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Review

Ways to mitigate greenhouse gas production from rice cultivation

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ABSTRACT

Rice cultivation boasts a rich historical legacy, serving as the primary sustenance for over 50% of the global population. However, the cultivation process gives rise to the emission of methane (CH_4) and nitrous oxide (N_2O), two potent greenhouse gases. Notably, the global warming potential (GWP) of CH_4 and N_2O surpasses CO_2 by 27–30 times and 273 times over 100 years, respectively. Addressing this environmental challenge necessitates exploring technical approaches and management strategies to curb gas emissions while sustaining rice yields. Several critical factors have been identified and analyzed for their potential to mitigate greenhouse gas production during rice cultivation. These include water management, fertilizer management, biochar application, cultivar selection, straw management, modified planting methods, and integration of new energy machinery. A comprehensive understanding and implementation of these methods can contribute significantly to achieving a dual objective: reducing emissions and maintaining optimal rice yields. Looking ahead, a synergistic integration of these diverse methods and management approaches holds promise for more effective results. Furthermore, the intricate water networks associated with rice cultivation should be carefully considered in the overall strategy. By adopting a holistic approach that addresses both emission reduction and sustainable water usage, the future of rice cultivation can be shaped to align with environmental stewardship and food security.

1. Introduction

Rice cultivation has a long history of over 7000 years and is vital in supporting around 50% of the global population. It has influenced most countries' cultures, dietary habits, and economies. According to Food and Agriculture Organization of the United Nations, rice is the leading food with a production of 776,461,457 metric tons in 2022 worldwide. The year 2004 is defined as the International Year of Rice to recognize its significance (Adjao and Staatz, 2015; Gnanamanickam, 2009; Durand-Morat et al., 2023).

Data from the Food and Agriculture Organization (FAO) show that the average rice yield worldwide now stands at 4.76 tons per hectare. This figure has doubled over the last half-century, mainly due to the introduction of recently developed rice varieties. However, this substantial production yield is accompanied by a declining growth rate. The growth rate decreased from 2.5% to 1.4%. It is predicted that by 2025, about 4.6 billion people will have rice as their primary food, marking a significant increase from the current three billion. Rice production faces severe challenges in keeping up with substantially rising consumption now (Adjao and Staatz, 2015; Gnanamanickam, 2009).

While rice can grow in various conditions, it prefers warm, water-rich environments. Currently, 88% of rice is cultivated in paddy fields during or after transplanting young seedlings (Gnanamanickam, 2009; Wei et al., 2019). However, in this situation, when fields are merged with water, the environment in the soil becomes anaerobic, and methane (CH_4) is produced. Nitrous oxide (N_2O) is produced simultaneously, and the production process is nitrification–denitrification. The primary source of N is the application of fertilizer, and the production process happens both under aerobic and anaerobic conditions (Islam et al., 2018). CH_4 and N_2O are two widely recognized greenhouse gases

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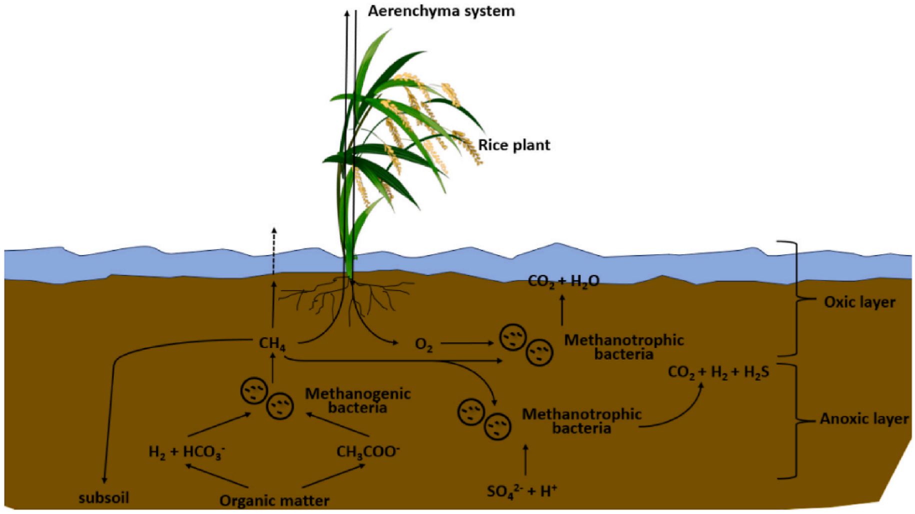

Fig. 1. How methane is produced and oxidized in paddy soil fields.

(GHGs). The global warming potential (GWP) of CH_4 and N_2O are 27–30 times and 273 times that of CO_2, respectively, in a life span of 100 years (Chauhan et al., 2017).

Data from FAO of the United Nations show that the CH_4 emissions from rice cultivation were about 686,111 kilotons of CO_{2eq} in 2020. Initially, atmospheric CH_4 levels were stable at 0.7 ppm. However, from the 19th century, CH_4 levels steadily increased, reaching 1.745 ppm by 1998 and stabilizing between 1.77 and 1.78 ppm since 2005. If the current growth rate continues, CH_4 levels could reach 2.55 ppm by 2050 (Nazaries et al., 2013).

The GWP of N_2O is much greater than that of CO_2. Emissions of N_2O from agricultural soils constitute approximately half of all human-induced sources (Zhang et al., 2024). This significant emission is primarily due to the application of nitrogen-based fertilizers. Due to the nitrogen deficiency in soils, nitrogen fertilizers are often utilized to boost the growth of plants and increase food productivity. However, during the process, approximately 1–5% of nitrogen fertilizer is lost into the atmosphere as N_2O emissions (Liu et al., 2019a; Tang et al., 2018).

In summary, the GHGs emission from rice cultivation is about 19% of the whole agricultural sector emissions by estimation (Zhang et al., 2022b). Governments worldwide have reached agreements that global warming should be limited to 1.5 °C; otherwise, irreversible environmental problems are likely to happen, which will cause disastrous consequences. To limit global warming to 1.5 °C, the cumulative carbon budget must stay within 570 $GtCO_2$ and reach net-zero CO_2 emissions globally by around 2050. Meanwhile, the emissions of other gases—mainly CH_4 and N_2O should be controlled (Ahmed et al., 2020).

Mitigating GHGs emissions from rice cultivation is urgent. The first reason is to control global warming, and the second is to ensure rice production's resilience in a changing climate. The primary goal of this article is to comprehensively review and analyze diverse management strategies and technical innovations aimed at decreasing CH_4 and N_2O emissions from rice cultivation, thereby offering new perspectives on the pursuit of sustainable rice farming.

2. Influencing factors on GHGs production

Soil methane is generally produced by methanogenic bacteria from organic matter in soil under anoxic conditions. This process is called methanogenesis. Other bacteria, such as hydrolytic, fermenting, syntrophic, and acetogenic species, are involved before methanogens. It can also be oxidized through aerobic oxidizing and anaerobic oxidizing. The net emission of methane is decided by both production and oxidation. In aerobic oxidizing process, methane is oxidized primarily by methanotrophic bacteria as below:

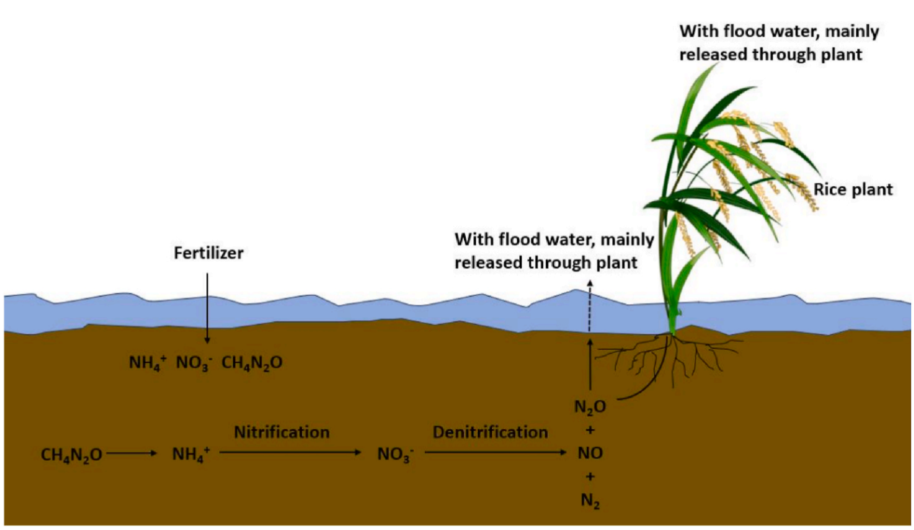

Fig. 2. How N_2O is produced in paddy soil fields.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

