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Mitigating atmospheric methane emissions from Asian rice fields: a review of potential and promising technical options

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Abstract: Agriculture serves as a significant anthropogenic source of methane emissions. Numerous recent studies have examined the factors influencing methane emissions and have developed emission models. However, there is no a bridging review study related to methane emissions in Asia as one of the primary methane emitters. This review is divided into two manuscripts. In this first manuscript, I explore the process of methane emission and the factors that impact methane production and emissions. Meanwhile, the present state of studies conducted in various Asian countries and knowledge gaps are elaborated in the second manuscript. I elaborate several factors that influence methane production and their roles in the emission process. Further, I highlight that the gas is mostly produced in zero oxygen condition, although, a little concentration of methane also can be generated in oxic condition. This finding provides basic knowledge that contribute to the future research on methane emissions in rice field ecosystems. Eventually, I also explore various recommended technical solutions to reduce the gas emission.

Keywords: Methane, GHG emissions, rice fields, agriculture, Asia

1. Introduction

Methane is the second most significant greenhouse gas after carbon dioxide (van Dingenen et al., 2018). It is the primary hydrocarbon in the atmosphere that could significantly affect the earth's temperature due to its ability to absorb and emit infrared radiation up to 30 times higher than carbon dioxide within its short time in the atmosphere (Chen, 2021; Mer et al., 2001; Neue et al., 1996; Topp & Pattey, 1997; van Dingenen et al., 2018). About 530 million tons are released into the atmosphere every year (Ito, 2015). About 70% of the methane emission sources are emitted from anthropogenic factors such as agriculture, mining, natural gas uses, and other sources (Choi et al., 2017; Khalil et al., 1993; Mer et al., 2001; Minamikawa et al., 2006; Topp & Pattey, 1997). Agriculture is the main anthropogenic source, as domesticated ruminants and rice fields are responsible for up to 40% of the methane emissions (Mer et al., 2001).

In Asia, the majority of methane emissions are emitted from agriculture, specifically rice fields. About 90% of rice fields are inundated, and most of the rice production in the world comes from Asia (Wassmann et al., 2009). Flooded soil will allow methanogens to produce methane under anaerobic conditions (Ariani et al., 2021). As a response to the rapid growth of its population, methane emissions from the rice fields are also increasing in the region.

Various studies regarding factors affecting methane emissions to emission modeling have been produced recently (Schulz et al.,1997; Van Dengenen et al., 2018; Zhu et al., 2018; Conrad, 2020; Gwon et al., 2022; Mboyerwa et al., 2022; Ouyang et al., 2023). However,

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there is no comprehensive review that frames previous studies to elaborate on the recent knowledge gap in this topic in particular in Asia as the biggest methane producers. To fill the gap, I write this review, which includes the methane emissions process, factors that affect production and emissions, and the present state of the research on methane in Asian countries. Due to page limitation, the review is divided into two parts, with the first manuscript (this paper) includes the first two topics, and the second review comprises the third topic. This paper provides critical aspects to be addressed in future research to comprehensively understand global methane emissions and their environmental implications, particularly in Asian countries.

2. Method

The references were collected from the search engines such as Google Scholar and Web of Science (Clarivate) with several keywords, such as methane and climate change issues, methanogenesis, factors that influence methane emission in the aquatic ecosystems, and methods in methane research in the rice field ecosystems. I collected hundreds of literature that were refined with several criteria, such as Asian countries and rice field ecosystems without a specific time period. Finally, the results were compiled in the Mendeley reference manager.

3. Methanogenesis in the rice field ecosystems.

Methane is formed as a final product of the reductive process done by methanogens (archaea and bacteria) (Minamikawa et al., 2006) under anaerobic conditions due to flooded rice fields. Methanogens are strict anaerobic archaea and obligate methane producers that break down one-carbon compounds (carbon dioxide, carbon monoxide, methanol, methylamines, and methyl sulphides), acetate or coal to methane gas through one of several methanogenesis pathways (Buan, 2018). However, some methanogenic archaea in soils can tolerate oxygen for a short period; methane production is also reported to occur in oxic conditions (Wagner, 2017). A comparison study between aerobic and anaerobic conditions in the saturated soil to methane production rate showed that anaerobic conditions were able to produce methane at 66% higher than the methane production rate in aerobic conditions. Methane production in aerobic conditions is only half compared to anaerobic conditions at a water potential of -6 and -30 kPa. Therefore, it is understandable that methanogenesis in the flooded soil, as well as other wetlands, becomes rapidly limited by oxygen.

