Received: 15 June 2024 | Accepted: 14 October 2024

DOI: 10.1002/sae2.70012

Global Initiative of Sustainable Agriculture and Environment
Harnessing Natural Resources

REVIEW ARTICLE

Advancing effective methods for mitigating greenhouse gas emissions from rice (*Oryza sativa* L.) fields

Shubh Pravat Singh Yadav[1] | Netra Prasad Ghimire[1] | Prava Paudel[1] | Dipesh Kumar Mehata[1] | Sangita Bhujel[2]

[1]Faculty of Science and Technology, G. P. Koirala College of Agriculture and Research Center, Purbanchal University, Gothgaun, Morang, Nepal

[2]Department of Plant Breeding, G. P. Koirala College of Agriculture and Research Center, Purbanchal University, Gothgaun, Morang, Nepal

Correspondence
Shubh Pravat Singh Yadav, Faculty of Science and Technology, G. P. Koirala College of Agriculture and Research Center, Purbanchal University, Gothgaun, Morang, Nepal.
Email: sushantpy8500@gmail.com

Funding information
None

Abstract

The implications of global warming present significant threats to both crop productivity and environmental sustainability. The global population greatly depends on rice as a staple food, contributing significantly to global warming and agricultural greenhouse gas (GHG) emissions. Agricultural soils play a crucial role in the release and uptake of essential GHGs, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), serving as both sources and sinks within the agricultural ecosystem. Notably, rice fields alone account for approximately 30% and 11% of global CH_4 and N_2O emissions from agricultural activities, respectively. As the demand for rice is expected to rise in the future, it becomes increasingly critical to address GHG emissions and minimise the detrimental environmental effects associated with rice production. This review provides a comprehensive synthesis of the available data regarding the influence of different crop management practices on GHG emissions in rice fields. We recognise the substantial potential for reducing GHG emissions through modifications in traditional crop management systems. Our analysis evaluates various options, such as adjustments in cropping practices, regulation of organic and fertiliser inputs, management of tillage techniques and irrigation strategies, and the selection of suitable cultivars, all of which can contribute to GHG emission reduction. It is crucial to consider that changes in management practices may have simultaneous and sometimes contradictory effects on different gases through various mechanisms. Therefore, our comprehensive evaluation aims to assess the potential global warming impact of each approach, considering the magnitude of their effects on all gases. This assessment seeks to identify suitable crop management practices that effectively reduce GHG emissions in rice cultivation while considering the overall environmental impact.

KEYWORDS

carbon dioxide (CO_2), crop management, global warming potential (GWP), methane (CH_4), nitrous oxide (N_2O)

1 | INTRODUCTION

Global warming is a significant challenge in today's world, primarily caused by the increased concentration of greenhouse gases (GHGs) in the atmosphere. This leads to the well-known "greenhouse effect" phenomenon (Burney et al., 2010). The average global temperature is rising significantly due to the intensified greenhouse effect. Projections indicate that by the end of the twenty-first century, temperatures could increase by approximately 1.1°C to 6.4°C (IPCC, 2007). Various factors, such as water vapour, ozone, methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), and chlorofluorocarbons, contribute to the increase in the earth's temperature (Hussain et al., 2015). The looming threat of global warming can significantly exacerbate the ongoing challenge of worldwide food insecurity. The repercussions of climate change are evident through escalating temperatures, fluctuating rainfall patterns, and a surge in climate-linked extremes like floods, droughts, cyclones, rising sea levels, salinity shifts, and soil erosion. Among all sectors, agriculture emerges as particularly vulnerable to these shifts, driven by the profound influence of regional and national climates on the characteristics of vegetation and crops. Climate change is also generating considerable challenges for global agricultural productivity, leading to increased food prices (Fahad et al., 2022). The literature shows an increasing trend in GHG emissions (IPCC, 2007; Smith et al., 2007), with predictions by Vergé et al. (2007) suggesting a potential 35%–60% increase in emissions by 2030 (Figure 1). Globally, CO_2, CH_4, and N_2O contribute 60%, 15%, and 5% to the anthropogenic GHG effect, respectively (Hussain et al., 2015). CH_4 and N_2O, which originate mainly from the agricultural sector, are the major contributors to GHG emissions. These gases have 298 and 25 times greater global warming potential (GWP) than CO_2, respectively (IPCC, 2007).

Rice (*Oryza sativa* L.) is an important crop that covers a vast area of approximately 1.38 million km^2 and accounts for 90% of the world's rice production in Asia, with a total agricultural area dedicated to cereal production of 20% (Belenguer-Manzanedo et al., 2022; Zhong et al., 2016). According to Van Nguyen and Ferrero (2006), it is projected that the global demand for rice will rise by approximately 24% over the next two decades. Moreover, rice fields are major sources of CH_4 and N_2O and can also be a source or sink of CO_2. The estimated annual CH_4 emission rates from rice fields are 6.15 million tons, which is equivalent to 17.9% of global methane emissions (Van Nguyen and Ferrero, 2006). Furthermore, rice fields cultivated through flooding are among the primary anthropogenic sources of methane emissions (Mohanty et al., 2017). Agricultural management techniques such as alterations in water management during rice cultivation, such as single drainage (SD) or multiple drainages (MD), can significantly reduce CH_4, N_2O, and CO_2 emissions by inducing frequent changes between aerobic and anaerobic states in rice fields (Yagi et al., 2020; Zhang et al., 2021). Additionally, recent studies have demonstrated that the broadcast application of nitrogen-based fertilisers increases N_2O emissions (Li et al., 2006; Liang et al., 2017). On the other hand, nitrogen-based fertilisers, particularly urea deep placement significantly reduce N_2O emissions in continuous flooding irrigation (Gaihre et al., 2015; Gaihre et al., 2018), while it increases N_2O emissions under alternate wetting and drying (AWD) irrigation (Islam et al., 2018). Moreover, coated fertilisers such as sulphur-coated urea and neem-coated urea have emerged as another promising solution for reducing GHG emissions. These coated fertilisers provide controlled-release mechanisms (Lawrencia et al., 2021). Khan et al. (2017) stated that the implementation of slow-release fertilisers holds the potential to diminish environmental pollution, encompassing the mitigation of GHG emissions, because of their enhanced and efficient nutrient utilisation. In the United States alone, urea and