Some yeast species, such as *Rhodotorula glutinis* and *Sporobolomyces roseus*, can also perform this process. In the anaerobic process, methane oxidizers and sulfate reducers can oxide methane as below:

$$2CH_4 + SO_4^{2-} + 2H^+ \rightarrow 4H^2 + 2CO_2 + H_2S \quad (2)$$

This process usually happens in environments rich in sulfate and is more likely in aquatic environments (Mancinelli, 1995; Nazaries et al., 2013). The method of methane production and oxidation is depicted in Fig. 1. The main tunnel for CH_4 to get into the atmosphere is plant transport through aerenchyma system.

N_2O emissions primarily result from two vital microbial processes: nitrification and denitrification as shown in Fig. 2. Various environmental and biological factors influence these two biological processes. The source of N is mainly fertilizer applied, including NH_4^+, NO_3^-, and CH_4N_2O. CH_4N_2O is first transformed into NH_4^+ to be absorbed by the rice plant. NH_4^+ can be transformed into NO_3^- through the nitrification process, and NO_3^- is further reduced into N_2O, NO, and N_2 by denitrification bacteria. In the nitrification process, N_2O is also produced during the initial stage of nitrification, which involves the oxidation of ammonia to nitrite (Maeda et al., 2015). When soil is flooded, N_2O is mainly transported into the atmosphere through rice plants, while in the absence of flood, the produced N_2O is primarily released through the soil surface (Xing et al., 2009).

The influencing factors on methane and N_2O emissions are various including physical parameters such as temperature, soil pH, soil phosphorous, soil type, and soil moisture, and management methods such as the application of fertilizer and straw incorporation. These factors influence the emissions of GHGs from their transportation, the amount of substrate to convert, the enzyme activity of relative microorganisms, and the community structure of relative microorganisms.

2.1. Influencing factors on CH_4 production

2.1.1. Temperature

Temperature is thought to be a primary factor affecting CH_4 production, as it has a direct influence on the activity of relevant microorganisms. A research study by Sass and Fisher (1997) has identified that CH_4 emissions respond rapidly to the change in soil temperature. The diurnal fluctuations in CH_4 emissions are also studied and it is primarily a result of temperature variances, and the daily patterns of CH_4 emissions can be attributed to the corresponding daily fluctuations in soil temperature (Peng et al., 2008). Sass et al. (1991) conducted a series of experiments in Texas mainly involving the cultivation of rice fields at different planting dates. Rice being planted at later date had lower production probably due to the lower levels of solar radiation.

2.1.2. Straw incorporation

The current rice straw management in many countries is integrating into the soil. There are both advantages and disadvantages. These advantages include improving nutrient availability. The side effect is that this might increase CH_4 production, and the reason for this might be that the carbon activity of soil can be improved (Jumat et al., 2023). Liu et al. (2014) found that straw returned significantly increased soil organic carbon concentration by about 12.8% on average, with a 27.4%–56.6% increase in soil active carbon fraction.

2.1.3. Soil type

Various factors of soil can significantly influence the production process and oxidation process of CH_4. These factors involve concentrations of oxygen, CH_4, ammonium, and the diffusivity, and content of water potential of soil. These factors either directly or indirectly influence the emission of CH_4. For example, oxygen concentration is the key parameter of methane oxidation, and different types of soil have different gas transport abilities which cause the fluctuation of oxygen content. Furthermore, soil particle size and texture are also reported to have a notable influence on CH_4 production. Kim et al. (2018) investigated the influence of soil type on CH_4. They focused on two distinct soil textures, sandy clay loam, and sandy loam, and they found that CH_4 emission in sandy clay loam was significantly higher than that in sandy loam. It has been concluded that the majority of these parameters impact the process through their interactions with CH_4 monooxygenase, which is a type of enzyme and works for the catalysing of the initial step in CH_4 oxidation (Mancinelli, 1995).

2.1.4. Nitrogen fertilizer

N fertilizers influence CH_4 production through two primary mechanisms. Firstly, N fertilizer is beneficial for the growth of plants. Thus, there can be more carbon substrates from the plant residues and secretions of plants. These carbon substrates can serve as the nutrition for methanogens in rice fields and boost their CH_4 production. Furthermore, the better growth of rice plants provides more plant transport systems for methane to enter the atmosphere (Cai et al., 2007). At the same time, more oxygen can get into the root area with a more robust root system, improving methane oxidation. Secondly, using N fertilizer significantly influences the microbial structure of microorganisms, especially methanogens and methanotrophs, by alleviating their nitrogen deficiency. For methane production, the application of N fertilizer can stimulate methanogenic bacteria. For methane oxidation, N fertilizer can also promote the growth of relative bacteria (Banger et al., 2012). Therefore, the overall impact of N fertilizers on CH_4 is complex.

Some researchers tried to clarify the overall effect and underlying mechanisms of N fertilizers on CH_4. Banger et al. (2012) analyzed 155 data, of which 98 show that the emission of CH_4 increased after the utilization of N fertilizer. They also found that the change in CH_4 emissions per kilogram of N fertilizer was more significant when fertilizer was below 140 kg/ha. This may be because N fertilizer can also stimulate the activity of methanotrophs, which consume CH_4, especially in cases of intermittent drainage. However, the continuous flood irrigation makes it difficult for methanotrophs to get enough oxygen, limiting their consuming ability; thus, under this circumstance, CH_4 is usually produced more. Furthermore, they noticed that sulfate-based N fertilizer had little impact on CH_4 emission compared to urea-based N fertilizer. This might be because sulfate can consume CH_4 produced, as mentioned in Section 2. Based on a meta-analysis, they concluded that N fertilizer mainly influences CH_4 production through interaction with microbial processes.

Another research by Tang et al. (2023) also proved that fertilizer influences methane production by changing the microorganism structure in the soil. They found that combining chemical fertilizer and organic fertilizer (winter crop straw) increased methane emissions by 34%. This is because of the enrichment of methanogens, which is proved by the increased abundance of *mcrA* genes.

According to Liu and Greaver (2009), 30–400 kg/ha per year of N addition can result in an average CH_4 increase of 95%, and this increase is not related to the form of N. However, they also paid attention to CH_4 uptake and found that the uptake of CH_4 was significantly decreased by NH_4NO_3, NH_4^+, NO_3^-, and urea, whereas urea ammonium nitrate did not have a notable effect.

Except nitrogen fertilizer. There are also studies targeted at other fertilizers, such as iron fertilizer. Wang et al. (2023b) evaluated CH_4 production from rice planted in hydroponic plant microbial fuel cells and found that the form and concentration of iron fertilizer greatly influenced the results The emission of methane decreased for two reasons: first, the iron directly inhibited methanogens; second, the electricity production efficiency was enhanced by iron fertilizer, which consequently decreased the production of CH_4. However, whether iron fertilizer can reduce methane emissions in soil-planted rice is still unclear, and its impacts on rice yields and environmental factors are unknown (Mujtahid Al Hussain et al., 2024).

