosphere, final emission and try to give some mitigation options of CH_4 emissions from paddy soils to slow down the global warming.

2. Rice cultivation, methane cycling and global warming

Global warming is a serious problem nowadays. CH_4 is one of the vital greenhouse gases that contribute to global warming. About 60% of global CH_4 emissions are occurred because of anthropogenic activities [17]. The main sources of anthropogenic CH_4 emissions are the oil and gas industries, agriculture, landfills, wastewater treatment, and emissions from coal mines. Globally, about 530 million tons of CH_4 (converted in terms of carbon) are emitted annually [17]. Rice fields are contributing to global warming, but it is a far bigger problem than previously thought. The conventional paddy field with continuous flooding irrigation is known as a major source of CH_4 emission [18]. The world's largest rice producers are China and India. After China and India, the next largest rice producers are Indonesia, Bangladesh, Vietnam, Myanmar, and Thailand. It is expected that economic activities will become more active in the next future mainly in Asia. Reportedly, of the Asian population of about 4200 million people, about 2700 million (60%) live on rice. Since Asia's population is expected to continue increasing, the total area of paddy fields in Asia will also increase. The paddy area in 2009 was 10,940,000 ha in Thailand, 4,410,000 ha in the Philippines, 7,420,000 ha in Vietnam and 12,100,000 ha in Indonesia [19]. So a hues amount of population needs more rice, more rice growing mean more CH_4 adding to the atmosphere. During 1 kg of rice grain production, paddy field contributes 100 g of CH_4 to the atmosphere. The default methane baseline emission factor is 1.3 kg CH4 $ha^{-1-day-1}$, in continuous flooding rice cultivation [20, 21]. Part of the CH_4 produced in the rice soil is consumed in the oxidized rhizosphere of rice roots or in the oxidized soil-floodwater interface. Soil bacteria also can consume CH_4 [22]. CH_4 is also leached to ground water, as a small part dissolves in water and most of it escapes from the soil into the atmosphere (**see Figure 1**). The important thing is most of the CH_4 is staying in the atmosphere for 10 years as it is or the increasing CH_4 abundance leads to a longer lifetime for CH_4 [23]. After a certain time later, the CH_4 is broken down into CO_2. Approximately 95% of the CH_4 produced in flooded soils is oxidized to CO_2 before it release to the environment [24]. It is still not clear exactly how much of the CH_4 is finally converted to CO_2 and how much might remain as other intermediate carbon-containing compounds without a significant direct effect on the climate [25]. However, CH_4 initially reacts with ozone in a 'chain' reaction that ultimately produces CO_2 and water vapor. CH_4 also creates ground-level ozone in the atmosphere. And ozone is not only harmful to human health but also contributes to climate change. CH_4 is much more effective than CO_2 at trapping heat (more than 60%) in the atmosphere [26]. Global temperatures in 2014 and 2015 were warmer than at any other time in the modern temperature record after 1880. And carbon emissions are the central cause of that rise. Rising temperatures and changes in rainfall have a significant effect on enhancing microbial activity and create ideal conditions for microbial CH_4

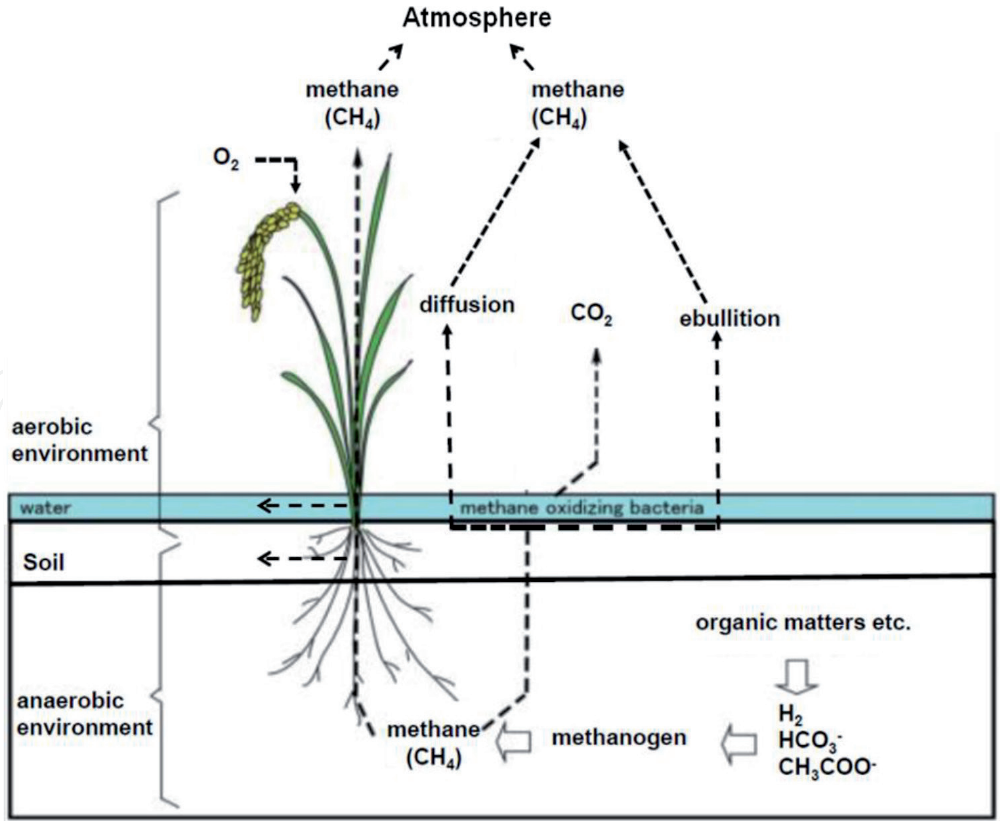

Figure 1.
Biogeochemical mechanisms of CH_4 production of paddy field and it's cycling (modify from [15]).

production of flooded rice fields. It is predicted that atmospheric temperature will rise 2°C by 2060. If it is actually going to happen, most of the agricultural plants cannot grow; it will make severe starvation for the world population. On the other hand, sea level will rise. The consequences will be so devastating, most of the low lands will go underneath the water and it will increase homeless people all over the world.