The carbon substrates used in the methanogenesis process are derived from the exudates and the sloughed tissues of the plants and soil organic matter (Minamikawa et al., 2006). Most methanogens are from domain archaea, with some species from anaerobic bacteria. There are two types of archaea based on the compound that they consume to produce methane: hydrogenotrophic methanogens (Methanosaeta and Methanosarcina) and Acetoclastic methanogens (Methanobacterium, Methanobrevibacter, Methanosprillum, Methanoculleus and Rice Cluster I (RC–I). The last type is a novel cluster of archaeal 16S rRNA genes sequenced from rice plant roots. Methanosarcinaceae, Methanobacteriales, Methanomicrobiales, and RC-I were mostly found in the soil of rice fields in China, the Philippines, Japan, and Italy (Conrad, 2007). In total, there are at least seven genera of archaea found living in rice fields (Mer et al., 2001; Minamikawa et al., 2006).

Methanogenesis (Figure 1) involves methanogenic species whose majority use acetate as C and an energy source to create methane, with less than a third of it requiring hydrogen as the energy source (Mer et al., 2001). There are two mechanisms used by methanogens to create methane in the rice field: acetate (acetoclastic methanogenesis) and hydrogen molecules (hydrogenotrophic methanogenesis). These mechanisms are able to help methanogens convert the molecules into methane with carbon dioxide and methane plus water (Conrad, 2007).

Soil redox potential (Eh), soil pH, and temperature are key factors that influence the methanogenesis process in the rice field because methanogens are generally mesophilic species that are active in temperatures ranging from 30 to 40 °C (Wihardjaka, 2016). Therefore, the decrease in temperature will result in low methane production (Topp & Pattey, 1997). Besides that, organic matter application will reduce Eh from below -200 to 150 mV and carbon sources supply. Generally, methane production begins at ± 150 mV (Minamikawa et al., 2006; Wihardjaka, 2016) by methanogens due to anaerobic conditions in flooded soil.

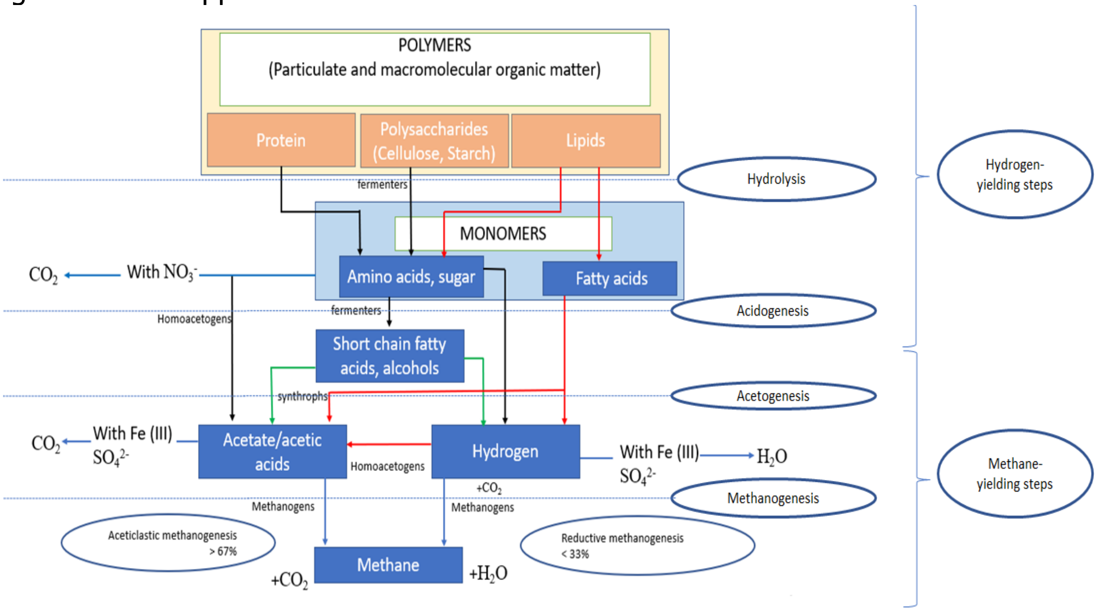

Figure 1. Pathways of the methanogenesis process (Source: Author's creation based on the modification of Conrad (2007), Parawira (2004), and Sikora et al. (2017)).

