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REVIEW ARTICLE

Strategies for controlling greenhouse gas emission from lowland rice fields: A review

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Abstract

Rice is one of the most extensively cultivated crops worldwide; however, traditional paddy cultivation has raised significant environmental concerns, particularly the emission of greenhouse gases (GHGs), namely methane gas. According to FAOSTAT 2020,energy consumption in agriculture is around 0.9 Gt CO_2-eq in 2018. Methane, a major GHG, is released into the atmosphere from rice fields through three primary pathways: diffusion, ebullition or rising bubbles and plant-mediated transport. Its production is primarily a microbially mediated anaerobic process, promoted by the flooded conditions typical of paddy systems. Methane emissions can vary considerably based on climatic factors such as air and soil temperature, as well as the season of cultivation. Rice fields emit GHGs even during fallow periods. Additionally, varietal differences among rice cultivars significantly influence methane release, with breeding efforts targeting low-emission varieties showing promising results. Agronomic practices, including alternate wetting and drying (AWD), optimized nutrient management and the incorporation of specific organic amendments, have been effective in reducing methane emissions from paddy fields. This review provides a comprehensive overview of greenhouse gas (GHG) emission especially methane, its production process or methanogenesis, emission pathways as well as the practical mitigation strategies to be adopted in lowland rice cultivation.

Keywords: greenhouse gas mitigation; lowland rice; methane emission; methanogenesis; seasonal variations; varietal difference

Introduction

The rising temperature of Earth and the GHG emissions linked with various agricultural practices have become critical concerns. According to IPCC (Intergovernmental Panel on Climate Change) 2022, GHG emissions from Agriculture, Forest and Land Use (AFOLU) is about 11.9 ± 4.4 $GtCO_2$-eq yr^{-1} from 2010 to 2019. From this rice cultivation contributes to 0.49-0.723 $GtCO_2$-eq yr^{-1} in 2010. About 70 % of methane, one of the most potent GHG is from anthropogenic activities namely, agriculture, agro based industries, mining etc (1).

Rice is an essential food for many of the global population, so balancing food security with emission reduction is complex. Asia is the largest consumer and producer of rice. It consists of largest area in rice field which significantly contributes towards GHG emission. In 2018, India and China emitted maximum methane through agriculture and each country contributed to its estimated 650 million tonnes (Mt) CO_2eq annual emissions as reported by FAOSTAT, 2020. The energy consumed in agriculture was 0.9 Gt CO_2-eq yr^{-1} in 2018, which had increased by 23 % since 2000 (2).

The major factors which contribute towards GHG emission are the peaty composition of soil in the wetland with high organic matter and a very low pH (2.6 to 6.3). The acidic environment can suppress certain microbial activities, though it remains conducive for methane-producing bacteria under flooded conditions. Rising temperatures, particularly during shorter rainy seasons, may increase methane emissions due to enhanced bacterial activity. Climate change brings additional complexities, including variable rainfall patterns, higher average temperatures and salinity shifts, all of which can intensify methane emissions from rice paddies.

Therefore, to identify more effective strategies to tackle the GHG emission from wetlands and to bridge the gap by knowledge of latest technology, this review explores methane emission pathways, influencing factors and the latest strategies to reduce emission from rice fields.

Literature review methodology

A systematic literature review of articles on the strategies for controlling GHG emission from lowland rice fields was undertaken. Articles were searched from multiple databases, including Google scholar search engine, Web of Science and Science Direct. Keywords such as methanogenesis, methane emission from rice field, mitigation strategies in rice fields etc. were used for searching of articles. These keywords form part of article title or abstract. The article search was limited to those published till 2024. Selected writings include research articles, review articles, conference papers and short communications with direct and contextual relationship to the GHG emission from the rice fields and its mitigation practices. Literatures were collected focussing the research studies in Asia, over past two decades (1997-2024).

This review article aims to connect three interconnected specific objectives:

i. To know in detail the process of methane emission from rice i.e. methanogenesis.

ii. To study the factors which boost GHG emission in rice.

iii. To assess the mitigation practices for controlling the GHG emission in rice.