3. Methane chemistry

CH_4 is a very special kind of molecule. CH_4 is an end product of the organic carbon decomposition under anoxic conditions and the simplest organic compound and member of the paraffin series of hydrocarbons [27]. It is colorless, odorless gas that occurs abundantly in nature and as a product of anthropogenic activities. Its chemical formula is CH_4 (**Figure 2**). CH_4 is lighter than air, having a specific gravity of 0.554. It is slightly soluble gas in water and burns readily in air, forming carbon dioxide and water vapor; the flame is pale, luminous and very hot. The boiling point of CH_4 is −162°C and the melting point is −182.5°C. Basically, CH_4 is very stable, but mixtures of CH_4 and air, with the content between 5 and 14% by volume, are explosive [28].

Reactions of Methane

1. Combustion (oxidation)

   a. Complete oxidation: $CH_4 + 2\ O_2$, flame or spark → $CO_2 + H_2O$ + heat

   b. Partial oxidation: $6\ CH_4 + O_2$, 1500°C → $CO + H_2 + H_2C_2$
   $CH_4 + H_2O$, 850°, Ni → $CO + H_2$

2. Halogenation
   $CH_4 + X_2$, heat → $CH_3X + HX$
   requires heat or light.
   $Cl_2 > Br_2$ no reaction with I_2.

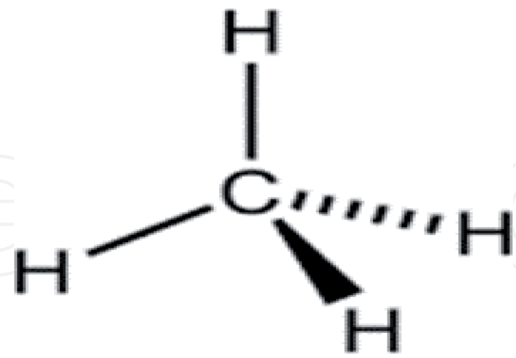

Figure 2.
Chemical formula of methane.

4. Biogeochemical mechanisms of methane production of paddy fields

The production of CH_4 is a microbiological process, which is predominantly controlled by the absence of oxygen and the amount of easily degradable actions [29]. Methanogens produce CH_4 under anaerobic conditions [30, 31]. Methanogens are prokaryotic microorganisms and belong to the domain of archaea. They are living in an anaerobic environment (e.g., soil or water) or in the intestines of animals. Methanogens mainly use acetate (contributes about 80% to CH_4 production) as a carbon substrate but another substrate like H_2/CO_2 and formats also contribute 10–30% to CH_4 production [32]. Acetate and hydrogen are formed by fermentation from hydrolyzed organic matter [29]. However, flooding of rice fields cuts off oxygen supply from the atmosphere to the soil, which leads to anaerobic fermentation of organic matter in the soil, resulting in the production of CH_4 [33]. And thereafter much of it escapes from the soil into the atmosphere via gas spaces in the rice roots and stems, and the remainder CH_4 bubbles up from the soil and/or diffuses slowly through the soil and overlying flood water (**Figure 1**). In flooded rice paddies, straw incorporation usually stimulates CH_4 production [34]. Root exudates and degrading roots are also important sources of CH_4 production, especially at the later growth stages of paddy. There are two major pathways of CH_4 production (e.g., acetoclastic and hydrogenotrophic). Acetoclastic methanogens use ATP to convert acetate to acetyl phosphate and then remove the phosphate ion via a reaction catalyzed by coenzyme A [12]. CH_4 is formed gradually by processes involving oxidized ferredoxin, tetrahydrosarcinapterin, coenzyme M, and coenzymes B. Taking account of all, CH_4 emissions from paddy soil are the net result of CH_4 production, oxidation and transportation. The complete CH_4 production process can be expressed as reduction and oxidation of two molecules of a simple hydrocarbon, one of which is reduced to CH_4 and the other of which is oxidized to CO_2: $2CH_2O \rightarrow CO_2 + CH_4$ [15].

5. Methane transportation from paddy soil to atmosphere

The total CH_4 emission process consists of three ways from soil to atmosphere e.g., transport via rice plants; bubble ebullition and molecular diffusion through the paddy water (see **Figure 1**). CH_4 can escape from the rice paddy soil via aerenchyma in the plant (90%), ebullition (10%), and diffusion through the soil and water layer (1%). CH_4 transports via the plant starts in the roots; CH_4 enters by diffusion through the epidermis and during the water uptake. It is likely that dissolved CH_4 is directly gasified in the root cortex and further diffuses upwards to the root-shoot transition zone traveling through intercellular spaces and aerenchyma. The aerenchyma system is developed by the plant to transport the oxygen necessary for respiration from leaves towards the roots. Just like CH_4 diffuses from the soil into the root system, oxygen diffuses from the root into the soil, creating a relative oxygen-rich zone in the rhizosphere. CH_4 is partly oxidized in the rhizosphere to CO_2 by methanotrophic bacteria. Methanogenesis in the rhizosphere itself is suppressed by oxygen. The transport of CH_4 to the atmosphere depends on the properties of the rice plant. The flux of gases in the aerenchyma depends on permeability coefficients, concentration gradients of roots and the internal structure of the aerenchyma. The number of tillers m^{-2}, root mass, rooting pattern, total biomass, and metabolic activity also influence gas fluxes.