2.1.5. Water regime

The water regime is a crucial factor influencing the emission of CH_4. It refers to the irrigation situation of not only rice, but also other plants planted on the same land during the non-rice season (Cai et al., 2000). The reason for the influence can be summarized into two major categories. First, the condition of the water regime can heavily influence the oxygen condition. CH_4 is produced by obligate anaerobes (Zhang et al., 2021); thus, the more and the more often a field is flooded, the less oxygen in the soil is likely to be, and the more active those microorganisms are. On the contrary, a thin layer of standing water, or none at all, on paddy soil surfaces allows more oxygen to penetrate the soil. This increased oxygenation converts soil organic carbon into CO_2 instead of CH_4, thereby decreasing CH_4 emissions (Ishfaq et al., 2020). Irrigation water with high oxygen content can also bring oxygen into the rhizosphere zone (Phung et al., 2020).

Second, according to Adhikary et al. (2023), water content in soil can influence phosphorus availability and transformation. Phosphorus is a crucial factor influencing methanotroph abundance, which can oxide CH_4 and thus reduce the relative emission (Veraart et al., 2015).

2.1.6. Elevated CO_2 concentration

It is widely documented that higher levels of atmospheric CO_2 led to increased CH_4 emissions from rice farming (Allen Jr. et al., 2003; Qian et al., 2020; Xu et al., 2004). Elevated CO_2 typically boosts carbon input into rice paddy soils, enhancing rice root growth and promoting root exudate release. This, in turn, stimulates the proliferation of methane-producing microorganisms (Qian et al., 2020).

It has been concluded that most studies have reported an increase of 3.2–60.0% in CH_4 emissions under elevated CO_2 in rice paddies (Wang et al., 2018). However, there are also some exceptions. According to Xu et al. (2004), elevating ambient CO_2 by around 200 mmol/mol increased the CH_4 emission by 78–200%. Allen Jr. et al. (2003) reported a four-fold increase in CH_4 production under elevated CO_2. Wang et al. (2018) found that elevated CO_2 enhanced CH_4 by 19.8–52.6% and 102.4–140.0%.

More and more studies are considering the combined effects of elevated CO_2 and other vital factors such as temperature, straw incorporation, and water management. Qian et al. (2020) found that elevated CO_2 significantly raised CH_4 emissions from paddy fields without straw incorporation but tended to lower CH_4 emissions from those with straw incorporation. This occurs because straw incorporation diminishes the contribution of root exudates to the overall substrate pool, thereby reducing the impact of increased root exudation due to elevated CO_2 on methane-producing microorganisms. Additionally, it has been estimated that elevated CO_2 increases global CH_4 emissions from rice paddies by 3.7%.

Qian et al. (2022) found that elevated CO_2 stimulated CH_4 emissions under continuous flooding by 46%–50%. However, under intermittently flooded conditions, it had no effect. This suggests that increased soil O_2 availability with intermittent flooding can limit methanogenic activity under elevated CO_2.

There are also some opposite conclusions which indicate elevated CO_2 decreases CH_4 production but regarding other plants. Qaderi and Reid (2011) studied the effects of temperature, CO_2 and watering regime on CH_4 emissions from six crops. Their results show that higher temperature and water stress significantly enhance CH_4 emissions, while elevated CO_2 had the opposite effect. It is worth noting that the crops they used are all grown under aerobic conditions rather than anaerobic or hypoxic conditions like rice under flooding. Similar results have been identified by Baggs and Blum (2004). They found elevated CO_2 did not significantly impact net CH_4 emissions when planting Lolium perenne. Musarika et al. (2017) also reported that atmospheric CO_2 concentration did not affect substantially the CH_4 fluxes. But the experimental crop is radish, not rice.

2.1.7. O_2 availability

Oxygen availability critically impacts whether carbon mineralization in soil gives rise to carbon dioxide only or to a mixture of carbon dioxide and methane (Chapman et al., 1996). Rice plants enhance soil ventilation and expand the oxic-anoxic boundary through their root systems, providing essential O_2 to aerobic CH_4-oxidizing bacteria. Consequently, they are crucial in methane oxidation within the rice rhizosphere (Gilbert and Frenzel, 1998; van Bodegom et al., 2001). Higher oxygen availability usually means less CH_4 production. Denier van der Gon and Neue (1996) found that incubation in an atmosphere with higher O_2 levels (40% O_2) than ambient air reduced CH_4 flux, indicating that enhancing oxidation in the rice rhizosphere could help lower CH_4 emissions from rice farming.

2.1.8. Rice cultivar

Many studies have shown that rice cultivars have different CH_4 emission patterns (Jia et al., 2006). Setyanto et al. (2013) concluded that CH_4 flux showed a notable correlation with parameters such as root weight, root length, aboveground biomass, and the number of plant tillers. Gutierrez et al. (2013) demonstrated that CH_4 emissions might depend more on the substrate-producing capacity and gas transport abilities inherent to each cultivar rather than external variables associated with plant growth. Butterbach-Bahl et al. (1997) compared two cultivars and tested their methane production, oxidation, and emission. The results show that methane emissions from one cultivar were 24–31% lower than the other. The reason is that the predominant pathway for methane emission was through plant-mediated transport from the sediment to the atmosphere. Cultivars with lower methane emissions showed notably decreased gas transport capacities through their aerenchyma systems compared to other cultivars. Thus, identifying and adopting high-yield rice cultivars with reduced gas transport capacities offer a cost-effective, environmentally friendly, and promising approach to mitigating methane emissions in rice paddy fields.

2.1.9. Plant growth stage

CH_4 emissions showed a marked increase in the rice-planted treatment compared to the unplanted treatment (Jia et al., 2001), meaning the plant and rice growth have a noticeable influence on CH_4 production. Some research further investigated CH_4 emission patterns at different rice growth stages. It has been reported that CH_4 emission rates from rice paddies have been reported to have one or more maxima during the middle and late periods of rice growth (Watanabe et al., 2001). They also found that the emission of CH_4 during the tillering stage surpassed that observed during the panicle initiation stage. At the rice ripening stage, CH_4 production was improved by approximately 72.3% at the rice ripening stage. This is because rice plants can transport CH_4 from belowground to the atmosphere, and their ability to transport it differs at different stages. Furthermore, it has been approved that the percentage of exudate-derived carbon converted into CH_4 varied from 61% to 83% and showed no variation due to cultivars or growth stages (Aulakh et al., 2001), which further demonstrates that the difference in transporting ability is the key.

2.1.10. Organic amendments

Adding organic amendments to flooded rice soils is required for sustainable agriculture and is encouraged by agriculturists. However, adding organic carbon to the soil, whether from the disposal of crop residues or as organic fertilizer, appears to be an essential factor in methane production (Khosa et al., 2010). Sampanpanish (2012) found that CH_4 emission in the set with adding organic fertilizer at 12.50 t/ha was more than three times that of the set without organic fertilizer. Van der Gon and Neue (1995) found that 11 t/ha of fresh green manure increased CH_4 emissions a lot.

2.1.11. Redox potential

Soil redox potential is one of the main factors controlling CH_4

Table 1
Water management effects on GHGs emissions.