Methanogenesis

Methanogenesis is the biological production of methane by microorganisms called methanogens. Agriculture and methane related emissions contribute towards methane sources about 130 and 100 Tg/year respectively, besides this waste related emission extents to 70-90 Tg/year. One of the major anthropogenic sources is biomass burning which causes emission by 35 Tg/year (3). Global methane emission due to paddy cultivation is approximately 46 Tg/year (4). In paddy field, under waterlogged conditions, the redox potential ranges from 250 to -300 millivolts (5). As the oxygen gets depleted in soil, reduction process occurs in sequence and methane is released when redox potential is less than -200mV (6). Fig. 1 depicting redox sequence, clarifies that reduction of nitrate and manganese compounds takes place first and then ferric compounds are reduced to ferrous form and lastly sulphate gets convert to sulphides.

The major role in methane production is done by methanogens (anaerobe archaea) through anaerobic conditions by converting carbon containing compounds to methane. The presence of anoxic zones in wetlands caters towards production of methanogens which produce methane and transfer it through atmosphere by the passage of rice aerenchyma and through general methods of diffusion and ebullition (8).

On the other hand, methanotrophs (methane oxidizing bacteria) in oxidized zone causes aerobic oxidation of methane which leads to production of carbon dioxide, this acts as an important biotic sink. By assessing physiochemical properties of soil, vegetation, soil fauna and climatic conditions the efficiency of methanotrophs is determined. Anaerobic zones are more prominent under high temperature and rainfall and this produces more methane. Apart from this, atmospheric pressure changes the apparent motion of methane which influences oxygen diffusion into system and prompts methane emission into the atmosphere (9).

Pathways of methane emission in rice field

In flooded rice soils, methane (CH_4) produced by anaerobic decomposition is released to the atmosphere through three main pathways:

Diffusion

Methane slowly diffuses through the soil and water layers into the atmosphere. This process is relatively slow but contributes to overall emissions (10).

Plant mediated transport

Rice plants play a major role in methane emissions by acting as conduits for methane to escape. Methane is taken up through the roots and transported through specialized gas channels (aerenchyma) in the plant stems and leaves, eventually being released into the atmosphere. This plant-mediated pathway is the most efficient route and accounts for the majority of methane emissions in flooded rice fields. About 90 percent of methane gas is released by paddy aerenchyma (11).

Rice cultivars with increased biomass and tiller numbers indeed play a crucial role in methane dynamics within flooded soils. The expanded aerenchyma tissue in these cultivars facilitates better oxygen transport from atmosphere to the rhizosphere (the root-soil interface). This oxygen availability encourages methane oxidation by methanotrophic bacteria in the soil, which convert methane into less harmful compounds before it can reach the atmosphere. Consequently, rice varieties with higher shoot biomass and larger aerenchyma volumes help mitigate methane emissions (12).

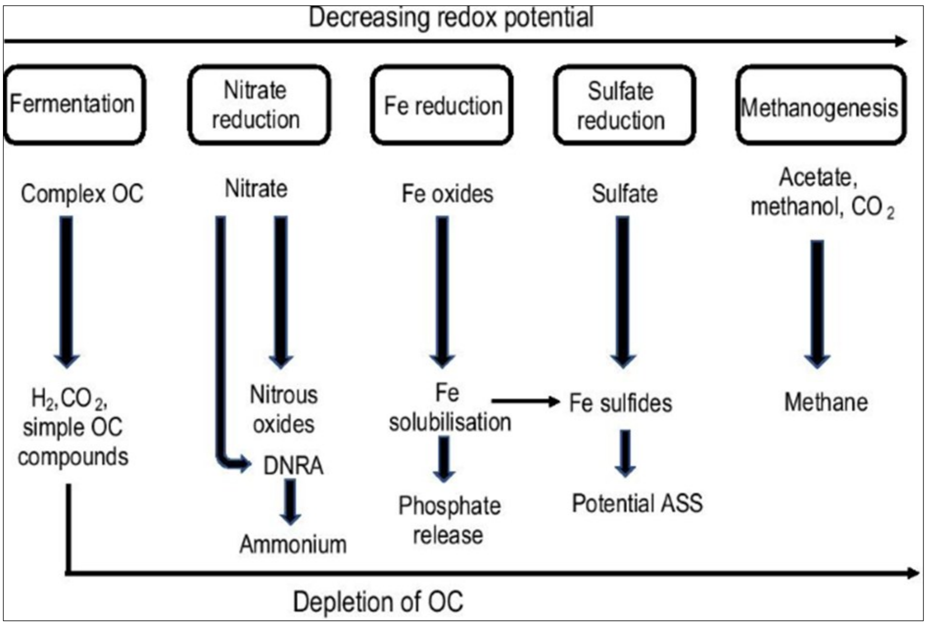

Fig. 1. Conversion of complex organic carbon to methane (7).