6. Factors effecting the methane production in paddy fields

6.1 Effects of temperature on methane production

Temperature is one of the major determining factors on the biological process (e.g., within the soil), which controls the CH_4 production. Previous studies showed that increased soil temperature leads to an increase in CH_4 production [35]. There is a lot of qualitative evidence showing that CH_4 production from rice field increase with the increasing temperature [35]. A laboratory experiment regarding CH_4 production from two rice cultures incubated at temperatures between 20 and 38°C showed E_α values of 41 and 53 kJ mol^{-1}. CH_4 production in anoxic paddy soil suspensions incubated between 7 and 43°C showed E_α values between 53 and 132 kJ mol^{-1} with an average value of 85 kJ mol^{-1} [36]. The paddy soil temperature could control the amount of CH_4 production and there is a positive and strong correlation in both soil temperature and CH_4 production pattern [37]. The effect of temperature on CH_4 production in paddy soil was investigated by [38], they found that in continuously flooded soil, the temperature optimum for CH_4 production was 40°C, however, this shifted to 45°C during a period of intermittent irrigation accompanied by a marked decrease in activity. The optimum temperature during the non-cropping season was also 45°C (**Figure 3**).

6.2 Effects of soil pH and Eh on methane production in paddy field

Soil pH is another influential factor in CH_4 production. The pH effects on CH_4 production in a flooded rice soil. Methanogenic bacteria are acid sensitive. Generally, the optimum pH for methanogenesis is 7.0. Introducing the acidic materials frequently results in a decrease in CH_4 production [39]. A slight decrease in soil pH can cause decreases in CH_4 production. A slight increase in soil pH (about 0.2 unit higher than the natural soil suspension pH) resulted in an enhancement of CH_4 production by 11 to 20% and 24 to 25% at controlled Eh of −250 and − 200 mV, respectively [40]. These results suggested that a small reduction of soil pH could be obtained a decrease in CH_4 production in paddy soil.

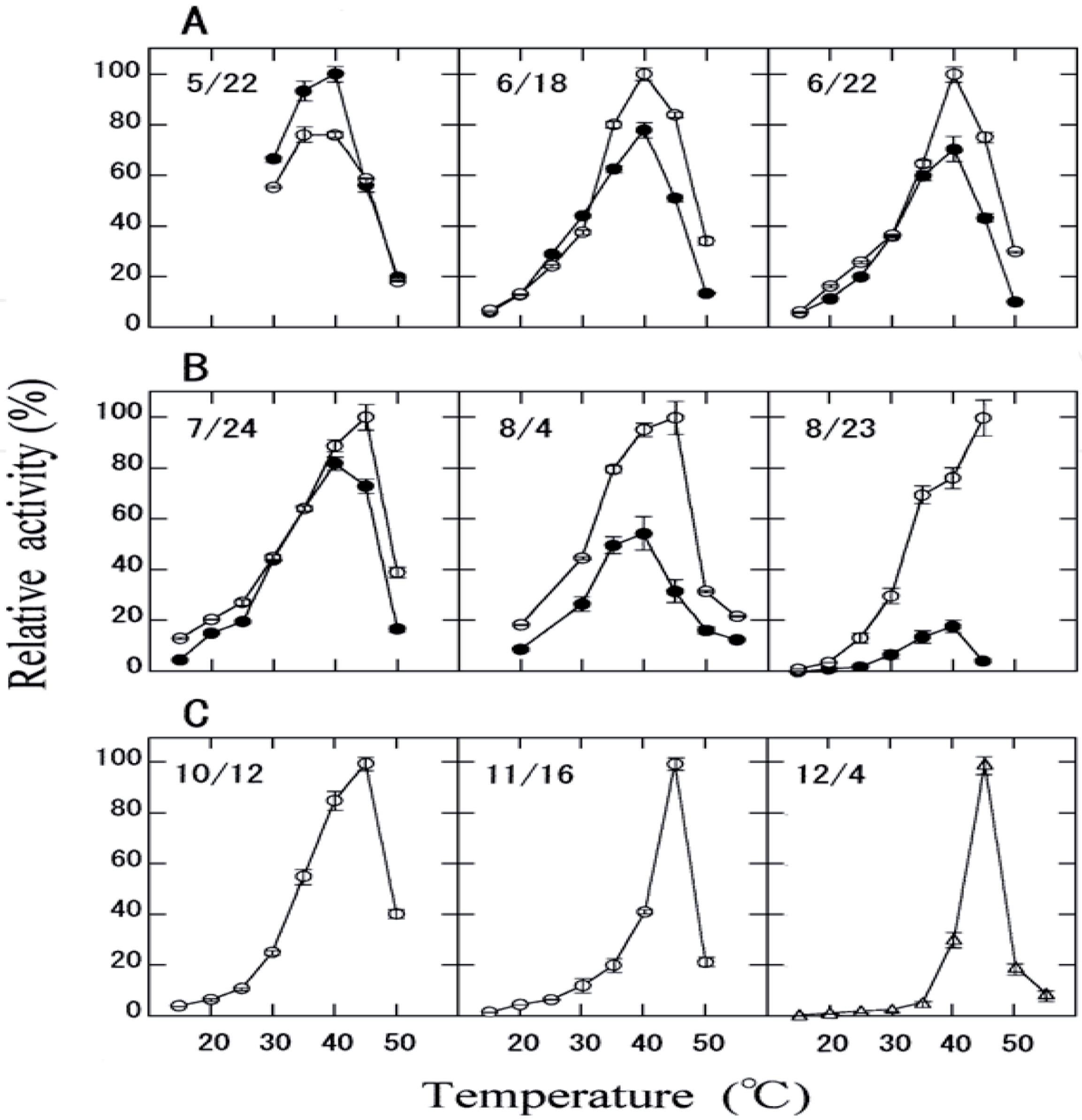

Figure 3.
Effects of temperature on CH_4 production in paddy soil shown in each figure. Periods of soil sampling: (A) continuous flooding (B) intermittent irrigation (C) from harvest to winter [38].