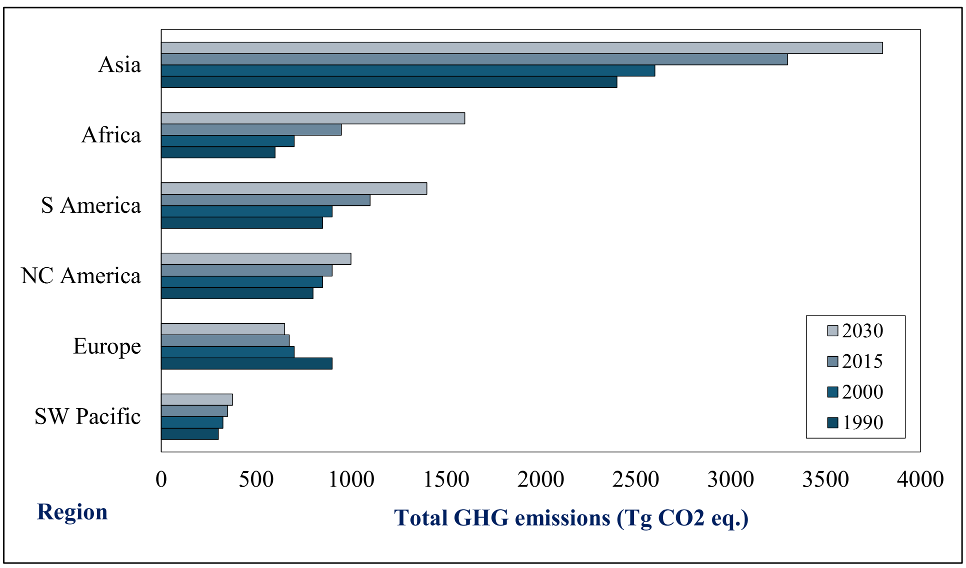

FIGURE 1 Global GHGs emissions trend categorised by regions: Southern America, North and Central America, South-West Pacific, Europe, Asia, and Africa. Retrieved from Hussain et al. (2015). GHGs, greenhouse gases.

ammonium sulphate fertilisers are predominantly used on approximately 3 million acres of rice farms annually, with urea being the most widely utilised nitrogen source (Snyder et al., 2009). To meet the demands of a projected global population of 9 billion by 2050, agricultural output is expected to rise by 70%–100%, leading to a greater reliance on the industrial Haber–Bosch process for nitrogenous fertiliser production. This increased reliance could potentially elevate GHG emissions (Win et al., 2021). Consequently, the resultant increased levels of GHGs may lead to higher temperatures that can disrupt essential plant functions such as enzyme activity, cell division, photosynthetic reactions, membrane integrity, growth, and productivity (Jiang et al., 2010).

The Intergovernmental Panel on Climate Change (IPCC) has projected a 2–4°C increase in global average temperature by the end of the 21st century due to GHG emissions and various factors, both human-induced and natural. This global warming trend has led to higher temperatures and altered crop yield potential, including for rice crops (Al-Zahrani et al., 2022). The anticipated temperature rise of 2°C by 2050 is foreseen to play a significant role in the escalation of heat stress in agriculture. Rice plants are particularly susceptible to heat stress, especially during their reproductive phase. As global warming continues, heat and drought stresses are expected to occur more frequently and unpredictably, which can cause a huge impact on growth and productivity of rice crops (Wu et al., 2019). Rice vegetative growth endures daytime temperatures up to 40°C, whereas floret development becomes markedly sensitive to temperatures surpassing 35°C, with nighttime temperature stress exerting a more detrimental impact than daytime stress. Studies have shown that current rates of global temperature change could lead to a significant reduction of 41% in rice yield by the end of the 21st century. Wu et al. (2017) have observed that high temperatures have adverse effects on various grain characteristics of rice, including reduced grain length, width, area, number of spikelets per panicle, head rice percentage, and milled rice percentage. Furthermore, Wu et al. (2022) also found that heat stress during the panicle initiation stage affected milling and appearance qualities in rice, with variations observed among different rice genotypes. Considering that the total global arable land available for rice production is assumed to remain unchanged, it becomes necessary to achieve intensified rice yields to ensure food security. This intensification must be accomplished in sustainable, profitable, and socially acceptable ways without increasing GHG emissions (Deng et al., 2022). Therefore, the development of innovative solutions is crucial to ensure food security while protecting the environment and natural resources by reducing GHG emissions (Win et al., 2021).

This paper provides a comprehensive analysis of GHG mitigation strategies specifically for rice cultivation, distinguishing it from previous reviews that focused on singular aspects or regional practices. By integrating recent advancements in crop management and evaluating their GWP, this offers a holistic view of effective strategies to reduce GHG emissions. An extensive array of practices is covered—from organic amendments and biochar application to cultivar selection and cropping regime modifications. The discussion not only highlights the effectiveness and trade-offs of these techniques but also emphasises the need for innovative approaches tailored to diverse agricultural systems and environmental conditions. By synthesising these multifaceted strategies and their impacts on GHG emissions, along with identifying critical areas for future research, this paper serves as a valuable resource for advancing sustainable rice production practices. Through this integrative approach, it aims to bridge knowledge gaps and offer actionable insights that can guide future research and policy development in the pursuit of more environmentally sustainable rice cultivation.

1.1 | Mechanism of GHGs emissions

Agricultural soils play a crucial role in the release of GHGs, including CH_4, N_2O, and CO_2, through complex interactions involving soil, plants, and microorganisms. Soil microbes, which are responsible for the breakdown and transformation of organic matter into stable soil organic matter (SOM), are the primary source of enzymes involved in these processes, thereby directly influencing GHG emissions, carbon storage, and carbon loss from the soil (Mohanty et al., 2017). In anaerobic conditions, such as those found in flooded rice fields, methanogens are responsible for the production of CH_4 (Figure 2) (Zhong et al., 2016). Methanogenesis occurs primarily through three pathways: hydrogenotrophic methanogenesis, where H_2 produced during organic substrate fermentation is utilised to reduce CO_2 to CH_4; acetoclastic methanogenesis, in which methanogens convert acetate—often generated from organic matter breakdown—into methane; and methylotrophic methanogenesis, where certain methanogens utilise methanol and other methylated compounds (Krüger et al., 2001; Narrowe et al., 2019; Stams et al., 2019). Temperature plays a significant role in microbial activity related to CH4 synthesis, initially increasing with temperature until an optimum is reached, after which it declines due to enzyme deactivation (Van Groenigen et al., 2013). N_2O is primarily generated through nitrification and denitrification processes (Kasimir-Klemedtsson et al., 1997), which can coexist in flooded rice soils (Bhattacharyya et al., 2013) (Figure 2). Nitrification, an aerobic process, involves the oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-), facilitated by ammonia-oxidising bacteria (AOB) and archaea (AOA) (Huang et al., 2019). Denitrification, an anaerobic process, reduces nitrate to N_2O and, ultimately, N_2 gas, with bacteria such as Pseudomonas and Paracoccus playing key roles (Van Spanning et al., 2005). The coexistence of these processes underscores the adaptability of microbial communities in response to fluctuating redox conditions, influencing N_2O emissions. Additionally, microbial activity in the decomposition of organic compounds leads to CO_2 emissions, with anaerobic conditions in flooded soils hindering complete carbon oxidation and promoting carbon deposition (Figure 2) (Gupta et al., 2021; Rahman & Yamamoto, 2020). However, the mineralisation of organic matter significantly contributes to CO_2 emissions, as soil microorganisms break down organic carbon pools, while agricultural residues and root exudates provide the carbon substrates necessary for this transformation.