Method	Water use	CH_4 emissions	N_2O emissions	GWP	Rice yields	References
AWD	Reduced by 19–56%	Reduced by 72–100%	Reduced by 12–70%	Reduced by 25–73%	No significant difference	Loaiza et al. (2024)
AWD		Reduced by 35%	\	Reduced about 35%	No obvious changes	Habib et al. (2023)
Incomplete AWD	Reduced by 13.72%	Reduced by 10.62%	Increased by 5.94%	Reduced about 5.32%	Decreased about 9.12%	Sriphirom et al. (2019)
Complete AWD	Reduced by 4.52%	Reduced by 23.1%	Increased by 14.79%	Reduced about 10.83%	Increased about 2.42%	Sriphirom et al. (2019)
AWD	Reduced by 59.9–63.2%	Reduced by 64.9%	Increased by 160%	Decreased by 42.2%	Decreased by 11.6%	Feng et al. (2021)
AWD		Reduced by 87.1%	Increased by 280%	\	No obvious changes	Liao et al. (2020)
MSD		Reduced by 63.4%	Not significantly influenced	Decreased by 59.7%	No obvious changes	Martinez-Eixarch et al. (2022)
MSD		Reduced by 52%	Increased by 242%	Decreased by 47%	No effect	Liu et al. (2019b)
Prolonging MSD	\	Reduced by 69.5%		Reduced by 72%	Slightly reduced by 3.8%	Itoh et al. (2011)
Furrow irrigation	\	Reduced by 34%	Decreased by 23%	Reduced by 30%	Decreased by 6.18%	Timm et al. (2024)
Furrow irrigation	Reduced by 10%	Reduced by 78%	\	\	Increased by 2.5%	Yousefian et al. (2024)
Ridge irrigation		Reduced by 45.6–70.3%	Slightly increased	Reduced by 45.2–61.4	Increased by 11.3–17.6%	Zeng and Li (2021)
Winter drainage	\	Reduced by 62.3%		\		Ji et al. (2022)
sub-irrigation with treated wastewater	\	Reduced by 80%		\	No effect	Phung et al. (2021)
Treated wastewater irrigation		Decreased by 95.6%	Increased by 5–15 times	Slightly decreased by 7%	Higher yield and protein content	Pham et al. (2021)
Treated wastewater continuous sub-irrigation	\	Decreased by 84%	Decreased by 28%	Decreased by 66%	Higher yield and protein content	Phung et al. (2020)

formation. Redox potential measures a substance's likelihood of acquiring electrons, leading to reduction. Environments with high redox potentials, abundant in oxygen, favour oxidation. Conversely, environments with low redox potentials, lacking strong oxidizers like oxygen, are conducive to methane release (Gathorne-Hardy, 2013). The critical soil redox potential for initiation of CH_4 formation is approximately from −150 to −160 mV (Setyanto et al., 2013).

2.2. Influencing factors on N_2O production

2.2.1. Soil pH

Studies have demonstrated that the pH of the soil can have a significant influence on the production of N_2O (Liu et al., 2010; Qu et al., 2014; Raut et al., 2012; Russenes et al., 2016; Zaman et al., 2007). Higher soil pH levels are reported to be associated with lower N_2O emissions. According to Žurovec et al. (2021), N_2O emissions decreased by nearly 39% in limed plots (with higher pH) compared to the unlimited control plots. Two main reasons for the influence are microbial processes and phosphorous availability. Lower pH levels encourage the growth of specific microbial communities that produce N_2O, such as denitrifying bacteria. These bacteria thrive in low-pH environments and contribute to N_2O emissions (Simek and Cooper, 2002). More specifically, such influence of denitrifying communities is defined as distal control, while the influence on denitrifying enzyme activity (DEA) caused by pH is defined as proximal control. According to (Cuhel and Simek, 2011), proximal control is the primary way pH influences N_2O emissions. Bakken et al. (2012) also reported that the synthesis of the N_2O reductase enzyme was hindered at lower pH values.

Additionally, soil pH is linked to the availability of soil phosphorus. Phosphorus is an essential nutrient for plant growth. Soil pH affects the solubility and availability of phosphorus to plants, which is also related to N_2O emissions and will be explained more specifically in the later part (Mori et al., 2013; Žurovec et al., 2021).

2.2.2. Soil phosphorous

Soil phosphorous is reported to influence N_2O by affecting the activity of related fungi. When soil P levels are low, certain fungi, such as arbuscular mycorrhizal fungi (AMF), become more abundant. AMF can reduce N_2O emissions through a symbiotic relationship with plants (Storer et al., 2018). They help plants with nitrogen (N) uptake, which can decrease the availability of N in the Soil for N_2O production. On the other hand, other soil fungi are also present in the soil and can be a significant source of N_2O. This is primarily because these fungi lack the N_2O reductase enzyme. N_2O reductase is an enzyme that can convert N_2O to harmless nitrogen gas (N_2). Without this enzyme, the soil fungi may contribute to the accumulation of N_2O, thereby increasing N_2O emissions (Randall et al., 2019).

Other studies further explored the influence of phosphorous combined with carbon availability on N_2O production. O'Neill et al. (2020) found that when there was a limited supply of C in the Soil, adding more P didn't significantly affect the N_2O emissions. However, when they said more C, they noticed that soils with substantial phosphorus had substantially higher cumulative N_2O emissions than soils with high phosphorus. In other words, soil under conditions with plenty of carbon, the phosphorus level in the soil has a noticeable impact on soil emissions.

2.2.3. Nitrogen fertiliser

The influence of nitrogen fertilizer on N_2O emissions is significantly correlated with the amount of fertilizer. According to Tang et al. (2018), there is a manifest positive correlation between emissions and fertilizer rates. A higher amount of fertilizer means a higher amount of N_2O emissions. This is because over-applied nitrogen fertilizer can lead to acidification of soils, which is responsible for increased N_2O (Qu et al., 2014; Raut et al., 2012). More specifically, the translation/assembly of N_2O reductase is more sensitive to low pH than the other reductases involved in denitrification (Liu et al., 2010).

Apart from the amount of nitrogen fertilizer applied, the form of fertilizer also matters, such as urea, ammonia, deep placement of urea, coating fertilizer. Ammonia is usually thought to lead to more N_2O emissions than urea. However, more studies regarding this need to be done (Linquist et al., 2012). Deep placement of urea is widely proven to be sufficient for reducing N_2O emissions (Gaihre et al., 2020; Yao et al., 2017). Gaihre et al. (2015) found that urea deep placement can significantly decrease the emission of N_2O compared to broadcast urea. Urea deep placement at 7–10 cm reduced N_2O emissions by 61%–84% compared to spreading it on the surface. This method keeps nitrogen in

NH_4^+ form, preventing it from quickly reaching the soil surface or floodwater. As a result, there's less nitrogen available in the most active soil zone, where it could otherwise turn into N_2O through specific processes.

Apart from deep placement, coating fertilizer is another way to reduce the speed of N release and increase N utilization efficiency, thus reducing N_2O emissions (Bordoloi et al., 2016). Bordoloi et al. (2020) reduced N_2O emissions by 12% %- 21% through coated fertilizer without affecting soil quality and nutrient status.

2.2.4. Soil moisture

Under the premise that enough and suitable N source is provided, soil moisture enhances the production of N_2O (Hussain et al., 2015). This is because there is more accessible access to N to produce N_2O than in dry Soil. It has been approved by Li et al. (2024) that N_2O emissions increased exponentially with soil moisture. Wei et al. (2022) also reported that when soil moisture was >70% water-filled pore space (WFPS), N_2O was the primary form of soil nitrogen loss. This influence is unrelated to microbial community exchanges because there are no significant differences in the denitrification and nitrification-related functional gene abundances in moisture and dry Soil (Ding et al., 2024).

3. Mitigate GHGs production: approach and management

Promising mitigation approaches and management methods include water management, fertilizer management, biochar application, modified planting meth rice cultivars, straw management, new energy machines, etc. These methods can reduce emissions by changing the microbial structures of the soil, the pathway of gas transportation, and the amount of substrate used to produce GHGs.

3.1. Water management

Efficient water management techniques in rice cultivation are essential to determining agricultural output and environmental results. How water management practices influence GHGs emissions, rice yields, and ecological sustainability is crucial for rice cultivation. Timing of water management during both the fallow and growing seasons, the application of treated wastewater, and the trade-off between CH_4 and N_2O emissions are all factors the previous studies have considered and need further exploration.