6.3 Effects of paddy cultivar, root and rhizosphere on methane production

The decomposition of organic matter by methanogens under anaerobic condition leads to the production of CH_4. Rice cultivars have significant effects on CH_4 production of planted soil due to large variation in composition and content of root exudates [41]. The roots of rice plants are colonized by methanogenic Archaea, which performs the last step in the production and emission of CH_4 [42–45]. It has previously been shown using pulse labeling of rice plants with $^{13}CO_2$ that plant photosynthesis accounts for more than 50% of total CH_4 emission [45, 46] and that a particular group of methanogens, the Rice Cluster I is responsible for the production of CH_4 from rice photosynthates [47]. It is well established that the type of rice cultivar affects the CH_4 production from rice fields [48]. In the randomly determined CH_4 production experiment found the initial production of CH_4 was much larger on roots grown in the rice field (RF) than in low-level river bank soil (LL), as shown by factorial ANOVA ($P < 0.0001$), while the effect of the different rice cultivars was not significant (P = 5 0.7401). The randomly determined CH_4 production rates during the initial 3–8 days activity of the methanogenic community are shown in **Figure 4a** [49]. The rates of CH_4 production also increased

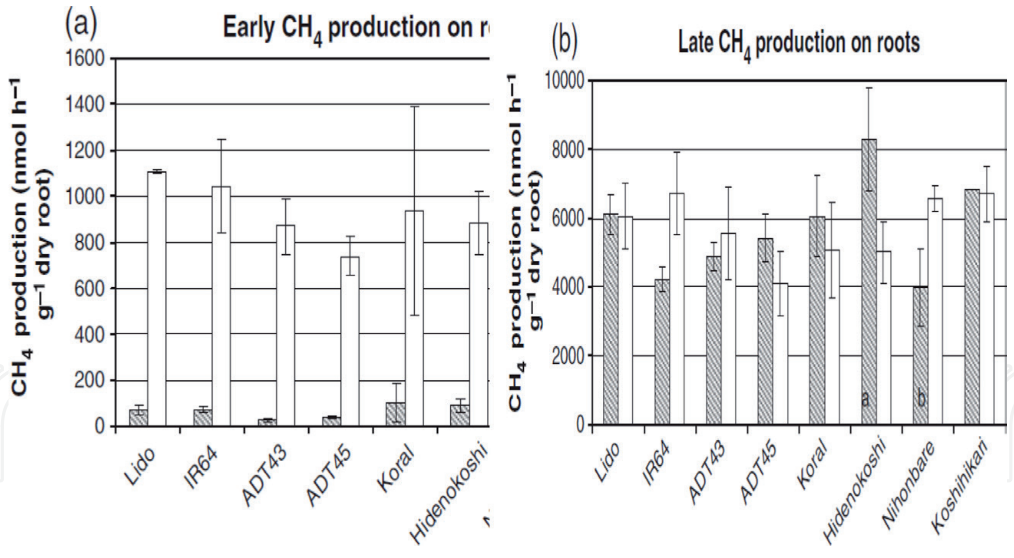

Figure 4.
Rates of CH_4 production on excised roots from eight different rice cultivars retrieved from microcosms consisting of RF soil (open bars) or LL soil (hatched bars). The rates of CH_4 production were determined (a) after 3–8 days of incubation and (b) after 17–28 days of incubation [49].

with incubation time, those of roots grown on LL soil after a prolonged lag phase, but in a late phase, arbitrarily chosen after 17–28 days, reached a similar value in all different root samples assayed (**Figure 4b**) [49]. The root morphophysiological traits were positively and significantly correlated with grain yield, whereas root length, specific root length, root oxidation activity, root total and active absorbing surface area were negatively and significantly correlated with total CH_4 emission [10]. However, rice plants can enhance CH_4 production by providing substrates for methanogenesis through the production of root litter and root exudates that contain carbohydrates and amino acids [50]. These nutrients stimulate microbial activities and lead to an increase in CH_4 production [51, 52]. In terms of the substrates, root exudates, especially in the form of acetate, represented a considerable source of CH_4 production at the rice ripening stage [53]. The CH_4 emission peak occurring at the rice ripening stage because this stage attributed to the easily decomposable organic matter exuded from roots [54]. The rhizospheric CH_4 oxidation at the different rice growth stages in detail. Under laboratory conditions, 29% of CH_4 oxidation in the rhizosphere was found one week before panicle initiation and no CH_4 oxidation occurred at the rice ripening stage. The CH_4 oxidation in the rhizosphere at the harvest stage may be negligible in the field [55]. The rhizospheric CH_4 oxidation rate varied with rice growing stages, being lower at the tillering stage (36.5% of CH_4 produced in rice rhizosphere) than at the panicle initiation stage (54.7%). This may be related to the oxidizing activity of rice roots varying with the rice growth stage [50]. At the late tillering stage, root exudates dominate CH_4 production of planted soil [41, 56]. This would probably be due to the stimulating effect of plant roots on O_2 released during the decomposition of soil organic carbon exceeding CH_4 oxidation in the rice rhizosphere [41, 57]. The relative contribution of root-associated CH_4 production to CH_4 emissions could be important in the rice paddies, as it varied between 4 and 52% [45].