Some parts of the formed methane resulting from the process are consumed by methanotrophs under oxidative conditions in the roots of paddy or the aerobic organic layer of the soil (Minamikawa et al., 2006; Mer and Roger 2001; Mboyerva et al., 2022). Meanwhile, the rest of it is emitted into the atmosphere in 3 ways: diffusion, ebullition, and paddy's aerenchyma (Ariani et al., 2021; Topp & Pattey, 1997; Wihardjaka, 2016). Further, the majority of the gas is released through the paddy's aerenchyma (20-90%), while ebullition and diffusion are only 2-9% and 0.01-1%, respectively. About 0.1-4% methane infiltrates into the deep layers of soil, and the rest of it is oxidized by methanotrophs in the aerobic layers and is transformed to carbon dioxide (Fig. 2). Methanotrophs in the rice field soil belong to the genera Methylocystis, Methylosinus, Methylobacter, Methylomicrobium, Methylomonas, Methylocaldum, and Methylococcus (Minamikawa et al., 2006; Rahalkar et al., 2021). The population usually enlarges with the growth of paddy, however, irrigation and fertilizer do not affect the growth population of methanotrophs (Minamikawa et al., 2006).

There are four main habitats for both methanogens and methanotrophs in the rice field: the bulk soil, organic plant debris, rice plant roots, and shallow aerobic surface layer in the flooded rice field (Conrad, 2007). These habitats generally get organic matter sources to create methane from rice straw since about 80% of methane emissions come from it, decomposed root cells, and degradation of soil organic carbon (Conrad, 2007; Conrad, 2020). Studies showed both methanogens and methanotrophs can maintain their population under disadvantageous conditions, such as drainage for anaerobic methanogens and flood conditions for methanotrophs (Mer et al., 2001). In other words, methanogens and methanotrophs are interconnected through their roles in the methane cycle, where methanogens produce methane. In contrast, methanotrophs consume and mitigate their release into the atmosphere, which is influenced by water regimes.