Alternate wetting and drying (AWD), mid-season drainage (MSD), furrow-irrigation, and winter drainage (or fallow period drainage) are commonly used water management methods. The widely studied water management methods are listed in Table 1 (all the results are compared with continuous flooding). AWD is usually performed by letting the water soil decrease below the surface by 5–15 cm and then rinsing. The reduction of CH_4 by AWD is evident, from 10.62% to almost 100% (Loaiza et al., 2024; Sriphirom et al., 2019). However, as for N_2O, some reported that it decreased (Loaiza et al., 2024; Phung et al., 2020), while for most research, it increased (Feng et al., 2021; Liao et al., 2020; Pham et al., 2021; Sriphirom et al., 2019; Liu et al., 2019b). AWD is also a suitable method because it can save irrigation water. From Table 1, we can see that AWD saved water by 4.52%–63.2%. It is essential that management methods can maintain the rice yield. Sriphirom et al. (2019) and Feng et al. (2021) reported slightly decreased rice yield, while others found it remained the same or slightly increased.

AWD effectively reduces CH_4 emissions because the water situation heavily influences the oxygen condition in the soil, which is a crucial parameter of CH_4 emission. AWD can introduce more oxygen to the soil to alleviate the anaerobic condition (Liao et al., 2021). On the other hand, soil is reported that AWD could also delay following CH_4 production when soils are re-flooded because of the increased sulfate and ferric iron. However, the potential increase of N_2O due to flooding and drying circles is a notable problem of these methods (Loaiza et al., 2024). This is because N_2O can be further reduced into N_2 under continuous flooding, and AWD can provide enough oxygen to the nitrification process, which is the basis for producing N_2O through denitrification. Another reason is that AWD can improve soil aeration and make it easier for N_2O to transfer into the atmosphere (Feng et al., 2021). Luckily, although N_2O emissions went up, the total impact on global warming was still lower with AWD compared to continuous flooding, reducing GHGs emissions by around 5.32–73%.

Some studies also reported that AWD decreased N_2O production (Loaiza et al., 2024). AWD can consistently reduce the amount of soil available P (Adhikary et al., 2023). As mentioned before, lower soil P can decrease the emissions of N_2O because of the change in microbial activity.

However, due to rainfall, AWD can be challenging to perform and maintain due to rains. Incomplete AWD caused by rainfall may reduce the effectiveness of reducing methane emissions (Sriphirom et al., 2019). Thus, it is essential to comprehensively investigate and consider the rainfall conditions in the target area before applying such measures.

Apart from rainfall conditions, the side effect of water management, especially AWD, including the reduction of rice yields, is another essential thing to consider. Although lots of studies have stated that the rice yields were not affected, it can be seen from the results that water management can lead to a relatively lower production (Loaiza et al., 2024). However, some studies pointed out that AWD could provide more oxygen for the roots area, increasing soil fertility and thus leading to higher production (Oo et al., 2018). Some researchers mention rice cultivars to overcome this shortcoming. The combination of AWD and drought-resistant rice cultivars can simultaneously reduce the production and GHGs and exhibit a significant advantage in terms of both water-use efficiency and rice yield (Feng et al., 2021; Zhang et al., 2021)

Another water management method is MSD. It is often considered a more targeted approach than continuous flooding or AWD. The mid-season rice stage requires much lower soil moisture than other growth stages (Liao et al., 2020). Thus, MSD specifically means removing all surface water from the rice crop at mid to late tillering for 7–14 days. The effect of MSD relies heavily on the time of drainage.

While most research focused on water management during the cultivation period of rice, water management in the fallow season is also essential. Sander et al. (2014) explored different water methods before planting in the fallow period. Some fields were flooded, some were left to dry, and some had a mix. The results showed that flooded fields produced the most CH_4. Dry fields made less gas. Winter drainage is another management method that can be studied in mountain areas without irrigation. These areas usually use winter flooding to store water for the next season. Winter drainage can not only reduce CH_4 emissions in the current fallow season and can also inhibit CH_4 emissions in the following farming seasons. This is because winter drainage decreased the content of methanogenic archaea (Ji et al., 2022).

Ridge or furrow irrigation is a water-conserving method used in paddy fields (Zeng and Li, 2021). The ridge-furrow irrigation system facilitates proper soil surface drainage and crop irrigation, reducing the risk of damage from excess water in low-lying areas. Rice grown using this method may need less water overall while still maintaining high grain yields, thus improving the efficiency of water usage per unit of grain produced (Massey et al., 2014; Timm et al., 2024). Furthermore, in ridge irrigation fields, rice plants develop deeper root systems with increased root volume and greater capacity for nutrient absorption compared to those grown in conventionally irrigated fields (Mitchell et al., 2013).

It is widely reported to be a water-saving and greenhouse gas-reducing irrigation method. According to Timm et al. (2024), ridge-furrow irrigation decreased CH_4 emission, N_2O emission and GWP by 34%, 23% and 30%, respectively. Yousefian et al. (2024) compared furrow irrigation and continuous flooding and found that furrow irrigation decreased methane emissions by 78% and increased water efficiency. Zeng and Li (2021) found that ridge irrigation decreased CH_4 emissions by 45.6–70.3%. Meanwhile, the yield of rice was improved.

Table 2
Fertilizer management effects on GHGs emissions.

Method	CH_4 emissions	N_2O emissions	GWP	References
Changing from chemical fertilizer to organic manure	Increased by 137%	Reduced by 28.34%	Increased by 219.31%	Zhao et al. (2015)
Changing from chemical fertilizer to combination of organic manure	Increased by 310%	Reduced by 69.41%	Increased by 97.51%	Zhao et al. (2015)
Changing from integrated plant nutrient system to prilled urea	Reduced by 2%–6%	Reduced by 7.5%–20%	Reduced by 2%–7.4%	Islam et al. (2022)
Changing from integrated plant nutrient system to urea deep placement	Reduced by 11%–15%	Reduced by 6.6%–52.5%	Reduced by 11.45%–14.75%	Islam et al. (2022)
Application of 150 compared to no	Reduced by 16.6%–44.9%	/	Reduced by 15.09%–43.76%	Mboyerwa et al. (2022)
Deep placement of urea briquette	Reduced by 38%	Reduced by 54%–67%	Reduced by 31%	Islam et al. (2024)
Coated controlled-release urea	Reduced by 20.98%	Reduced by 74.41%	Reduced by 22.91%	Ming et al. (2024)
Vermicompost	Reduced by 13%–19%	Reduced by 4%–9%	Reduced by 13%–17%	Haque and Biswas (2021)

The decrease in CH_4 emissions from paddy fields could be attributed to reduced physiological activity and CH_4 transport capacity in rice plants as they progress from the late tillering stage to the milking stage. Increased oxygen diffusion into the soil leads to CH_4 oxidation before releasing it into the atmosphere. Additionally, rice plants naturally close their leaf stomata to conserve water during periods of low field moisture or drying, limiting CH_4 emission (Zeng and Li, 2021). Since furrow irrigation of rice is intermittent, there is no continuous water coverage, leading to increased soil aeration and the absence of anaerobic conditions favoured by methane-producing bacteria. This reduces the conditions conducive to significant CH_4 emissions in rice irrigation (Kögel-Knabner et al., 2010).

Apart from managing irrigation water, many researchers have devised the idea of using wastewater in rice cultivation. Using treated wastewater for irrigation is a promising approach to rice cultivation, which can simultaneously reduce the use of nitrogen fertilizer and inhibit the production of CH_4 while maintaining the rice yield. Phung et al. (2021) investigated the effectiveness of continuous sub-irrigation with treated wastewater to recycle and grow protein-rich rice. They found that even without using fertilizers, the system produced as much rice as usual but reduced CH_4 emissions from the rice fields by 80%. Pham et al. (2021) found that treated wastewater irrigation can lead to impressive rice production and quality, significantly reducing CH_{4c} emissions by up to 95.6%.

The top challenge of water management is that as most of the rice is grown by individual farmers, it's difficult to persuade them to adopt these more complicated processes, as this does not earn them any visible profits. Thus, more policies should be implemented to encourage farmers.