6.4 Effects of paddy growing stages on methane emission

More than 90% of the total CH_4 emitted during the cropping season of the rice plants. Emission through rice plants may be expected to show great seasonal variations as a function of changes in soil conditions and variations in plant growth. The CH_4 emissions varied during the growth period of the rice plant. The CH_4 emission low during the early growth stages of the rice plant [58]. This may be due to low levels of methanogenesis in this stage. And the high amounts of CH_4 emissions were measured during the reproductive and ripening stages. This was happened probably due to the higher availability of fatty acids and sugars in this stage [58]. A significantly high amount of CH_4 emission occurred at the reproductive stage of the rice plants in the paddy field (**Figure 5**) [59].

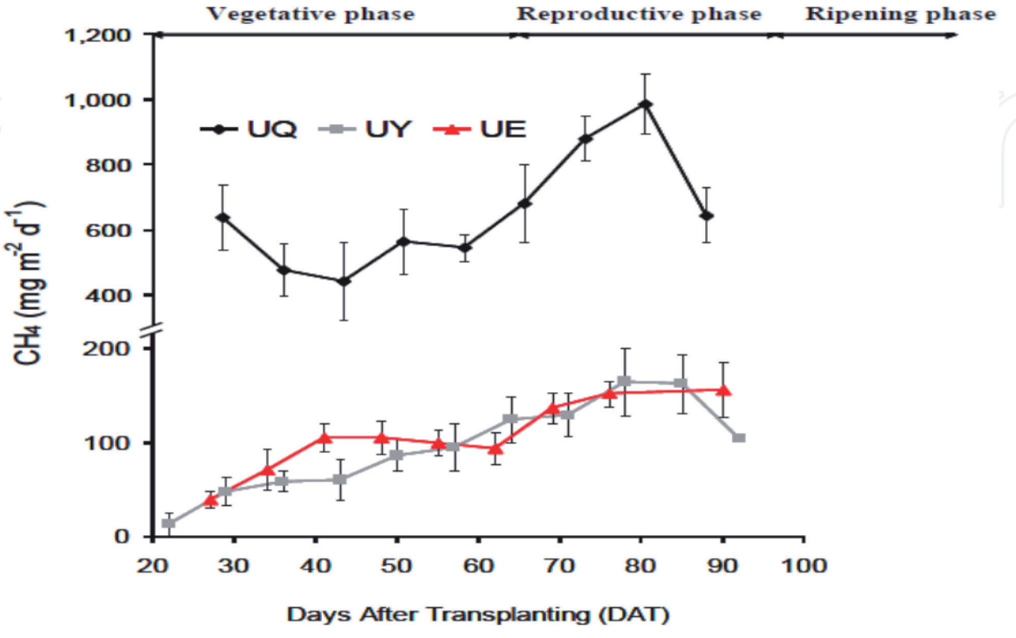

Figure 5.
CH_4 emission pattern of different stages of rice growth [59].

6.5 Effects of field management (fertilization, water management, farming operations) on methane production

In the rice paddy filed, organic fertilizer application (such as animal manure, sewage sludge, crop residues) significantly enhances soil nutrient availability, microbial biodiversity and their activity [60]. Consequently, the increased availability of carbon after the application of organic fertilizer increases CH_4 emissions and leads to a clear shift in the dominant methanogens in paddy soil [2, 61]. The CH_4 emission and soil fertility both were significantly increased by multiyear organic fertilization in paddy soil [62]. The **Figure 6** shows the effects of organic fertilizer on the pathway of CH_4 production from rice soil. In the rice production, water management and nitrogen (N) fertilizers are the two main driving factors of greenhouse gas emissions [63]. N application can increase the production of CH_4 in paddy fields. The level of the microbial community and NH^{+4} stimulates the growth and activity of CH_4 oxidation bacteria, reducing CH_4 efflux [64]. N fertilizers might also affect CH_4 production at the level of the microbial community [65]. In terms of water management, controlled irrigation can reduce CH_4 production compared to flood irrigation. Flooding conditions in the fields cause limited oxygen and other gasses such as sulfates in that soil environment. This condition promotes methanogenesis activities that release more CH_4 emission to the atmosphere [66]. Field burning of agricultural residues also results in release of CH_4, nitrous oxide and other minor GHGs. Rice straw is a perspicuous type of organic matter to apply in terms of the carbon cycle in paddy field. The rice straw increased CH_4 emission significantly [67].