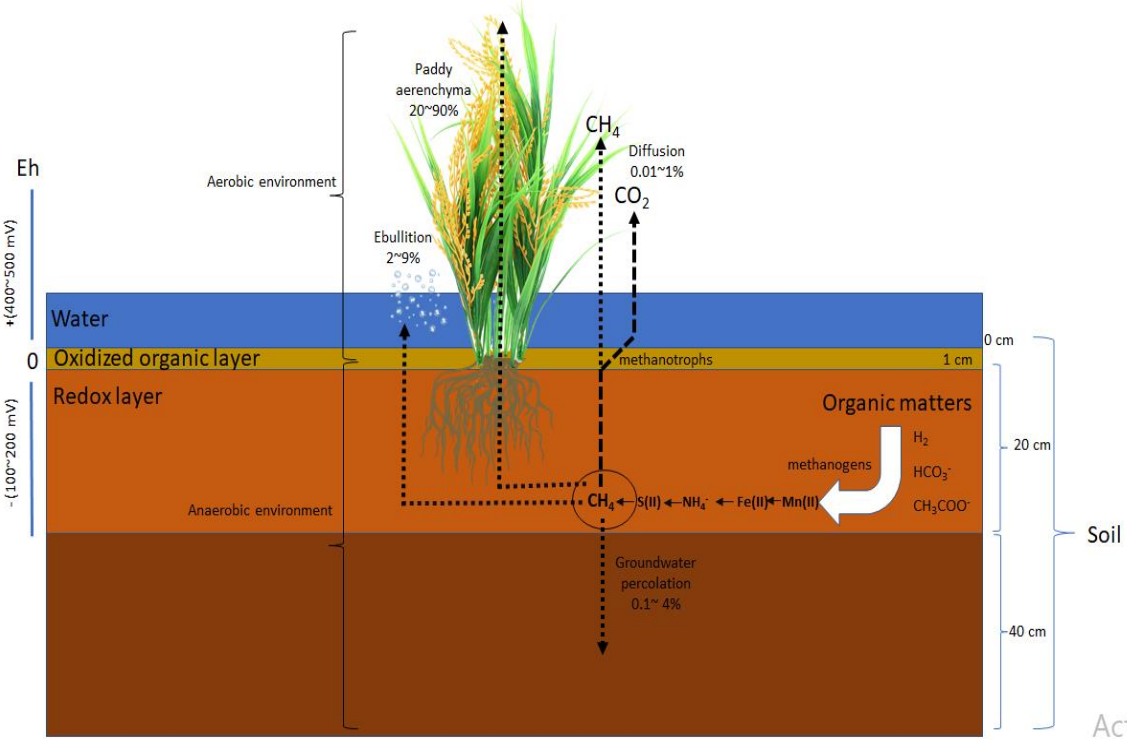

Figure 2. Methane production and emission in the flooded rice field (Source: author's creation based on the modification based on the diagram published by Ariani et al. (2021), Ito (2015), Topp & Pattey (1997), and Wihardjaka (2016))

4. Factors Influencing Methane Emission from Rice Fields: Role of Rice Cultivar and Environmental Conditions

Several factors that affect methane emissions from rice fields comprise rice cultivars, cultivation processes, climate/weather, and soil characteristics.

4.1 Rice cultivars

About 90% of methane is emitted from paddy aerenchyma; therefore, rice cultivation is one of the critical points that affect methane emissions from rice fields to the atmosphere. The formed methane in soil diffused to the passage through aerenchyma to evaporate. Aerenchyma in leaves, roots, and culms allows efficient gas exchange between the atmosphere and anaerobic soil. Moreover, the degrading roots and exudates are important carbon sources in methanogenesis (Neue et al., 1996). Therefore, the right choice of rice variety can lead to reduced methane emissions from soil. Many studies proved that rice-planted soil has higher methane emissions than fallow soil. The ability of rice to form methane is strongly dependent on aerenchyma cavities, number of tillers, rice biomass, root pattern, oxidizing ability, exudates, and microbial activities surrounding the roots (Arianti et al., 2022; Mer et al., 2001; Setyanto, 2006; Wihardjaka, 2016). Methane emission rates from paddy plants greatly depend on their traits because some varieties could emit less methane while producing a high-yielding crop (Ariani et al., 2021).

In a warmer environment, rice plants tend to produce more leaves area as well as tiller numbers to do photosynthesis, which leads to increases in emissions. GHG emission is positively correlated with leaf area, leaf number, tiller number, and root dry weight (Ariani et al., 2021). In addition, the amount of water and nutrients in the soil also affects the amount of GHG emissions, as plants need it to grow. Moreover, root exudate also affects the emission; the cultivar that has more arrangement of roots will form more methane because the exudate of roots acts as one of the carbon sources in methanogenesis (Wihardjaka, 2016). Finally, the length of the growing season also affects the amount of GHG emissions, as plants produce more GHG during longer growing seasons (Lu et al., 2000). Rice cultivar, which has more roots and higher stems because of the length of its growing period, tends to have more methane emission (Mer et al., 2001). Therefore, breeding new rice cultivars with low methane emission and high yield through traditional or biotechnology breeding techniques is one of the best ways to reduce methane emissions.

4.2 Cultivation process

The dynamics of methane emissions in different ecosystems are influenced by gas diffusion in relation with CH_4 transfer, microbial activities, methanogenesis process, and methane-mono-oxygenase activity (Mer et al., 2001). Most reports stated that methanogenesis takes place in anaerobic environments such as aquatic sediments, animal guts, flooded soils, peatlands, and coastal wetlands. The process is connected to the water availability during the flooding and draining periods when the soil is seasonally submerged (Conrad, 2020). As an example, methane emissions in the peatland and gley marsh decreased after the water was lowered to -10 cm, and after 7 days of drying, emissions in the peatland and gley marsh depleted by 28% and 10% respectively (Zhu et al., 2018). In addition, a study in rice growth related to the water regime showed that a significant level of methane emissions occurred soon after transplanting in the wet soil. This condition is mainly because of the increasing of trapped methane through diffusion in aerenchyma young rice plants (Trolldenier, 1995).