Ebullition

Methane can form bubbles (ebullition) in the soil, which rise and burst at the water surface, releasing methane directly into the atmosphere. This is a quicker release mechanism, often occurring when methane concentrations in the soil reach a threshold that triggers bubble formation. Methane ebullition from paddy field can be controlled by atmospheric pressure, soil temperature and water table (13). Reduction in atmospheric pressure causes lesser formation of methane bubbles in peatlands (14). A study conducted in Thailand demonstrated that a decline in atmospheric pressure led to a reduction in methane ebullition (15).

It was reported that rise in temperature from 5 to 35 °C increased CO_2 emission rate by 2.4-3.7 times in swamps and peat wetlands (16). Temperature elevation can also stimulate nitrogen mineralization in soil which provides nutrient supply for nitrification and denitrification finally leading to N_2O production (17). The pathways of methane emission are detailed in Fig. 2.

Seasonal variations in GHG emission

Seasonal variations in GHG emissions from rice fields are indeed significant, with distinct differences observed between the *Kharif* (monsoon) and *Rabi* (dry) growing seasons. In regions of eastern India where two rice crops are cultivated, studies have shown that methane (CH_4) emissions were about 1.8 times higher during the *Kharif* season (July-November) than during the *Rabi* season (January-April) during national campaign 2002 as shown in Table 1 (19).

Several factors contribute to this seasonal disparity. In coastal saline soils of Odisha, India, during wet season, the cumulative seasonal CH_4 flux ranged between 119.51 and 263.60 kg/ha, while in dry season, a lower CH_4 emission of 15.35-100.88 kg/ha was observed (20). Methane production was remarkable in non-saline alluvial soil (630.86 ng CH4/g) compared to acid sulphate pokkali soil (12.97 ng CH4/g) due to presence of sulphates. It was also observed that methane production was low in coastal saline soil (142.36 ng CH4/g) but increased upon leaching the soil of its salt content (21). Waterlogged conditions are conducive to anaerobic decomposition promoting methane production (22), hence monsoon rains in kharif results in higher methane emission compared to dry rabi. Other factors such as elevated CO_2, increase in temperature and its combination has increased the methane emission by 28-120 %, 38-74 % and 82-143 %, respectively (23).

There is significant effect of water management in the fallow season as it controls the production and emission of CH_4 during the fallow and the following rice seasons. The population and activities of methanogens are lower in rice fields that are drained and dry in the fallow season (24). In fallow season, the methanogenesis is prevented by draining the overlaying water layer. This has a significant influence on CH_4 production and emission in subsequent rice season, because after reflooding much time is taken by methanogens to regain the population (25). But CH_4 is continuously produced and emitted in flooded rice fields in the fallow season (26). Therefore, CH_4 flux is found in flooded condition and not in drained fields during fallow season (27).

Investigation on the impact of different rice straw treatments on methane emissions in different seasons showed that the incorporation of rice straw especially in the second crop season resulted in substantially higher methane fluxes compared to removing rice stubble or burning the straw (28).

Post-harvest management significantly influences the net Global Warming Potential (GWP) of paddy rice cultivation by altering GHG emissions during the post-harvest period and the subsequent growing season, without compromising the carbon sequestration potential. Specifically, the combined use of non-winter flooding and delayed straw incorporation is