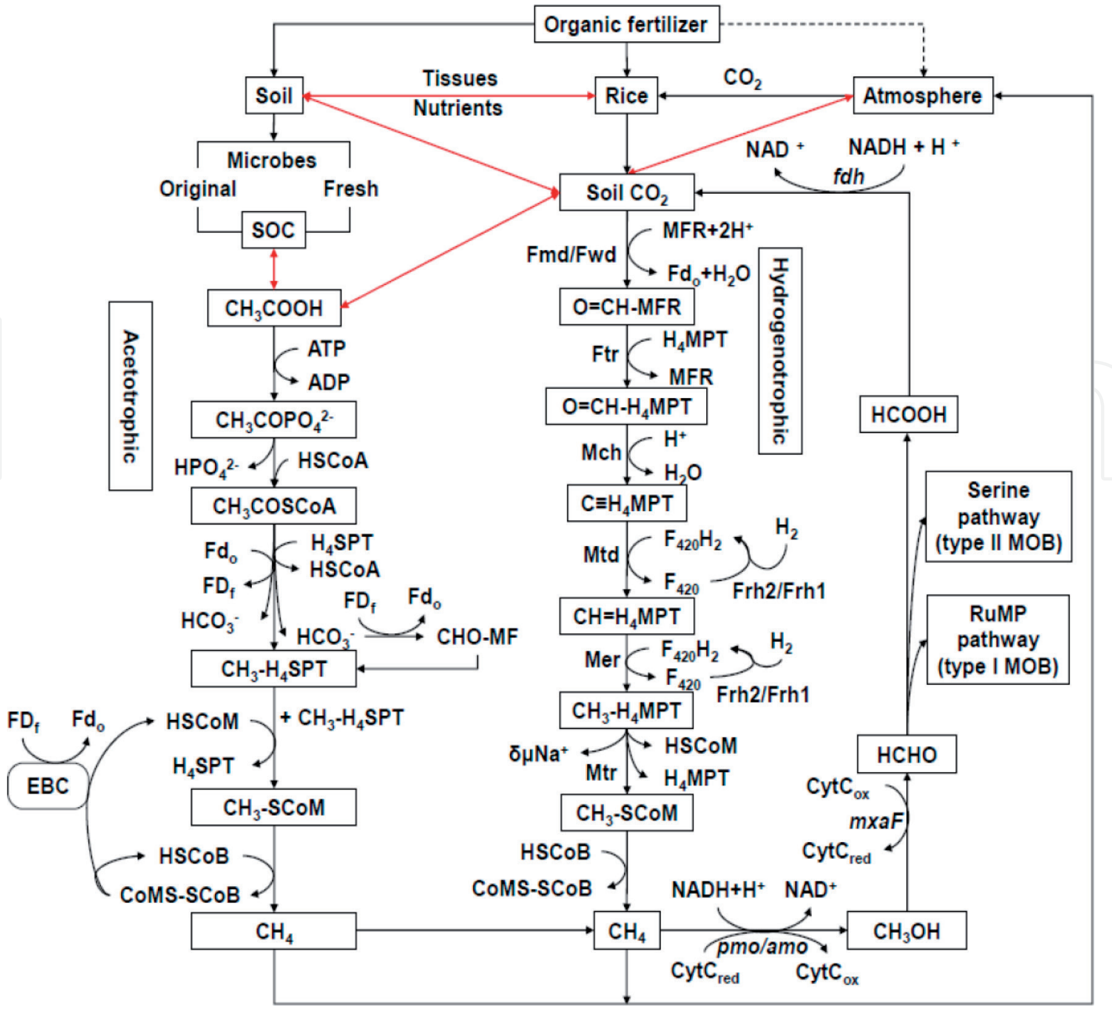

Figure 6.
Effects of organic fertilizer on the pathway of CH_4 production from rice soil [12].

7. Oxidation process of methane in the paddy field soil

In paddy fields, CH_4 production and oxidation happen simultaneously, so it is difficult to directly determine CH_4 production and oxidation separately. CH_4 oxidation may occur in aerobic and anaerobic ways. Previously CH_4 oxidation was usually determined by comparing CH_4 fluxes from flooded soils under aerobic and anaerobic incubation conditions [68]. By using this approach, CH_4 oxidation accounted for up to >90% of CH_4 production [52]. With the development of CH_4 oxidation inhibitors and isotopic methods, CH_4 oxidation is now widely measured using these approaches and shows relatively low ratio (less than 70%) to CH_4 production [69]. Generally, CH_4 emission is extremely influenced by the balance between CH_4 production and CH_4 oxidation in paddy fields [70]. Oxidation of CH_4 reduces the emission of CH_4 in the soil of rice field to the atmosphere. CH_4 is relatively inert in anoxic environments, but is oxidized by methanotrophic bacteria as soon as oxygen becomes available [71]. Aerobic methanotrophic bacteria are present in the oxic surface layer of the submerged paddy soil and in the rhizosphere where oxygen is available in a shallow layer around the rice roots. The most distinctly possible sites for CH_4 oxidation in rice fields are the water–soil interface and the rhizosphere. It has been shown that CH_4 oxidation is taking place within these zones of the paddy soil so that part of the produced CH_4, does not reach the atmosphere [72]. The increase of CH_4 production may, in turn, stimulate methanotrophic growth and CH_4 oxidation [73], but methanotrophic growth can be limited by low oxygen concentrations [74, 75]. Because larger rice plants stimulate oxygen transport into the rhizosphere, water management practices can also affect CH_4 oxidation rates through their effect on plant growth. The anaerobic CH_4 oxidation in the subsoil of a rice paddy was below 5% of the CH_4 emission during 38 whole growth periods [76]. The microbial aerobic oxidation activity of CH_4, the population of aerobic CH_4 oxidizers and the factors influencing the activity of CH_4 oxidation were investigated in three types of paddy rice soil in Zhejiang Province, China. The experiment results concluded that the population of CH_4 oxidizing bacteria was at maximum within the peak-tillering, heading and flowering stages, during which the largest population of methanogenic bacteria also appeared. Temperatures from 25 to 35°C and pH from 6 to 8 were the optimum conditions for aerobic oxidation of CH_4 in paddy rice soil [77]. Soil particle sizes also significantly affect the activity of CH_4 oxidation. Approximately 95% of the CH_4 produced in flooded soils is oxidized to carbon dioxide before it is released to the environment. Therefore, the oxidation is important for the biogeochemical cycling of CH_4 [24].