3.2. Fertilizer management

The worldwide consumption of fertilizers was about 172.2 million metric tons, among which approximately 14.3% was applied to rice cultivation, including nitrogen fertilizer, sulfate fertilizer, farmyard manure, and green manure, etc. (Chauhan et al., 2017). Merely one-third of the nitrogen fertilizer applied is effectively absorbed by the rice crop. The remaining two-thirds is mostly released into the environment through processes such as ammonia volatilization, denitrification, as well as leaching, and surface runoff, and a small portion is immobilized by soil organisms (Chauhan et al., 2017).

Fertilizers can influence the emission of GHGs in various ways at different levels. First, at the ecosystem level, fertilizer can increase plant growth. The growth of plants contributes to increased carbon availability for methanogens and provides a more significant pathway through aerenchyma cells for CH_4 transport from the soil to the atmosphere. Additionally, NH_4^+ inhibits CH_4 consumption at the biochemical level, possibly because of similarities in size and structure between CH_4 and NH_4^+. This leads to CH_4 monooxygenase binding and reacting with NH_4^+ instead of CH_4. Furthermore, N fertilization enhances the growth and activity of CH_4-oxidizing bacteria (methanotrophs), ultimately reducing emissions (Zhong et al., 2016).

Fertilizer management regarding reducing the emission of GHGs during rice cultivation can be classified into two aspects. One is studying the relationship between fertilizer amount and GHGs production and thus controlling the amount of fertilizer supplied. Another is fertilizer modification or developing new types of fertilizers. These different methods are listed in Table 2.

As for the amount of fertilizer used, Linquist et al. (2012) divided the usage into three categories: low, moderate, and high. Different amounts have different effects. With low nitrogen levels (around 79 kg N/ha), CH_4 emissions increased by 18%. At moderate levels, nitrogen didn't affect CH_4 emissions much, but with high levels (about 249 kg N/ha), CH_4 emissions dropped by 15%. N_2O emissions increased as nitrogen levels went up. More specifically, N_2O emissions increased by 162.5% when fertilizer was increased from low to high.

Zhong et al. (2016) also investigated the influence of different nitrogen fertilizer rates. They suggested that the optimal rate of fertilizer was 225 kg N/ha. However, this may vary depending on weather conditions and geological conditions.

Wang et al. (2024) found that after five years of N fertilizer reduced application, the NO_3^--N content in soil was 32% lower than the control group, which indicates that the application of N fertilizer control could have a long and profound effect. This is because the proportion of N transformed relative microorganisms, leading to a reduced emission of N_2O. However, Snyder et al. (2009) suggested that simply reducing the amount of applied nitrogen is not advisable because applying less than the optimal amount can deplete soil organic carbon and reduce long-term soil productivity. Maintaining high soil productivity supports efficient crop production, lowering GHGs emissions and reducing the need to convert natural forests, grasslands, and wetlands for agriculture to meet global food demands.

Modified fertilizers have been studied more regarding reducing GHGs, including organic manure (Zhao et al., 2015), deep placement of urea briquette (Islam et al., 2024; Linquist et al., 2012), enhanced-efficiency nitrogen fertilizer (Ming et al., 2024), vermicompost (Haque and Biswas, 2021), nitrogen inhibitors and application of dicyandiamide (Linquist et al., 2012).

N_2O and CH_4 may respond differently to changes in fertilizer composition. For example, Zhao et al. (2015) found that the application of organic manure significantly decreased N_2O emission by 28.34%–69.41% while increasing the emission of CH_4 by 137%–310%, resulting in a significant increase in GWP from 97.51% to 219.31%. Hussain et al. (2022) found that N_2O release rose to 24%, and CH_4 emission decreased to 40% when ammonium sulfate was applied instead of urea.

As for deep placement of urea briquette, it is reported to reduce GWP and methane emissions by 31% and 38% respectively and reduce N_2O production by 54%–67% (Islam et al., 2024). Because deep placement of urea briquette can keep the NH_4^+-N available for a long time, which is good for the growth of soil methanotrophs. Meanwhile, the use of deep placement of urea briquette can boost the growth of rice root, which can increase the oxygen level in the root area. For the emission of N_2O, it is also suggested that the deep place of fertilizer reduces the amount of

Table 3
Effect of biochar applications.

Method	CH_4 emissions	N_2O emissions	GWP	References
biochar + continuous flooding	Decreased by 18.8%	Decreased by 35.1%	Decreased by 22.4%	Shen et al. (2024)
biochar + AWD	Increased by 20.5%	Decreased by 27.0%	Increased by 18.3%	Shen et al. (2024)
biochar + MSD	Increased by 145.7%	Decreased by 27.0%	Decreased by 5.5%	Shen et al. (2024)
high biochar with medium fertilizer	Decreased CH_4 by 82%		\	Iboko et al. (2023)
low biochar with low fertilizer	Increased by 114%	\	\	Iboko et al. (2023)
high biochar combined with low fertilizer	\	Decreased by 91 %	\	Iboko et al. (2023)
medium biochar and high fertilizer	\	Increased by 82%	\	Iboko et al. (2023)
biochar	Decreased by 30.37%	Decreased by 55.2%–72.9%	\	Qi et al. (2020)

NH_4^+-N in the oxide area, thus less NO_3^- is produced, leading to the reduction of nitrous oxide (Akter et al., 2022).

Enhanced-efficiency nitrogen fertilizer is another hot research topic. Excess NH_4^+ induced by nitrogen fertilizer is thought to be an inhibitor for CH_4 oxidation, while enhanced-efficiency nitrogen fertilizer can reduce this effect because it can regulate the uptake of NH_4^+ by crops. The results of Ming et al. (2024) show that the utilization of enhanced-efficiency nitrogen fertilizer (nitrogen inhibitor and coated controlled-release urea) decreased CH_4 emissions by 24%–25.3%.

Vermicompost is a kind of new environmentally friendly fertilizer. Vermicompost led to substantial reductions in CH_4, CO_2, and N_2O emissions of 13–19%, 17–21%, and 4–9%, respectively (Haque and Biswas, 2021). These reductions were accompanied by lowered GHGs emission factors, which decreased by 8–17%, and a decreased GWP of 13–17% when compared to the use of cow dung (Haque and Biswas, 2021).

Nitrogen inhibitors has been reported to lower emissions of both CH_4 and N_2O (Linquist et al., 2012; Zhang et al., 2018). This is partly because nitrification inhibitors are capable of inhibiting the microbial enzymes responsible for the transformation of NH_4^+-N into NO_3^-N (Upadhyay et al., 2011). However, it is important to note that nitrification inhibitors can also promote NH_3 volatilization because nitrification inhibitors can lead to the accumulation of NH_4^+ in water (Lam et al., 2017; Xia et al., 2017). The reduction of direct N_2O emissions by nitrification inhibitors may be counteracted by the indirect N_2O emissions brought on by NH_3 deposition (Denier van der Gon and Bleeker, 2005; Lam et al., 2017). As an alternative approach, root zone fertilization appears to be feasible, and this is usually simplified applied for just one time and can result in mitigating production while optimizing rice yield. This is achieved through the improved retention of NH_4^+.

Other practices, such as water irrigation, also influence the effectiveness of fertilizer management. Islam et al. (2022) compared four fertilizer management methods, including urea deep placement, integrated plant nutrient system, prilled urea and no fertilizer under two water irrigation methods, which are AWD and continuous flooding, and found that prilled urea can reduce the emission of N_2O compared to integrated plant nutrient system under AWD while resulting the same emissions in constant flooding. Urea deep placement can significantly reduce CH_4 emissions by 15% compared to integrated plant nutrient systems under AWD, while only reduced by 11% under continuous flooding. Therefore, when considering reducing GHGs emissions through fertilizer management, paying attention to other significant factors that impact GHGs emissions is essential.