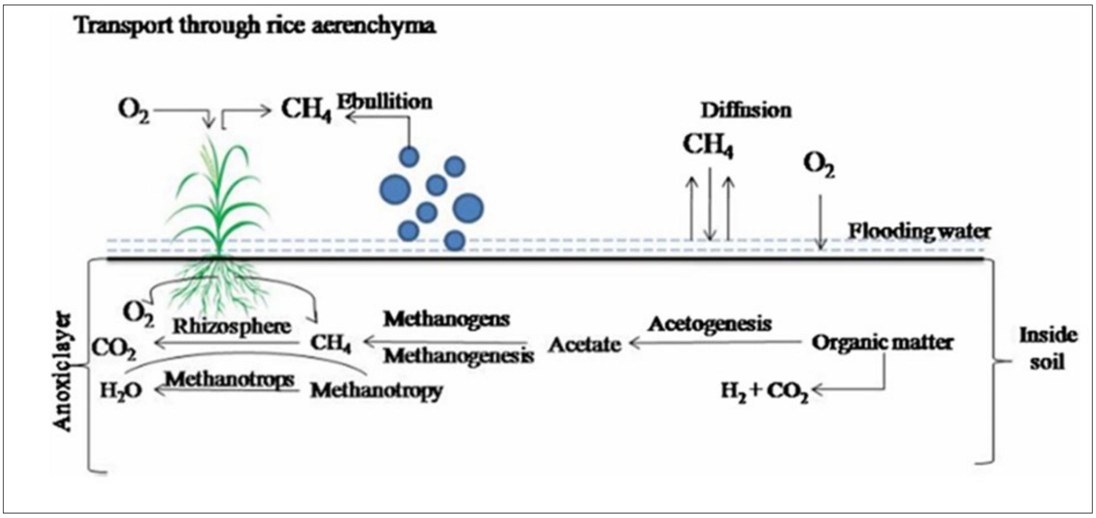

Fig. 2. Pathways of methane emission in rice (18).

Table 1. Effect of seasons *Rabi* and *Kharif* on methane flux

Seasons	Soil organic carbon (%)	Methane flux (g/m²)	Enhancement factor
Rabi	1.08	12.98	
Kharif	0.92	23.04	1.8

more effective in reducing both methane (CH_4) and carbon dioxide (CO_2) emissions. This effectiveness is primarily due to avoiding straw incorporation during periods of higher temperatures conditions that favour increased CH_4 production and enhancing soil redox potential (Eh) in the next growing season, which suppresses anaerobic microbial activity responsible for methane emissions (29).

Impact of varietal difference in methane emission

Studies have shown that certain hybrid rice varieties with 50-60 % more shoot biomass emit less methane than traditional indica varieties as it has enhanced aerenchyma which improves oxygen flow to the rhizosphere, thereby fosters methane oxidation and reduces methane emissions (30). In Indonesia, the amounts of CH_4 emitted for 1 kg grain production ranged from 53 (Atomita-4) to 74 (Kapuas and Walanai) when chemical fertilizer was added and from 89-93 (IR-64, Bengawan solo and Atomita-4) to 121 (Kapuas) g CH_4/kg when chemical fertilizer along with rice straw was used as soil amendment as shown in Table 2 (31).

Similarly, study on varietal variation in methane emission was conducted in Bangladesh and Binadhan-17 recorded lowest emission among the six varieties tried (32). This variation among the rice cultivars might be due to distinguishing characters of root exudates, root tissues and leaf litter decay, low photosynthate in grain and pattern of growth duration (33). In China, three mid-season *japonica* rice cultivars (Wuyujing 3, Zhendao 88 and Huaidao 5) were studied for root morphological and physiological traits, but it was negatively correlated with methane flux. The root exudates (malic acid, succinic acid and citric acid) promoted the abundance and activity of methanotrophs, which was the primary factors underlying the low CH_4 emissions in the paddy fields (34).

It is also reported that long-duration varieties namely, Ratna and Shyamla, emitted more CH_4 than short duration varieties Ananda and Kranti (35). On the contrary, reports also show that, irrespective of the cultivar, the methane emission proportionately increased with soil temperature during day but decreased exponentially as soil pH increased beyond 7 (36).

Table 2. Amount of methane emitted for 1 kg of rice production for different varieties

Varieties amended with chemical fertilizer	Amount of methane emitted for 1 kg grain production
Bengawan solo	67.3
IR-74	65.1
IR-64	67.2
Atomita-4	52.6
Cisanggarung	66.9
Way seputih	58.6
Kapuas	70.8
Walanai	73.9
Varieties amended with rice straw and chemical fertilizer	
Bengawan solo	89.7
IR-74	97.3
IR-64	88.9
Atomita-4	92.9
Cisanggarung	108.2
Way seputih	112.7
Kapuas	120.6
Walanai	107.1

Effect of nitrogen application on GHG emission

Nitrogen (N) application is indeed critical for achieving high rice yields, but it also influences GHG emissions, especially nitrous oxide (N_2O) and methane (CH_4).