1.2 | Agriculture shares in GHG emissions

Agriculture is a significant contributor to global GHG emissions, accounting for approximately 20% of worldwide GHG emissions (Bhattacharyya et al., 2013). The production of rice results in substantial emissions of GHGs, including CH_4, N_2O, and CO_2 (Figure 3). China, with its extensive rice fields covering over 160 million hectares, stands as the largest rice producer globally, accounting for 28% of the world's rice production in 2013. Approximately 75% of the world's annual rice production takes place on the 79 million hectares of irrigated land dedicated to rice farming (Xu et al., 2016). According to Xia et al. (2016), China's rice cultivation contributes to approximately 22% of the country's total GHG emissions from cropland, with annual emissions estimated at around 7.4 Tg CH_4 and 32 Gg N_2O. Overall, agriculture is responsible for approximately 50% and 60% of global CH_4 and N_2O emissions, respectively, accounting for approximately 10%–12% of

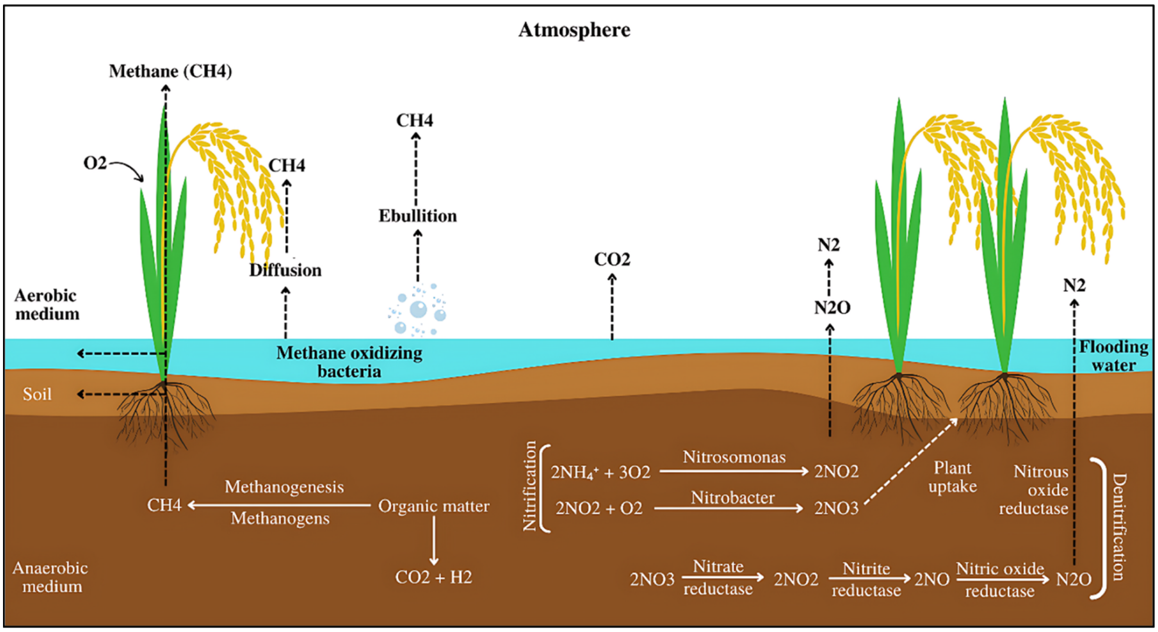

FIGURE 2 Mechanism of production and emissions of GHGs from rice fields: CH_4, N_2O, and CO_2.

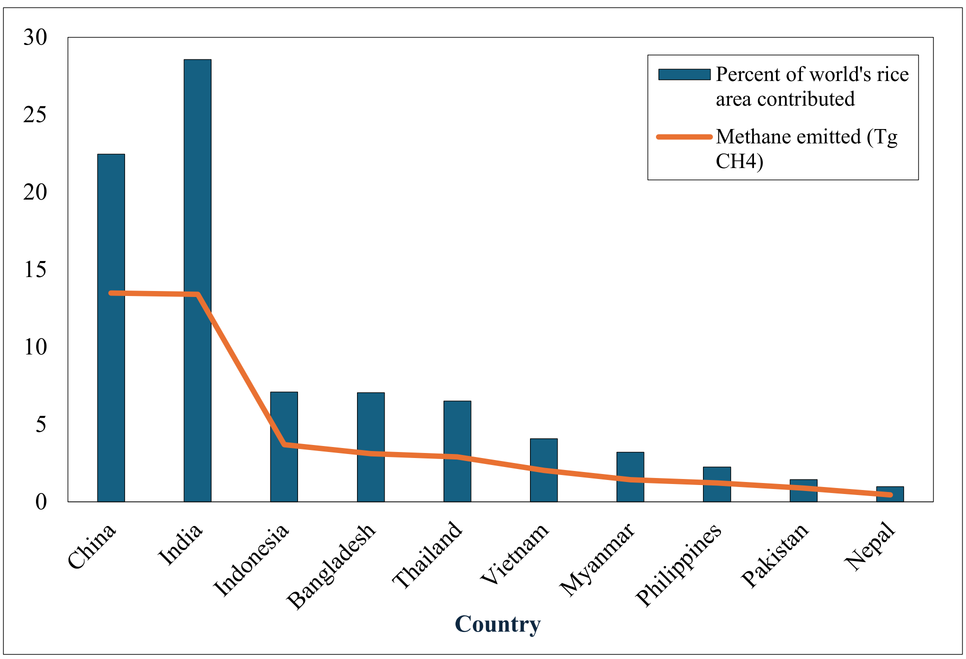

FIGURE 3 Graph illustrating the percentage of the world's rice area contributed and methane emission from rice fields in various Asian nations. *Source*: Sass (2000).

total anthropogenic GHG emissions (Xu et al., 2016). Studies have indicated that rice fields contribute to 30% of annual nitrous oxide emissions, 57% of carbon dioxide emissions, and 13% of methane emissions. These percentages correspond to approximately 16.0% of global nitrous oxide emissions, 78.2% of global carbon dioxide emissions, and 5.8% of global methane emissions (Kudo et al., 2014).