Further, a study in Korean upland rice fields found that intermittent irrigation reduces 25.1% GHG emissions compared to continuous flooded treatment (Lee et al., 2020). Flooded soil also lowers redox potentials that restrict the aerobic zone around the roots and allows anaerobic organisms to decompose the resulting exudate and debris to methane (Trolldenier, 1995). In Southeast China, methane emissions were reported to be 61% lower with intermittent draining systems than in continuous flooding irrigation systems, with no significant differences in rice biomass and grain yields (Lu et al., 2000; Wihardjaka, 2016). Overall, it shows that the water regime in an area plays an essential role in methane production as redox potential would deplete in a submerged environment, and it allows methanogens to proliferate in anoxic conditions. Proper drainage of the soil during the growing season could be an effective method without compromising the yields.

Another cultivation process that affects methanogenesis is organic matter, which is often used to increase the yield of rice. Some amendments such as rice straw, green manure, farmyard manure, and compost are more abundant in organic carbon than in chemical fertilizers (Mer et al., 2001). It is known that the rate of methane emission depends on the amount, kind, and prior treatment of the organic components; thus, methane emissions are highly dependent on the amount and condition of readily decomposable carbon contained in the additional substances (Sass, 2003). The application of organic amendments triggers methanogenesis, nitrification, and denitrification since the anaerobic fermentation of organic amendment produces an assemblage of organic matter that is not found in the oxic environment (Ariani et al., 2021; Neue et al., 1996). Organic amendments lower soil Eh and provide carbon sources for increasing menthane production in flooded soil (Wihardjaka, 2016). It is proven that in a hectare of rice field, five tonnes of rice straw could increase methane emission 10-fold compared with mineral fertilizers (Neue et al., 1996). In addition, silicate and zeolite could reduce GHG emissions by 14.1% and 21.7% in the rice field and additional salt, sulfate, N, Fe, gypsum, Mn4+, and SO42- -containing fertilizers also could reduce methane emissions (Lee et al., 2020; Minamikawa et al., 2006; van der Gon, 1996; Wihardjaka, 2016). More evidence from Japan supported that methane emissions vary in the different soil types with the same cultivation and irrigation types (Yagi & Minami, 1991). Further, the annual emission rates in the soil added with rice straw and mineral fertilizers are 1.8 to 3.5-fold higher than the soil that has mineral fertilizers only (Minamikawa et al., 2006; van der Gon, 1996; Wihardjaka, 2016).

4.3 Climate/weather

The next factor that influences methane production is temperature because temperature changes in the soil would affect the methanogens (Schulz et al., 1996; Chandrasekaran et al., 2022). Seasonal temperature variation strongly affects methane flux during the plantation period in various rice field locations in Japan (Yagi & Minami, 1991). Similarly, Chandrasekaran et al. (2022) reported that methane emissions increase linearly to the increase in soil temperature in India. Temperature affects methane emissions through anaerobic digestion reactors, which are done by mesophilic (20~42°C) or thermophilic (42~75°C) organisms such as methanogens (Parawira, 2004). At the same time, methanogenesis takes place at a temperature ranging from 30 to 40°C (Mer et al., 2001).

In temperate or cold regions, seasonal fluctuations in methane emissions were found to be closely associated with changes in soil temperature (Mer et al., 2001). In addition, temperature also affects methane transport through rice plants and daily emissions in the rice field. To be detailed, the production of methane from acetate reached its peak at the temperature of 36 to 40°C, and methane production from H14CO3- was only detected when the temperature reached at least 22°C and decreased after it reached 30°C (Schulz et al., 2006).

Other evidence that promotes the effects of temperature on methane emissions is obtained from The U.S. and Chile. In Winconsin, The U.S., methanogenesis achieved optimum level when temperatures are ranging between 35 and 45°C (Zeikus & Winfrey, 1976). Meanwhile, in Chile, it was found that under uncorrected conditions, 5°C temperature changes could double the methane production rate while the microbial community of the aquatic sediments is not changing (Lavergne et al., 2021).