Nitrous oxide emission: Rice plant is considered as channel between soil and atmosphere for N_2O emission. It might be formed in mitochondria via the nitrate-nitrite-nitric oxide (NO_3-NO_2-NO) pathway when the cells experience hypoxic or anoxic stress by using enzymes cytoplasmic nitrate reductase (NR) (37). The application of traditional N fertilizers in rice paddies has been observed to increase N_2O emissions, which is significant, given N_2O's high global warming potential (approximately 298 times that of CO_2 over 100 years) (38).

High rates of N fertilizer application correlate with increased N_2O emissions. This is because excess N in the soil promotes nitrification and denitrification processes, particularly under intermittent wet and dry conditions. Under flooded, anaerobic conditions, N_2O emissions are typically low, but as the field dries, N_2O can be released in substantial quantities (39).

Methane emission

Nitrogen fertilizers also stimulate the growth of methanogens (methane-producing microbes) in the rhizosphere. These microbes thrive in anaerobic conditions and decompose organic matter to produce methane. Thus, higher N applications can inadvertently increase methane emissions by fostering conditions favourable to methanogens (40).

Factors affecting methane emission

Environmental factors including high soil saturation and temperature

Anaerobic condition is prominent in saturated soil which makes a conducive environment for CH_4 emission because of dominance of obligate anaerobic methanogens. The drying of saturated soils makes it aerobic and reduces CH_4 emission (41). Recent studies have evaluated the impact of elevated temperatures under free-air temperature increase (FATI) conditions, simulating a 2 °C rise in ambient soil temperature. Interestingly, this moderate warming did not significantly alter the abundance of *mcrA* and *pomA* genes, which encode key functional proteins in methanogens and methanotrophs, respectively. This suggests that the methanogenic and methanotrophic microbial populations are relatively resilient to moderate increases in soil temperature.

Mid-season drainage (MSD) practices, especially when implemented after the rice tillering stage and irrigation resumed post-heading, were found to improve soil oxygenation. Enhanced O_2 availability during these stages led to a notable reduction in CH_4 emissions during the late growth period of rice (42). Under warming conditions, there was a significant increase in the abundance of ammonia-oxidizing archaea (AOA) and bacteria (AOB), indicating enhanced nitrification activity. This was attributed to increased soil mineralization driven by higher temperatures (43). The intensified ammonia oxidation resulted in greater nitrate (NO_3^-) availability, subsequently promoting denitrification processes. This was evidenced by a substantial rise in the abundance of the nirS gene, which encodes for cytochrome cd1-type nitrite reductase. In contrast, the abundance of other key denitrification genes such as *narG* (nitrate reductase) and *nirK* (copper-containing nitrite reductase) remained unaffected by warming. This suggests that denitrifier populations harboring these genes are either less responsive or less sensitive to elevated temperature regimes (44).

Fertilizer type

In alkaline soil, application of urea may cause decrease in CH_4 emissions. Urea hydrolysis increases soil pH, which limits the proliferation of neutrophilic methanogens (45). However, in acidic soils, shifting of soil pH from acid to neutral due to urea hydrolysis causes methanogenesis. Studies have indicated that urea can be substituted by ammonium sulphate which reduces CH_4 emissions in high acidic soil (46).

Soil type and tillage

Gradual rise in methane emission was observed during early transplant stage loam and clay loam soil, but sudden increase was noticed in sandy loam. The total amount of methane emitted was highest in sandy loam, followed by loam and clay loam. Hence, the highest amount of methane emission was in sandy loam, succeeded by loam and clay loam (47). However, when tillage depth was increased from 10 cm to 20 cm the emission was reduced in all three types of soil texture.

Organic inputs

Excessive use of organic materials works as substrate for methanogenic bacteria which increases methane emission (48). Application of organic matter causes decrease in Eh and is a potent source of C which has an influencing role in increase of methane production (49). However, methane production rate depends on the quantity and quality of organic materials applied (C/N ratio, cellulose content, degree of humification and others).