Extensive tillage and regular agricultural irrigation practices have a significant impact on CO_2 emissions. In India, the cultivation of puddled rice alone contributes to approximately 24% of the country's total agricultural methane emissions, amounting to 3.37 million tons. The application of nitrogenous fertilisers also leads to the production of around 0.14 million tons of N_2O emissions in rice (Gupta et al., 2016). Soil cultivation and annual crop growth processes accelerate the transformation of soil carbon into CO_2 through the activities of soil microorganisms. Initially, the depletion of soil carbon increases, but after several decades of cultivation, it tends to stabilise at a lower level (Vergé et al., 2007). While CO_2 emissions are a concern, the primary focus in agriculture is on N_2O emissions, primarily caused by the application of nitrogen in soil and cropping systems. Agricultural practices play a crucial role in managing soil and fertiliser use, which directly influences N_2O emissions. Although N_2O emissions are a modest component compared to CO_2 emissions in the overall GHG issue, they are a key consideration due to their association with agricultural practices (Snyder et al., 2009). The increasing demand for rice cultivation has led to a significant expansion of fertiliser use and rice-growing areas worldwide over the past 70 years. This expansion has contributed to the rise in atmospheric emissions of CH_4 and N_2O (Gupta et al., 2021).

Over the past 20 years since the Green Revolution, rice production per acre in numerous Asian countries has doubled. With the projected global population reaching nine billion by 2050, the Food and Agriculture Organisation estimates a 60% increase in agricultural output, including rice production, to meet the growing demand (Maraseni et al., 2018). However, the increased use of synthetic nitrogen (N) fertilisers, as highlighted by Zhao et al. (2015), may contribute to a 60% increase in agricultural emissions of CH_4 and N_2O over the next two decades. To mitigate GHG emissions, various strategies can be employed, such as carbon sequestration, reducing soil erosion, and implementing measures to decrease N_2O and CH_4 emissions. It is important to note that management techniques aimed at reducing emissions may have complex and sometimes contradictory effects on different GHGs (Nayak et al., 2015).

2 | METHODS AND METHODOLOGY

In this study, we systematically searched five prominent online databases, namely Scopus, Google Scholar, ScienceDirect, Web of Knowledge, and SpringerLink, to identify relevant research papers investigating the practical techniques for reducing GHG emissions from rice fields from 2012 to 2022. The meta keywords used were GWP, GHGs, nitrous oxide, carbon dioxide, methane, and rice. After the initial search, we obtained 800 records from the five databases. We eliminated duplicates during the screening process, which resulted in 628 unique records. These records were screened based on the title and abstract study, and we excluded 546 records that did not meet the study's inclusion criteria. The inclusion criteria required the investigations to report at least two GHG emissions: N_2O, CH_4, and CO_2. The papers had to be written in English and test at least one GHG reduction strategy. After screening based on the title and abstract study, we proceeded with a full-text review of the remaining 82 records. Among them, we excluded 54 studies that did not meet the inclusion criteria, such as those that reported on only one GHG emission or did not test any GHG reduction strategy. Lastly, we obtained 28 studies that met the PRISMA flow diagram's full-text study criteria (Figure 4). These studies were used to analyse and evaluate the various alternatives for reducing GHG emissions from rice fields.

3 | STRATEGIES FOR MITIGATING GHGS FROM RICE FIELDS

Numerous studies on rice paddies have been carried out worldwide due to growing worries about rice fields' vulnerability to GHG emissions and their critical contribution to global warming. Table 1 lists the mitigating strategies investigated and reported in the studies we encountered. Furthermore, Table 2 presents the related research, including soil types, field management techniques, fertiliser sources, average GHG emissions, GWP trends, and locations. Based on our interpretation of the findings, we recommend several technical agronomic management strategies for rice paddies, including controlled irrigation, application of nitrogen inhibitors, reduced usage of nitrogen fertiliser, application of mixed synthetic and organic fertilisers, conservation tillage, rice planting techniques, and rice cultivar selection (Figure 5). By implementing these strategies, total GHG emissions from upland crops can be lowered, ultimately preventing global warming (Nayak et al., 2015; Xu et al., 2016; Yagi et al., 2020). Future research needs to continue investigating and improving these techniques to sustain long-term and eco-conscious rice production practices.

3.1 | Water management

Water management is a critical factor in reducing GHG emissions from rice fields (Figure 6) (Maraseni et al., 2009). Various strategies, including midseason drainage (MD), sequential soil soaking and drying, occasional watering, and regulated irrigation, effectively minimise GHG emissions compared to traditional flooded rice production (Hussain et al., 2015). However, the practical implementation of these strategies faces several challenges. Economic costs associated with adopting new practices can be significant barriers, particularly for smallholder farmers who may struggle to invest in new technologies or infrastructure (Monaco et al., 2016). However, in Vietnam, research by Hoang et al. (2023) and Tran et al. (2018) showed that AWD not only decreased methane emissions but also improved water efficiency, leading to a reduction in water usage. These