8. Measurements techniques of methane emission from paddy field

Recently, scientists are applying several techniques for measuring the CH_4 emission from the paddy field.

8.1 Closed chamber method

The most common technique for measuring the CH_4 emission in the rice paddy field is the closed chamber method (**Figure 7**) [24]. Normally, the chamber made of plexiglass (size: 50 cm length × 50 cm width × 100 cm height). The chamber equipped with a fan to make sure the inside gas mixing during chamber deployment. The chamber basement equipped with a water seal. Gas sampling needs to do simultaneously at three points per plot once a week. Normally, gas samples collect at 0, 5, 10, 20, and 30 min after the chamber deployment between 7:00–10:00 am. The samples taken by a syringe and store in evacuated glass vials and then subjected to the laboratory analysis using gas chromatography. The best hour for representing average daily flux is when temperatures are close to the daily mean, i.e., at 10 a.m. This is the best way to estimate the daily cumulative value from a unique measurement of the day [67]. The main advantages of this method are detecting low fluxes, of being easy to manipulate, low costs and flexibility [78].

8.2 Eddy covariance method using an open-path gas analyzer

The eddy covariance method is a complex, expensive and advanced method for measuring the CH_4 emission from the real-life rice paddies (**Figure 8**). The eddy covariance method calculates fluxes of a scalar of interest (i.e. CH_4, CO_2, LE, and H) at the same time, measuring turbulent fluctuations in vertical wind speed and the scalar and then computing the covariance between the two [79]. A sonic anemometer-thermometer (CSAT3) measures three-dimensional wind speed and sonic temperature. An open-path CO_2/H_2O gas analyzer (LI-7500A) measures fluctuations in CO_2 and water vapor densities and an open-path CH_4 analyzer (LI-7700) measures CH_4 concentrations [79]. CSAT3, the point of reference, has to fix at certain meters above the ground. The data from CSAT3, LI-7500A, and LI-7700 sampled at 10 Hz using a data logger (CR3000). The eddy covariance raw data need to process and quality control use EddyPro software to compute the fluxes of CH_4, CO_2, LE, and H over a 30-minute interval.

Eddy covariance can give a better picture of how much CH_4 real-life rice paddies are emitting, for example, detect and quantify CH_4 from rice paddies [80]. Compare

Figure 7.
The closed chamber technique of CH_4 sampling in rice planted paddy field.

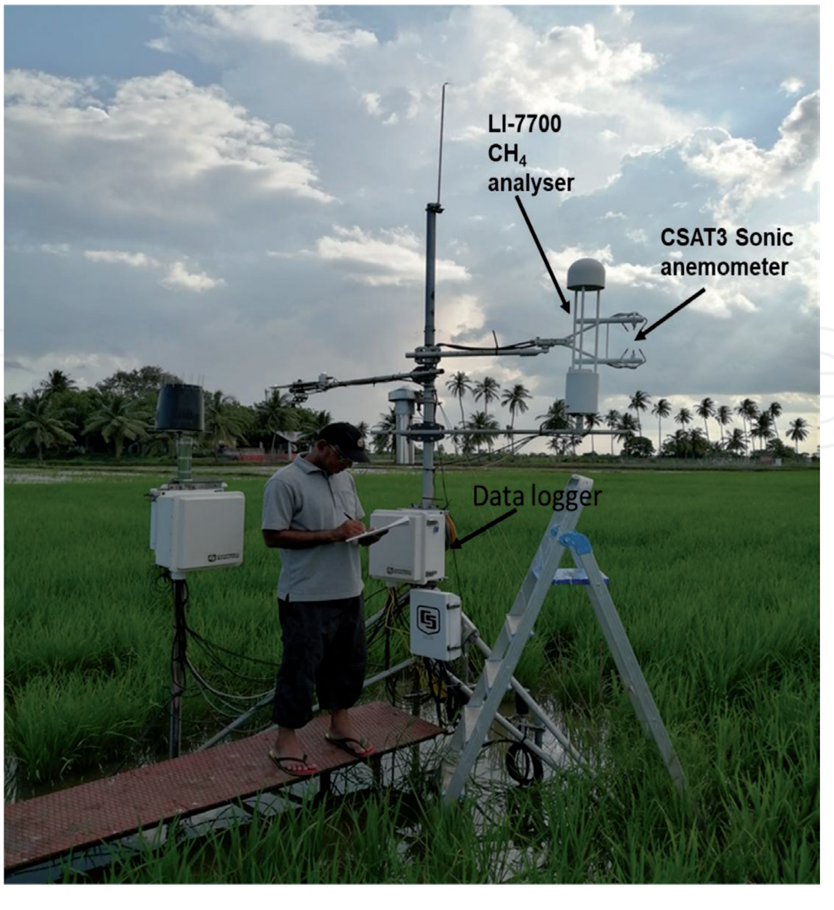

Figure 8.
Set-up of eddy covariance system with CSAT3 sonic anemometer, LI-7500A open-path CO_2/H_2O analyzer, and LI-7700 open-path CH_4 analyzer.

with an open-path and a closed path CH_4 analyzer to provide advances in understanding the performance and limitations of the eddy covariance method applied to CH_4 measurements, from an instrumental and flux processing point of view. Closed-path CH_4 analyzers require high flow rates for significantly reduced optical cell pressures to provide adequate response time and sharpen absorption features [81]. Closed path CH_4 analyzer can detect low fluxes and it is less expensive and flexible, on the other hand, the eddy covariance method using an open-path gas analyzer is highly sensitive, expensive and complex but gets a better estimation of CH_4 flax from paddies [82].