3.3. Biochar application

Biochar is formed from organic matter residues that mainly come from the agricultural sector, such as rice straw. These organic residues are burned to form a charcoal-like substance, and that is biochar. Biochar is a hot topic regarding its ability to mitigate global warming (Lehmann et al., 2021; Wang et al., 2023a). Biochar can improve soil adsorption capability, which can increase soil nutrient content via decreasing leaching. Furthermore, biochar can also influence other properties of soil, such as pH, microbial structure, and porosity etc (Singh et al., 2024).

It has been widely reported that the application of biochar can reduce the production of CH_4 and N_2O as listed in Table 3. According to Qi et al. (2020), the application of biochar decreased CH_4 and N_2O by 30.37% and 55.2%–72.9% respectively. The co-effect of biochar and other mitigation methods were also widely investigated. For example, the combination of AWD or MSD can more effectively reduce CH_4 emissions than biochar alone. However, N_2O emissions were higher than biochar applied under continuous flooding conditions (Shen et al., 2024). The effect of co-application of biochar and fertilizer has also been widely studied. The effect on GHGs emissions varied with the different amounts of biochar and fertilizer applied. According to Iboko et al. (2023), a high amount of biochar combined with a medium amount of fertilizer is the best combination to decrease CH_4 emission, while a lower amount of biochar and fertilizer would stimulate the emission. Increased biochar application rates could also decrease the emissions of N_2O under a certain amount of fertilizer.

The potential mechanism is that the increased soil pH induced by biochar can lead to the prosperity of methanotrophs, thus reducing the emission of CH_4 (Iboko et al., 2023). For the reduction of N_2O, the reason is that biochar could effectively increase *nosZ* gene copies (Shen et al., 2024). *NosZ* gene is more likely to co-occur with *nirS*, which is a symbol of stronger and more complete denitrification. Therefore, N_2O is consumed more thoroughly by the denitrification process (Graf et al., 2014).

Wang et al. (2023a) analyzed results from other articles and came up with the conclusion that returning straw as biochar has great potential to reduce CH_4 emissions, a reduction that is equivalent to 10% of the total decrease in all anthropogenic emissions.

Although it is reported that biochar can reduce GHGs emissions effectively, the production process of biochar can contain large amounts of GHGs emissions. The trade-off needs to be considered from a more comprehensive view such as LCA methodology. Also, the effective role of biochar is based on a relatively large amount of use, which is a burden economically. The production line of biochar needs to be improved to lower the dosage (Singh et al., 2024).

3.4. Cultivar selection

Rice forms and textures are commonly used to categorize different varieties. With more than 100,000 rice accessions, the International Rice Research Institute has the most extensive collection of rice cultivars. Gnanamanickam (2009) has pointed out that the potentials for the future include rice improvement towards nutrition, such as improving vitamin A deficiency and improving iron deficiency in rice. Selecting or genetic coding of GHGs reduction in rice cultivars is also a future focus.

Among various related studies, drought-resistant rice has attracted a lot of attention. This novel rice variety is known as a water-saving and drought-resistant rice. It exhibits exceptional water use efficiency and strong resilience to drought. According to Xia et al. (2022), from 2000 to 2022, at least 22 water-saving and drought-resistant rice varieties have been developed and granted national and/or local certifications after rigorous field tests. Remarkably, water-saving and drought-resistant rice can be cultivated using dry farming techniques, which benefits upland

Table 4
Rice cultivar effects on GHGs emissions.

Rice cultivar	CH_4 emissions	N_2O emissions	GWP	References
Water saving and drought resistant rice 7Y88 and 7Y370	Reduced by 8.5%–10.51	Reduced by 11.17%–13.76%	Reduced by 10.66%–13.13%	Feng et al. (2021)
Water saving and drought resistant rice	Reduced to zero	Increased by 7.6%	Decreased by 95%	Zhang et al. (2022a)
Water saving and drought resistant rice Hanyou 73	Reduced by 8.2%–21.64%	Reduced by 20.69%–76.56%	Reduced by 11.48%–20.83%	Zhang et al. (2023)
Binadhan-17	Reduced by 27.78%	/	Reduced by 27.78%	Habib et al. (2023)
Oryza sativa L. cv. Huayou 14	Reduced by 42.98%–62.13%	/	/	Sun et al. (2016)
Rice cultivated with *Azoarcus* sp. KH32C	Reduced by 17.2% and 23.5%	/		Sakoda et al. (2022)

crops. The influence of water-saving and drought-resistance rice is listed in Table 4. It is reported that drought water-saving and drought resistance rice can reduce CH_4 and N_2O emission by 8.2%–100%, 7.6%–76.56%, respectively, and reduce GWP by 10.66%–95% (Feng et al., 2021; Habib et al., 2023; Sun et al., 2016; Zhang et al., 2022a, 2023).

Other types of rice are not strictly classified into drought-resistant rice. Hu et al. (2023) used gas chromatography to analyze the relationship between CH_4 emissions and 22 distinct rice genotypes. The study identified the northern Chinese cultivar Heijing Five as a low-CH_4 rice variety.

New research has also explored inoculating rice seeds with certain kinds of bacteria to achieve GHGs reduction. In a study by Sakoda et al. (2022), they introduced the bacterium *Azoarcus* sp. KH32C to rice seeds, resulting in a notable alteration of the bacterial community composition in the soil associated with rice roots. Rice cultivated with KH32C vaccination led to the decrease of soil methanogens and methanotrophs, leading to 17.2% and 23.5% reduction of CH_4 under non-fertilized and nitrogen-fertilized circumstances, respectively. Amazingly, these advantages were obtained without sacrificing rice grain output. Others also reported that rice variety affiliated with bacterium induced a lower N_2O emissions (Gao et al., 2017).

3.5. Modified planting methods

Different planting methods, such as direct seeding rice and no tillage have been explored and analyzed to reduce GHGs emissions and maintain rice yield. When rice is planted directly in the field instead of transplanting seedlings from a nursery, it is called "direct seeding" (Susilawati et al., 2019). No tillage generally means a set of practices that leave at most of the soil surface virtually undisturbed (Gangopadhyay et al., 2023). These methods generally decrease CH_4 emissions by 14.51%–81.82%, while sometimes increase N_2O emissions (Grohs et al., 2024; Pathak et al., 2013).

Pathak et al. (2013) assessed the potential of direct seeded rice in mitigating GHGs emissions and conserving water and labour resources compared to transplanted rice. Based on their results, it is estimated that the GWP will be reduced by 30% if the whole area is transferred into direct seeding of rice. Ahmad et al. (2009) further explored the influence of different tillage systems on direct seeding rice. No-tillage significantly reduced CH_4 emissions and GWP by 28% and 12%, respectively. However, it had no significant effect on N_2O emissions.

Hobbs et al. (2008) also points out that no-tillage is an effective way to reduce the emissions. When applying the no-till method, it is essential to pay attention to the amount of straw left in the soil because it has been reported to significantly influence the effect of planting methods. It is noted by Grohs et al. (2024) that the straw remaining in the soil of no-till area increased the availability of C for methanogenesis, thus affecting the performance of no-till.

The reason for this might be that in the conventional planting method, there can be soil disturbance near rice sowing in the traditional method of planting, increasing the possibility of organic matter being degraded by methanogenesis. On the contrary, direct seeding can increase soil density, which can partly stop emissions from the soil to the atmosphere (Farooq et al., 2011; Liu et al., 2024).

In addition to no-till, changing the crop rotation and using plastic film can also effectively mitigate GHGs emissions (Xu et al., 2023). Tran et al. (2023) using a sesame rotation in rice-based farming reduced CH_4 and N_2O emissions by 30.5% and 18.7%, respectively. Ji et al. (2022) found that plastic film mulching cultivation substantially mitigated CH_4 emissions by 59.2%. Mitigation is related to controlling the microbial structure of methanogenic bacteria and other bacterial communities in paddy soil. Similar findings have been made by another study, which shows that adding a mineral cover layer dramatically reduces the annual emissions of GHGs (Wust-Galley et al., 2023).