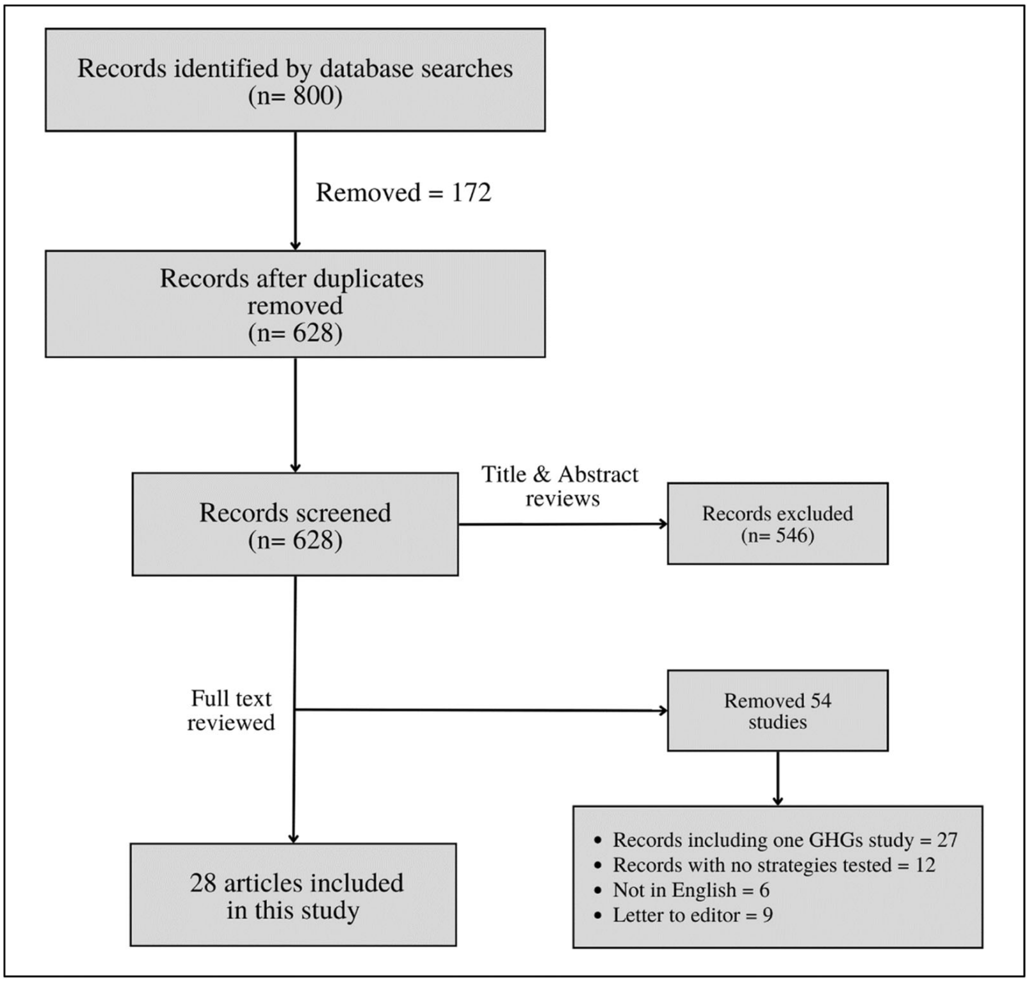

FIGURE 4 PRISMA flow chart illustrating the study selection process.

examples illustrate the potential benefits of adopting these strategies but also emphasise the need for tailored approaches that consider local conditions and farmer capabilities. The transition between dry and wet seasons is vital, allowing soil to shift from aerobic to anaerobic conditions, which enhances root activity and soil structure. This shift significantly reduces methane production and decreases the long-term need for water inputs (Gupta et al., 2021). Enhancing oxygen diffusion into the soil is a key strategy for mitigating methane emissions, as oxygen inhibits methanogenic microbes (Peyron et al., 2016). Research by Islam et al. (2020), Linquist et al. (2018), Wang et al. (2020), and Zhang et al. (2021) indicates that the AWD irrigation technique can reduce methane emissions by an average of 38% compared to continuous flooding (CF). However, this method is associated with a 34% increase in nitrous oxide emissions, highlighting the trade-offs involved. While AWD effectively curtails methane, it raises concerns about increased N_2O emissions, necessitating careful management. Maneepitak et al. (2019) emphasised that AWD can sustain low yield-scaled GWP in irrigated lowland double-rice farming, even without rice straw application, indicating its potential for sustainable agriculture. Additionally, Meijide et al. (2017) confirmed that flooding and multiple drainages (MD) are effective techniques for reducing methane fluxes in rice fields. Understanding the biochemical and physiological mechanisms behind these emissions is crucial. The reduction in methane can be attributed to disrupted anaerobic conditions that hinder methanogen activity. Conversely, the rise in N_2O emissions under AWD may result from increased nitrification and denitrification in intermittently moist soils. This underscores the need for tailored water management strategies that minimise trade-offs between methane and nitrous oxide emissions. Future research should focus on the microbial communities involved in these processes and explore synergistic combinations of AWD with innovative soil amendments or microbial inoculants to enhance mitigation potential while reducing N_2O emissions. Collaborative interdisciplinary research can uncover holistic solutions for sustainable rice cultivation, reducing its environmental footprint while ensuring food security.

3.2 | Tillage management

Tillage practices significantly influence GHG emissions in rice fields, highlighting the complex interactions between soil dynamics and

TABLE 1 Mitigating approaches investigated and described in selected publications.

References	Location	Data				Potential GHGs mitigation strategies tested								
		CH_4	N_2O	CO_2	SC/MA	Water management	Tillage management	Fertiliser & other amendments	Nitrification inhibitors/ slow-release fertilisers	Straw/ residues management	Manure application	Biochar application	Cultivar selection	Modifying crop regime
Bhattacharyya et al. (2013)	India	✓	✓	✓	⊕◊			*						
Xu et al. (2016)	China	✓	✓	✓	-	*								CR
Mohanty et al. (2017)	India	✓	✓	✓	⊕◊				*					DSR, PTR
Xia et al. (2016)	China	✓	✓	X	-			*		*				CR
Hasanah et al. (2019)	Indonesia	✓	X	✓	-	*								SRI
Zhang et al. (2021)	China	✓	✓	X	-	*							*	
Qin et al. (2016)	China	✓	✓	X	-					*		*		
Belenguer-Manzanedo et al. (2022)	Spain	✓	✓	✓	-	*								
Zhong et al. (2016)	China	✓	✓	✓	-			*						
Liang et al. (2017)	China	✓	✓	X	-	*								
Zhao et al. (2015)	China	✓	✓	X	-						*			
Kudo et al. (2014)	Japan	✓	✓	X	-	*								
Gupta et al. (2016)	India	✓	✓	X	-		*							DSR
Meijide et al. (2017)	Italy	✓	✓	✓	-	*								
Bhattacharyya et al. (2012)	India	✓	✓	✓	◊					*	*			
Liu et al. (2016)	China	✓	✓	X	⊕			*		*	*			
Guo et al. (2019)	China	✓	✓	X	-				*					DRCS
Islam et al. (2022)	Bangladesh	✓	✓	X	-	*			*					
Peyron et al. (2016)	Italy	✓	✓	X	-	*								
Wang et al. (2020)	China	✓	✓	X	-	*								
Maneepitak et al. (2019)	Thailand	✓	✓	X	⊕	*				*				DRCS