4.4 Soil characteristics

Soil as a medium during methanogenesis plays a vital role in methane emissions from rice fields. Physicochemical soil properties such as soil Eh, oxygen availability, pH, soil texture, and mineralogy are the critical keys to managing methane emissions in rice fields (Mer et al., 2001). In addition, soil cultural practices also influence methane emissions, hinted by lower emissions and nitrous oxide concentration in the soil without tillage compared to the perfectly tillaged soil under the same water regime conditions (Wihardjaka, 2016; Yoo et al., 2016). This condition is related to the slow decay process of available organic matter, which makes less biomass returned to the soil.

However, decreasing methane emission by the no-tillage method is subjected to other soil characteristics, such as the depth of irrigation and the content of Fe(III) inside the soil. Thus, it is necessary to consider the long-term effects because of the accumulation of rice residues on and in the soil and the changes in soil physical properties (Minamikawa et al., 2006).

Meanwhile, soil texture affects the percolation rate in soil by providing the structure that allows water to pass through. The crack in the soil that is present during the drainage period allows the trapped methane to be released into the atmosphere. Thus, the texture of the soil can lead to maintaining the methane emissions in the rice field (Ariani et al., 2021). One supporting study conducted in Japan showed that Andosol soil has lower methane emissions than gley soil (Yagi & Minami, 1991) due to rapid percolation in Andosols, possibly reducing the emissions, while gley or peat soil tends to perform slow percolation. Whereas Inceptols, the most common soil type in rice fields in Indonesia, could lower methane emissions compared to Vertisol (Susilawati et al., 2015). A similar finding was also obtained from the country when comparing Inceptisol and Alfisol (Subadiyasa et al., 1997).

Not only are the chemical components of the soils that affect methane emissions, but their textures, pH, and oxygen levels are equally important. Soils rich in clays are good at retaining water and nutrients, whereas sandy, silty, and kaolinite soils are not. Meanwhile, the sandy soil density is less compact, slowing down pH, Eh variation, and organic matter decaying process (Mer et al., 2001).

Another vital element that affects methane emissions in aquatic ecosystems is the oxygen level (Conrad, 2020). The availability of light, which boosts phytoplankton photosynthetic activities, can increase the area of oxic soil layers, which then further leads to the rising methane oxidation reaction (Mer et al., 2001). In connection with this, soils with neutral pH tend to have the highest oxygen levels and methanogenesis is usually optimum within a neutral pH or slightly alkaline environment due to the sensitivity of methanogens to the change of pH level. In contrast, methanotrophs tend to be less sensitive to soil pH variations (Mer et al., 2001). To add more evidence, a study using three different varieties of rice plants in India showed that methane emissions diminish when soil pH rises beyond 7 because a higher pH would inhibit the hydrolysis and acidogenesis phase of methanogenesis (Chandrasekaran et al., 2022).

5. Conclusions

Paddy fields have a substantial potential for emitting methane into the atmosphere, which is necessary to provide accurate scientific information regarding GHG emissions; thus, it is imperative to study about the topic comprehensively. It is concluded that rice cultivars, cultivation processes, climate/weather, and soil characteristics are critical factors that affect methane emissions in the rice field. Furthermore, the impacts of some proper irrigation systems, rice cultivars, soil types, soil tillage techniques, and some fertilizer or amelioration are also essential to control the emissions. Therefore, future research must address the challenges of how to reduce emissions by regulating appropriate farming techniques. The recommended solutions are implementing appropriate water irrigation, crop varieties, amendments, and less tillage in a fit soil texture in order to reduce the methane emissions in the rice field ecosystems. Moreover, a wider framework and multidiscipline approach will be needed in order to enhance understanding the GHG emissions from various types of rice fields. It is expected that the results of this review can guide the decision-makers, scientists, and practitioners to formulate suitable plans to alleviate methane gas emissions.

Data availability statement

Data is available upon request.

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Author contribution

IGAAPP: Conceptualization, Writing-original draft, Methodology, Investigation, Data curation, and Writing – review and editing.

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