8.3 The calculation of the total methane emission (E_{CH4})

The CH_4 can be calculated by following Equation (1).

$$ {}^{E}CH_4\left(= E_{plant} + E_{bubble} + E_{diffusion}\right) \quad (1) $$

At first, E_{plant} is given by.

$$ E_{plant} = k_p \times k_{tp} \times \int_{root} \times LAI \times C_{CH4soil} \cdot \quad (2) $$

Where k_p is the turnover rate of the methane emission via rice plant (=0.03 day^{-1}), $\int_{tp}$ is a factor of CH_4 emission defined for each paddy type (=15.0), $\int_{root}$ is a distribution factor of rice root in the soil, and LAI is the leaf area index (m^2 $m^{-2)}$.

E_{bubble} is given by.

$$ E_{bubble} = k_b \times (C_{CH4soil} - C_{thresh}), \quad (3) $$

Where k_b is a turnover rate of the CH_4 emission as bubble (=1.0 day^{-1}), and C_{thresh} is the dissolved CH_4 threshold at which CH_4 bubble formation occurs (=6.0 gC m^{-3}).

$E_{diffusion}$ is given by,

$$ E_{diffusion} = (C_{CH4soil} - C_{CH4atm}) \times \int_{dif} \times \int_{tor} \times p_{soil}, \quad (4) $$

Where C_{CH4} atm is the atmospheric CH_4 concentration (=1.0 × 10–3 gC m-3), $\int_{dif}$ is a diffusion coefficient of CH_4 (=1.73 × 10^{-4} m^2 day^{-1}), $\int_{tor}$ is a tortuosity coefficient of the soil (=0.66), and p_{soil} is the soil porosity defied for each soil type (mm mm^{-1}).

9. Mitigation of methane emission from paddy field

CH_4 emission increases during flooding condition and decrease when water drain from the field [83]. Therefore, the irrigation system is one of the most vital tools of rice farming and is the most important effort for CH_4 mitigation. Thus, the water level is one of the main factors affect the production and emission of CH_4 in rice paddy fields. In irrigated rice, a short aeration period at tillering has been shown to increase yield. Single mid-season drainage may reduce seasonal emission rates by about 50% [52]. In a controlled experiment, CH_4 emissions can be significantly reduced when the field is drained and dried at mid tillering and before harvest [53]. Higher yielding rice genotypes could be viable options for reducing the release of CH_4 from paddy fields to the atmosphere [13]. System of Rice Intensification (SRI) is the alternative rice farming for climate change adaptation and mitigates greenhouse gas emission from paddy fields. The study showed that the SRI paddy field with intermittent wetting-drying irrigation reduced CH_4 emission by up to 32% [84]. SRI application can save water irrigation up to 28%, 38.5% and 40% in Japan, Iraq and Indonesia, respectively [85]. SRI also reduced greenhouse gas emission that is represented by reducing global warming potential up to 37.5% in Indonesia [86] and 40% in India [87].

The activity of CH_4 producing bacteria is inhibited from the oxidizing condition of paddy soil by water management. CH_4 emission factor for intermittently flooded paddy fields can decrease by approximately 20% [88]. Water management and organic material management are significant for reducing CH_4 emissions from rice paddy fields. Mid-season drainage and intermittent flooding are effective for increasing the productivity and quality of rice as well as reducing CH_4 emissions. Mitigation of CH_4 emissions from rice paddy fields by water management has huge potential to be marketed. A field experiment in the Philippines showed that direct seeding techniques reduced CH_4 emissions by 18% as compared with transplanted rice. Another study, in Japan, showed that global warming potential declined by 42% just by changing the puddle of rice seedlings to zero tillage. Moreover, CH_4 emission can be reduced by shifting to more heat-tolerant rice cultivars and by adjusting sowing dates. It will also prevent yield decline due to temperature increases [89]. A multi-criteria evaluation ranking score for CH_4 mitigation strategy is been done in Egypt. They found that short duration rice varieties got the highest score. This strategy could be reduced 25% of CH_4 emission, reduce 20% of water consumption without any reduction in rice productivity. On the other hand, fertilizer management strategy was in the second-ranking and followed by the midseason drainage [90]. The heat-tolerant improved rice variety with low CH_4 emission is a potential mitigation option [91].

10. Conclusions

The most important aim of studies on CH_4 emission from paddy fields is the mitigation of global warming and adaptation with climate change. CH_4 emission is controlled by several factors such as temperature, soil pH, Eh, rice cultivar, root, rhizosphere, group of methanogens, paddy growing stages and field management.

From the above-mentioned discussion, it is clear how CH_4 cycling in paddy fields, also how much CH_4 release to atmosphere and leached to ground water and soil.

CH_4 can be reduced from paddy field through management practices like, the mid-season drainage, alternate wetting, drying irrigation and using alternative fertilizers have been shown to reduce CH_4 emissions from rice paddies and achieve sustain rice production.

By using a combination of feasible mitigation technologies there is great potential to reduce CH_4 emission from rice fields and increase rice production. Crop improvement strategies such as breed high yielding and high stress tolerant rice varieties with reduced CH_4 emissions will help the CH_4 mitigation. These rice varieties should be adaptable to changing climate e.g., the stress and water management conditions.

Cultivation of high-yielding and more heat-tolerant rice cultivars will be a promising approach to reduce CH_4 emissions from paddy fields and slowing down global warming.

Future research needs to focus on global paddy field CH_4 budgets, climate change adaptation policy and sustainable agriculture technology, creating more disease and heat resistance rice variety.

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Conflict of interest

The authors declare no conflict of interest.

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