(Continues)

TABLE 1 (Continued)

References	Location	Data				Potential GHGs mitigation strategies tested								
		CH_4	N_2O	CO_2	SC/MA	Water management	Tillage management	Fertiliser & other amendments	Nitrification inhibitors/ slow-release fertilisers	Straw/ residues management	Manure application	Biochar application	Cultivar selection	Modifying crop regime
Bayer et al. (2014)	Brazil	✓	✓	×	⊕		*							
Islam et al. (2020)	Bangladesh	✓	✓	×	-	*								
Xu et al. (2015)	China	✓	✓	✓	-	*							*	
Li et al. (2018)	China	✓	✓	×	⊕	*			*					
Jain et al. (2014)	India	✓	✓	×	-									PTR, SRI
Lagomarsino et al. (2016)	Italy	✓	✓	×	⊕	*								
Linquist et al. (2015)	USA	✓	✓	×	-	*								CR

Note: *: Describe the research that is referenced in that specific database; ✓/X: Indicate Yes/No if CH_4, CO_2, & N_2O are reported in the study; ⊕: Indicate the inclusion of soil characteristics (SC); ◊: Indicate the inclusion of microbial activity (MA); ⊕◊: Indicate the inclusion of both soil characteristics and microbial activity (SC + MA).

Abbreviations: CR, crop rotation; DRCS, double rice cropping system; DSR, direct seeded rice; GHG, greenhouse gas; PTR, puddled transplanted rice; SRI, system of rice intensification.

emission pathways. In some regions, reduced tillage has been associated with increased organic matter storage, including organic carbon (OC) and organic nitrogen. While this can enhance soil health, it may also lead to higher nitrous oxide emissions and affect net global warming potential (NGWP) (Snyder et al., 2009). Tillage accelerates the oxidation of soil carbon to CO_2 by promoting aeration, facilitating interactions between agricultural residues and the soil, and enhancing microbial activity (Hussain et al., 2015). Integrating no-till systems in flood-irrigated rice fields represents a promising approach to mitigate GHG emissions. Studies by Bayer et al. (2014) and Zhang et al. (2015) found that no-till practices reduced methane emissions by 21% compared to traditional tillage. Additionally, Del Grosso et al. (2009) demonstrated that using no-till systems with nitrification inhibitors significantly decreases net GHG emissions, suggesting that these practices are particularly beneficial in regions with SOM deficiency, such as Asia's rice-wheat belt. Research studies in China have shown that the use of drainage alongside no-till practices led to the reduction in N_2O and CH_4 emissions, highlighting the effectiveness of this combination (Hao et al., 2016). Chirinda et al. (2018) proposed that soil compaction in no-till systems could extend methane residence time, enhancing its oxidation by methanotrophic bacteria and further reducing methane emissions from rice plants. This underscores the intricate relationship between soil conditions and methane dynamics in rice production. Shah et al. (2017) confirmed that the combination of fertiliser type (urea) and tillage practices (no-till and conservation tillage) influenced N_2O emissions. Specifically, when anhydrous NH_3 was used as a fertiliser, N_2O emissions were higher in conventional tillage systems. These findings highlight the need for tailored management strategies that consider the interactions between fertiliser sources and tillage practices to effectively mitigate N_2O emissions.

3.3 | Fertiliser management

A significant portion of GHG emissions in agriculture is attributed to the manufacturing and transportation of fertilisers (Snyder et al., 2009). Promising results have emerged from effective fertiliser management techniques aimed at reducing GHG emissions from rice fields. These include using slow-releasing fertilisers, properly incorporating fertilisers into the soil, adjusting application rates and timing to meet crop requirements, and avoiding excessive applications (Gupta et al., 2021). A study in Vietnam demonstrates that using slow-release fertilisers reduced N_2O and CH_4 emissions while maintaining rice yields, highlighting the potential benefits of this approach (Trinh et al., 2017). Optimising fertiliser application rates is crucial for achieving high rice yields while minimising GHG emissions and nitrogen consumption. Peak emissions of CO_2, N_2O, and CH_4 are typically observed during critical growth stages, such as the vegetative and reproductive phases of rice cultivation (Zhong et al., 2016). Moreover, improving fertiliser use efficiency can help reduce GHG emissions, particularly N_2O, and indirectly decrease CO_2 emissions associated with nitrogenous fertilisers (Hussain et al., 2015). However, challenges remain, such as the need for

TABLE 2 Research on GHG emissions from rice fields, mitigation strategies employed by researchers, and trends of GWP.