Estimation of greenhouse gas

GHG is estimated by closed chamber method in which gas is collected through syringe and analysed by gas chromatography. According to recent studies conducted in Indian Institute of Rice Research- ICAR, Hyderabad, India, samples are taken using chamber (50 cm 30 cm 100 cm) built of 6 mm acrylic sheets. The chambers are kept on aluminium stand, which is inserted in soil. The system is made airtight by filling the water in channel beneath the aluminium stand. Thermometer is placed inside the chamber to measure temperature during sampling and a battery is placed to homogenize the air inside the chamber as shown in Fig. 3. Gas sample of approximately 20 mL is collected from the syringe and sampling was done at 0, half hr and one hr (50). The greenhouse gas intensity (GHGI) indicates the amount of emission released during per unit production of grain. It can be calculated by dividing global warming potential (GWP) to grain yield (51).

$$\text{GHGI (kg } CO_2 \text{ eq kg}^{-1} \text{ grain)} = \text{GWP (kg } CO_2 \text{ eq ha}^{-1}) / \text{grain yield (kg ha}^{-1})$$

Solutions to minimise the emission from rice fields

Breeding low emission rice varieties

Breeding paddy for reducing methane emission without compromising the yield is an effective mitigation practice. The rice cultivar SUSIBA2, which contains a transcription factor for sugar signalling from barley, suppressed CH_4 emissions by allocating more photosynthates to aboveground biomass than to roots, whereas photosynthate allocation was reduced in grains after the removal of spikelets which markedly increased CH_4 emissions (52). The enhanced expression of starch biosynthesis genes (OsSUT1, OsSUT5 and OsDOF11) in panicles and grains of Milyang360 rice variety led to increase in sucrose absorption by cells and its transport to the grains, resulting in better yields. The downregulation of root exudate transporter

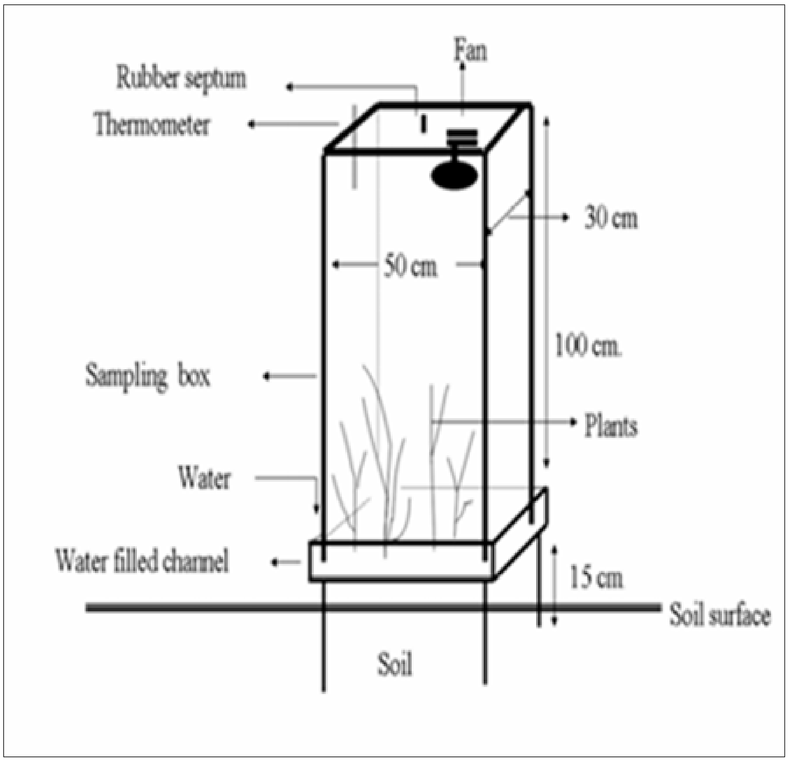

Fig. 3. Gas sample collection using close chamber technique (50).

genes, including *OsALMT1*, *OsSWEET11* and *OsSWEET14* led to reduction in root exudates, which ultimately reduced CH_4 emissions as methanogens feed on these root exudates (53). The variety SUSIBA-2 emits 70 % less methane compared to the conventional variety Nipp rice. Presence of low fumarate levels and high ethanol in roots decreased the methanogenesis process (54).

Alternate Wetting and Drying (AWD)

The AWD system is a water saving technology in rice cultivation. It uses water 20-25 % lesser than continuous flooding. In Thailand, in acid sulphate paddy field the total water use was reduced by 42 % after following AWD (55). While effective drainage through AWD significantly lowers methane emissions, its efficiency depends on factors like soil type, water management and agricultural practices (56). AWD at a threshold of -15 cm did not cause any yield reduction because rice roots could absorb moisture from saturated soils (57). Moreover, AWD reduced unregulated water use and, in many cases, enhanced grain yield due to optimized water availability supporting root development, grain filling and improved carbon allocation from source to sink (58). However, it's important to note that in some locations, AWD has led to a yield reduction of 8-11 % compared to conventional irrigation methods (59).