3.6. Straw management

The utilization of rice straw includes open burning, soil incorporation, direct combustion for electricity generation, producing bioenergy, etc. (Yodkhum et al., 2018). In most countries, rice straws are usually burned after cultivation, which induces environmental problems such as GHGs emissions and particulate matter formation (Singh et al., 2021). Meanwhile, the transportation of rice straw can be another source of GHGs (da Silva et al., 2021).

Among these ways, open burning of rice straw resulted in the highest GHGs emissions. It is reported that more than 100 million tonnes of rice straw are being burnt yearly worldwide (Singh et al., 2024). In contrast, soil incorporation is considered more environmentally friendly and popular in most areas because of its easy operation and ability to increase soil carbon. However, this method will likely increase GHGs emissions. According to He et al. (2024), although straw return can significantly lower the emission of N_2O, the benefits were fully counteracted by significant increase in CO_2 and CH_4. The reason might be that methanogens can have more substrate to survive on and convert into CH_4 and CO_2. According to Hou et al. (2013), the emission of CH_4 increased from 185% to 289% with straw continuous return. To solve this problem, Jumat et al. (2023) decomposed rice straw with a microbial substrate for one week before the straw was returned to the soil and found that CH_4 emission was reduced in this way. Ma et al. (2009) pointed out that ditch mulching of rice straw can decrease CH_4 emissions compared to soil incorporation. Apart from this, postponing the time of straw incorporation also leads to lower CH_4 emissions (Belenguer-Manzanedo et al., 2022). Delay the time for straw incorporation means lower soil temperatures, reducing methanogenic bacteria's activity. However, from a long-term perspective, this only temporarily alleviates methane emissions.

Turning rice straw into value-added products is another hot topic. Most researchers focused on utilizing rice straw to produce bioenergy, biochemicals, and other bioproducts, and there are also other applications, such as nanomaterials and the development of low-silica rice through molecular breeding and genetic engineering (Singh et al., 2024). Singh et al. (2016) studied the utilization of rice straw in bio-ethanol production, and they found that the GHGs emitted are significantly lower than those from the direct burning of rice straws. However, during bio-ethanol production, GHGs can be emitted from transporting straw and using chemicals and enzymes, by-product combustion, and ethanol burning as fuel. Thus, a more comprehensive comparison should be made.

Another management way of rice straw is to help remove nitrogen in

Table 5
Cultivation methods effect on GHGs emissions.

Method	CH_4 emissions	N_2O emissions	GWP	References
Direct seeding	Reduced by 81.82%	Increased by 50.00%	Reduced by 34.38%	Pathak et al. (2013)
No tillage	Reduced by 21.65%–22.34%	Increased by 28.46%–32.21%	Reduced by 10.19%–12.89%	Ahmad et al. (2009)
No tillage	Reduced by 14.51%	Increased by 109.60%	/	Grohs et al. (2024)
sesame-rice rotation	Reduced by 30.5%	Reduced by 18.7%	Reduced by 20.6%	Tran et al. (2023)
plastic film mulching cultivation	Reduced by 59.16%	/	/	Ji et al. (2022)
Direct seeding	Reduced by 16%–54%	/	/	Corton et al. (2000)

wastewater. Zhang et al. (2019) found that using rice straw increased N_2O emissions by 131.5% in low-strength wastewater treatment, but it reduced N_2O emissions by 37.2–43.7% in medium and high-strength treatments compared to not using rice straw (Zhang et al., 2019). The influence of straw management on GHGs emissions is listed in Table 6.

3.7. New energy machine

Nowadays, agriculture heavily relies on fossil fuels energy. From this perspective, it can be described as a technology that converts fossil fuels into food (Bardi et al., 2013). According to Elsoragaby et al. (2019), due to the use of fuel in the rice production process, the GHGs emissions from this source account for 13.92% of the total GHGs emissions in rice production due to the use of fuel in the rice production process. As technology continues to develop and become more affordable and accessible, energy-efficient machinery will probably be used more often in agriculture, reducing GHGs emissions simultaneously. These new energy machines include electric tractors, solar-powered equipment, autonomous machinery, energy-efficient irrigation, biogas generators that can produce electricity from organic waste, and so on—invented a piece of machinery capable of ploughing, soil block crushing, topsoil mulching, and sowing tasks (Kar et al., 2023). According to their results, the application of this innovative machine led to a notable reduction in direct energy consumption, amounting to a 33.5% decrease (Apazhev et al., 2019). However, the practical applications need to consider the size and type of the farm, as well as the availability of infrastructure and incentives.

Furthermore, evaluating the life cycle emission from this new energy machine is essential. Emissions from the manufacturing and production processes, energy-generating processes, maintenance, and end-of-life disposal must be considered. Meanwhile, a more effective and precise approach for measuring the emissions should be developed (Ouyang et al., 2023).

4. Future perspectives

Adopting a comprehensive strategy incorporating co-management techniques for carbon, nitrogen, and water is essential to address the challenges associated with GHGs emissions in rice cultivation. The combination of these strategies holds great promise in mitigating the potential for global warming. Moving forward, combining advanced modelling techniques with survey methods is the most efficient and economical way to gather data and monitor emissions. This approach can encompass data collection through various means, such as remote sensing, crowd-sourcing, and direct measurements. Establishing sturdy monitoring systems can be facilitated using trustworthy soil emission data. Such systems play a pivotal role in designing and implementing mitigation programs. They may also play a crucial role in guaranteeing the achievement of set mitigation goals.

Apart from technologies and management methods, policy is another thing that should be focused on in the future, such as how to educate farmers and encourage them to adopt those complicated and not-for-profit-based methods. A comprehensive inventory system of countries is also essential; thus, the monitoring can be more accurate with the highest precision.

Another aspect that demands particular attention in future research and agricultural practices is the emissions within the water network of rice cultivation. Achieving significant reductions in GHGs emissions requires an understanding of the emissions within the complex systems of rice fields and associated water networks.

5. Conclusion

The cultivation of rice gives rise to the emission of CH_4 and N_2O. These two potent greenhouse gases have notable global warming potential. It is essential to address this environmental challenge while maintaining rice yields. Two significant directions explore technical approaches and management strategies, including water management, fertilizer management, biochar application, cultivar selection, straw management, modified planting methods, and integration of new energy machinery. These technical approaches and management strategies can contribute significantly to achieving reducing emissions and, at the same time, maintaining optimal rice yields. However, future studies also should pay more attention to the synergistic integration of these diverse methods and management approaches to achieve more effective results.

CRediT authorship contribution statement

Yang Chen: Writing – original draft, Resources, Formal analysis, Data curation, Conceptualization. **Wenshan Guo:** Writing – review & editing, Supervision, Resources, Formal analysis. **Huu Hao Ngo:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Wei Wei:** Resources, Formal analysis, Conceptualization. **An Ding:** Resources, Methodology, Formal analysis, Data curation. **Bingjie Ni:** Writing – review & editing, Resources. **Ngoc Bich Hoang:** Resources, Formal analysis, Data curation. **Huiying Zhang:** Writing – review & editing, Resources, Project administration, Conceptualization.

Declaration of Competing interest

All the authors have read the manuscript and agreed to submit to this journal. We confirm the work has not been published before and is not being submitted to any other journal for publication. The authors declare that they have no conflict of interest.

Table 6
Straw management effects on GHGs emissions.

Methods	CH_4 emissions	N_2O emissions	GWP	References
straw incorporation	/	/	Reduced by 31%	Gummert et al. (2020)
removing rice straw in flooded rice	/	/	Reduced by 45%	Gummert et al. (2020)
complete straw removal	Reduced by 35.38%–83.08%	Reduced by 26.3%–50%	Reduced by 56.75%	Romasanta et al. (2017)
Application of rice straw	/	Reduced by 16.20%–31.40%	/	Rassaei (2023)
late straw incorporation	/		Reduced by 206%	Belenguer-Manzanedo et al. (2022)

Data availability

Data will be made available on request.

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