Author	Soil type	Field management	Source of nutrients	Mean GHGs emissions	Trends of GWP	Location
Bhattacharyya et al. (2013)	Aeric Endoaquept	The field plots were maintained with continuous flooding (CF) until the water level reached 7 ± 3 cm, and the water was drained 10 days before harvest throughout the plant development period.	Control, Nitrogen, FYM, FYM + Nitrogen, NPK, FYM + NPK	CH_4: 0.23–5.06 mg m^{-2} h^{-1}; CO_2: 4.6–36.9 mg m^{-2} h^{-1}; N_2O: 0.24–0.83 kg ha^{-1}	GWP significantly varied between control and FYM + NPK treatments −2649 to 5084 kg CO_2 eq. ha^{-1} during wet season −2381 to 4395 kg CO_2 eq. ha^{-1} during dry season	Odisha, India (2013)
Xu et al. (2016)	Gleysol	Three irrigation treatments were applied, including CF, Flooded and wet intermittent irrigation (FWI), and Rain-fed with limited irrigation (RFL).	NPK	CH_4: 12.74 mg m^{-2} h^{-1}; CO_2: 432 mg m^{-2} h^{-1}; N_2O: 0.33 mg m^{-2} h^{-1}	Annual GWP from water-saving treatments was lower than CF water regime due to significant mitigation of CH_4 emissions and trade-off in N_2O emissions.	Huaqiao, China (2016)
Mohanty et al. (2017)	Aeric Endoaquept	In the puddle transplanted rice (PTR) plot, 3–5 cm of static water was maintained from transplanting to 2 weeks before harvest.	Control, Prilled urea (PU), Neem coated urea (NCU), PU + FYM	CH_4: 0.77–4.3 mg m^{-2} h^{-1}; CO_2: 0.01–0.05 mg m^{-2} h^{-1}; N_2O: 0.95–1.09 kg ha^{-1}	GWP under different N management approaches significantly altered −1197 to 1993 kg CO_2 equivalent ha^{-1} in AR −1435 to 2659 kg CO_2 equivalent ha^{-1} in PTR	Odisha, India (2014)
Xia et al. (2016)	Anthrosol	In the submerged rice (SR) plot, the water level was maintained at 3–5 cm for a month after transplanting, followed by draining the water for a week and occasional watering.	Different NPK doses	CH_4: 17.32–33.33 mg m^{-2} h^{-1}; N_2O: 0.14–0.35 kg ha^{-1}	Lower NGWP obtained by reducing N application rates (RW180), but yields of rice suffered significant losses.	Jiangsu, China (2016)
Hasanah et al. (2019)	-	System of Rice Intensification (SRI) method was applied in experimental pots under varied water tables of +2, 0, −3, −5, −7, and −12 cm.	Microorganism local (MOL) liquid fertiliser	CH_4: 20.44–31.78 mg m^{-2} h^{-1}; CO_2: 0.55–0.93 kg/m^2	SRI's GHG emissions ranged from 0.48 to 1.3 kg CO_2/kg yield - corresponds to a GWP reduction of 40-50% per kg of rice grown - some estimates reaching 60%	Bogor, Indonesia (2014)
Zhang et al. (2021)	Silty-loam	Three cultivation conditions were applied, including CF, AWD, and Dry cultivation (DC).	NPK	CH_4: 32.8 Kg ha^{-1}; N_2O: 12.0 kg ha^{-1}	AWD treatment decreased CH_4 emissions and GWP by 7%–64% and 9%–39%, respectively.	Shanghai, China (2020)
Qin et al. (2016)	Latosolic red soil	Irrigation involved flooding two weeks before planting.	NPK, Biochar, Rice straw,	CH_4: 0.72-14.92 mg m^{-2} h^{-1}; N_2O: 96.4 µg m^{-2} h^{-1}	Over 8 years of rice cultivation, GHG emissions reduced by 61.44%, 65.39%, and 25.7%, respectively, compared to RI, RS, and control treatments.	Huizhou, China (2015)
Belenguer-Manzanedo et al. (2022)	Silt-loam	The water level was maintained at a depth of approximately 5–15 cm throughout the growing season until September when the plots were drained for harvest.	Straw amendments	CH_4: 3.10–7.26 mg m^{-2} h^{-1}; CO_2: 95.2 ± 5.2 mg m^{-2} h^{-1}; N_2O: 0.14–0.19 mg m^{-2} h^{-1}	Significant decreases in net global warming potential (NGWP) with avoidance of winter feeding - ranged from 121% to 206% - showed negative GWP balance compared to positive balance in WFL regimens	Ebro Delta, Spain (2018)

(Continues)

TABLE 2 (Continued)

Author	Soil type	Field management	Source of nutrients	Mean GHGs emissions	Trends of GWP	Location
Zhong et al. (2016)	Loam-clay	The water level was adjusted during the rice cultivation stage and maintained at 2–5 cm before 80 days, then dried after 80 days to conform with local standard agriculture standards.	Different NPK doses	CH_4: 19.62–32.95 mg m^{-2} h^{-1}; CO_2: 26.85–2841.81 mg m^{-2} h^{-1}; N_2O: 65 µg m^{-2} h^{-1}	CO_2 > CH_4 > N_2O contributed to GWP for all treatments - greater GWP attained with greater nitrogen treatments	Hangzhou, China (2014)
Liang et al. (2017)	Clayey-loam	The field water layer was maintained at 2–5 cm during transplantation, and mid-season drainage was carried out at 25 DAT to limit the overdevelopment of tillers until 10 days after significant panicle formation occurred.	NPK	CH_4: 126.2 kg ha^{-1}; N_2O: 0.47–3.81 kg ha^{-1}	OPTN + AWD reduced GWP by 22.0% in early rice and by 40.7% in late rice compared to farmer nitrogen and water management.	Guang-dong, China (2016)
Zhao et al. (2015)	Pup-Orthic Entisol	All plots were inundated with a water level of approximately 5 cm throughout the rice season, except for mid-season draining times.	Urea, Organic manure, Urea + Organic manure (OM), Control [Organic manure = Poultry waste + Organic matter]	CH_4: 0.87–98.49 mg m^{-2} h^{-1}; N_2O: 78.88–624.66 mg m^{-2} h^{-1}	Organic fertiliser applications increased NGWP of CH_4 and N_2O emissions; OT had the highest GWP value of 7240.48 kg CO_2/ha.	Qingpu, China (2013)
Kudo et al. (2014)	Low-humic Andosol	Intermitted drainage (ID), CF except mid-season drainage, and a compound (CP) treatment with both flooding and mid-season drainage were applied.	Rice straw + NPK	CH_4: 1.5 mg m^{-2} h^{-1}; N_2O: 0.6 mg m^{-2} h^{-1}	CP had much lower direct emissions than CF and ID, each by 47.1%.	Kawasaki, Japan (2012)
Gupta et al. (2016)	Typic Ustochrept	Different crop cultivation methods were used, including Conventionally tilled wheat (CTW), Zero-tilled wheat (ZTW), Transplanted puddled rice (TPR), Direct seeded rice (DSR), Intermittent wetting and drying (IWD), application of NCU, and surface application of rice residue (RR).	NPK	CH_4: 6.7–43.4 kg/ha; N_2O: 0.81–0.94 kg/ha	ZTW followed by DSR had lower GWP than previous wheat and rice treatments; resulted in GWP reductions of around 44%–47% compared to standard CTW-TPR system.	New Delhi, India (2013)
Meijide et al. (2017)	Calcic Gleysol	The rice was flooded throughout the growing season, and the land was left noncultivated after harvest until the next crop.	Urea, NOK	CH_4: 0.98–1.12 mmol m^{-2} s^{-1}; CO_2: 17–20 mmol m^{-2} s^{-1}; N_2O: 2.26 nmol m^{-2} s^{-1}	Control of water table was key factor in reducing CH_4 emissions and lowering GWP.	Pavia, Italy (2010)
Bhattacharyya et al. (2012)	Aeric Endoaquept	All field plots were flooded with a water level of 6–2 cm throughout the crop development period.	Control; Urea; Rice straw + Urea; Rice straw + Green Manure (GM)	CH_4: 1.9–5.7 mg m^{-2} h^{-1}; CO_2: 10.5–87.8 mg m^{-2} h^{-1}; N_2O: 0.84-1 kg/ha	GWP significantly varied after the combined application of rice straw and green manure, from 5862 kg CO_2 eq. ha^{-1} in control group to 10163 kg CO_2 eq. ha^{-1}.	Cuttack, India (2011)
Liu et al. (2016)	Fluval-aquic soil	The water regime applied was flooded-mid-season drainage-flooding-wet intermittent irrigation, but no waterlogging was allowed.	Control; NPK; NPK + RSB; NPK + RSM; NPK + RSM + GM	CH_4: 0.10-18.27 mg m^{-2} h^{-1}; N_2O: 78.70–84.90 µg m^{-2} h^{-1}	NEB of NPK + RSM + GM treatment was about 2 times higher than NPK + RSM.	Jingzhou, China (2013)