Adding soil amendments

Farmers use soil amendments increasingly to get better yield and decrease the GHG emissions. Research indicates that the application of vermicompost can help lower methane emissions (60), while biofertilizers like Blue-Green Algae (BGA) and Azolla increase dissolved oxygen levels in flooded rice fields. This rise in oxygen suppresses methanogenic activity, thereby contributing to climate change mitigation (61). In contrast, addition of organic material such as rice straw can increase methane emission. In China, biochar based slow released fertilizer decreased methane emission by 33.4 % compared to organic fertilizer treatments in rice cultivation (62). Similarly, in India, when rice straw was added with green manure it increased the methane emission by 75 %. This spike is likely due to the wide carbon-to-nitrogen (C: N) ratio of *Sesbania aculeata*, which delayed nitrogen release and encouraged anaerobic decomposition (63).

When silicate fertilizers were applied to paddy fields, the percolated water contained high concentration of dissolved iron materials. The concentration of active and free iron oxides in soil which acts as an oxidizing agents and electron acceptor also increased, leading to decreased CH_4 emissions during the rice growing seasons. By the application of silicate fertilizer @ 4 mg/ha, there was a decrease in CH_4 emission by 16-20 % and increase in rice grain yield by 13-18 % (64). Methane production can also be supressed by controlling the Co-enzyme M, a potent inhibitor of methanogenesis. The use of 2-Bromoethanesulfonate (BES) @ 80mg/kg reduced methanogenesis as it is structural analogue of Co-M (65).

Addition of sulphate containing amendments such as gypsum, phosphogypsum and sodium sulphate to paddy field led to reduction in methane emission as it enhances the activity of bacteria involved in methane oxidation (*pmoA*) sulphate reduction (*dsrA* and *dsrB*) (66). In saline alkali paddy fields application of desulfurized gypsum has decreased the CH_4 emission by 78.05 % and organic fertilizer has decreased CO_2 and CH_4 by 11.62 % and 65.84 % respectively. Despite the reduction of methane and carbon dioxide, there was increase in ammonia volatilization. Desulfurized gypsum and organic fertilizer increased ammonia emission by 26.26 % and 45.23 % respectively. Nitrous oxide emission was also increased by 41 % in desulfurized gypsum and by 12.31 % in organic fertilizer (67).

Efficient fertilizer use

Nitrogen fertilizers play a dual role in agricultural ecosystems. Nitrogen stimulates crop growth and increases carbon inputs into the soil through organic root exudates. These carbon substrates serve as an energy source for methanogens (68). But there are contradictory reports also which suggest that addition of urea 200-400 kg N/ha stimulated the growth of methanotrophs and resulted in greater methane oxidation in soil (69). Prolonged application of sulphur coated urea combined with uncoated urea could maintain rice yield and reduce methane emission (70). Polymer coated controlled release urea (CRU) reduced NH_3 volatilization (45.9 %), N_2O emission (27.7 %) and N leaching (24.3 %), while increasing crop yield (7.7 %) (71). The application of different microbial consortium increased the efficiency of inorganic fertilizers by 25 %, rice production by 33.5 % and decreased methane emission by 37.2 % (72). Application of urea briquette and placement by use of applicator at subsurface region could reduce ammonia volatilisation and nitrous oxide emission (73).

Conclusion

Paddy cultivation provides a conducive environment for methanogens, leading to significant methane emissions. Therefore, obtaining accurate scientific data on GHG emissions is crucial. Factors such as rice cultivar selection, seasonal weather variations, soil characteristics, irrigation methods and fertilizer application play critical roles in determining emission levels. Consequently, it is essential to analyse long term, location-specific challenges and implement practical, targeted strategies to mitigate emissions from paddy fields. Comprehensive studies focusing on the mitigation of GHG emissions through various agronomic practices and breeding approaches should be undertaken to develop effective solutions.

Authors' contributions

The collection of the review articles and drafting was done by ATM. The correction and editing was done by DT and SAK.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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