TABLE 2 (Continued)

Author	Soil type	Field management	Source of nutrients	Mean GHGs emissions	Trends of GWP	Location
Guo et al. (2019)	Hydragric	All plots were kept at a height of 3–7 cm from the soil surface until mid-season drainage.	Farmers' fertiliser practice (FFM); Polymer coated urea (PCU); nitrapyrin-treated urea (CP); Equiponderate culture solution (EM)	CH_4: 0.02–40.49 mg m^{-2} h^{-1}; N_2O: 1.62–531.95 µg m^{-2} h^{-1}	Traditional urea with EM marginally increased yearly GWP compared to FFP; PCU and CP lowered GWP.	Jingzhou, China (2015)
Islam et al. (2022)	Silt-Clay-Loam	Irrigation was mainly carried out by tapping groundwater, and IPNS was linked to two irrigation systems, AWD and CF.	Control; Urea deep placement (UDP); PU; Poultry manure + PU (IPNS)	CH_4: 16–445 mg m^{-2} d^{-1}; N_2O: − 0.24-2.49 mg m^{-2} d^{-1}	UDP lowered GWP by 8% and 15%, respectively, compared to PU and IPNS treatments.	Gazipur, Bangla-desh (2019)
Peyron et al. (2016)	Fluvaquen-tic Epiaquept	Different rice seeding methods were used, including water seeding and continuous flooding (WFL), dry seeding with flooding at tillering stage (DFL), and dry seeding with intermittent irrigation (DIR).	NPK	CH_4: 198–231 kg CO_2-eq ha^{-1} d^{-1}; N_2O: 329–357 kg CO_2-eq ha^{-1} d^{-1};	DFL therapy resulted in a 56% average reduction in GWP compared to WFL over both years.	Castello d'Agogna, Italy (2013)
Wang et al. (2020)	Hydro-morphic	The flooding-midseason drainage-flooding (FDF) regime was used as the conventional irrigation (CI), while flooding-moist by AWD was also applied.	NPK	CH_4: 30.91 kg/ha; N_2O: 1.41 kg/ha	AWD irrigation reduced GWP by 21% (1.07 t CO_2 equivalent ha-1) compared to FDF due to lower N_2O and CH_4 emissions.	Chuzhou, China (2018)
Maneepitak et al. (2019)	Riverine alluvium	Two irrigation methods, CF and AWD.	RS incorporation (RS-I), RS burning (RS-B), and without RS incorporation and burning (WRS)	CH_4: 7.34 mg m^{-2} h^{-1}; N_2O: 0.19 mg m^{-2} h^{-1}	GWP under AWD was much lower (2886.94 kg CO_2-eq. ha-1) compared to CF (3648 kg CO_2-eq. ha^{-1}).	Ayutthaya, Thailand (2018)
Bayer et al. (2014)	Haplic Gleysoil	No-till systems (NT) and conventional tillage (CT).	Ryegrass biomass	CH_4: 3.5–4.5 kg ha^{-1} d^{-1}; N_2O: 2.27–3.21 mg m^{-2} d^{-1}	NT treatment yielded 23% reduced pGWP emissions on average (13.3 and 10.3 Mg CO_2 eq ha^{-1} GS1 for CT and NT treatments, respectively).	Cachoeir-inha, Brazil (2013)
Islam et al. (2020)	Inceptisol	Two irrigation methods were applied including CF irrigation regime, and AWD	NPK	CH_4: 79–815 mg m^{-2} d^{-1}; N_2O: 1.36–2.99 mg m^{-2} d^{-1}	AWD irrigation lowered the overall GWP by 36% compared to CF irrigation and reduced greenhouse gas intensity (GHGI) by roughly 34%.	Gazipur, Bangla-desh (2018)
Xu et al. (2015)	Hydro-morphic	Three irrigation methods were applied including CF, FWI, and FDI.	NPK	CH_4: 34.26 mg m^{-2} h^{-1}; CO_2: 509–631 mg m^{-2} h^{-1}; N_2O: 0.31–0.34 mg m^{-2} h^{-1}	CH_4 emissions declined from 71% to 15% of the overall GWP, while CO_2 and N_2O emissions increased from 23% to 73% and 6% to 12%, respectively, with less water usage.	Huaqiao, China (2012)

(Continues)

TABLE 2 (Continued)

Author	Soil type	Field management	Source of nutrients	Mean GHGs emissions	Trends of GWP	Location
Li et al. (2018)	Hydragric	CI, Surface water drainage (SWD)	Urea; PCU; Nitrapyrin-urea composition with hydroquinone (NU + HQ)	CH_4: −1.8–55.9 mg m^{-2} h^{-1}; N_2O: 752.2–777.9 μg m^{-2} h^{-1}	The integrated impacts of water and nitrogen management on CH_4 and N_2O emissions must be assessed for total GHG.	Jingzhou, China (2015)
Jain et al. (2014)	Alluvial soil	PTR, conventional SRI, and modified SRI (MSRI)	NPK	CH_4: 0.02–5.07 kg ha^{-1} d^{-1}; N_2O: 4.41–19.86 g ha^{-1} d^{-1}	GWP was reduced by 27.5% for SRI and 30.2% for MSRI compared to PTR planting.	New Delhi, India (2009)
Lagomarsino et al. (2016)	Mesic Thapto-Histic Fluvaquent	Permanent flooding (PF) and AWD.	NPK	CH_4: 15.71 kg ha^{-1} d^{-1}; N_2O: 1.76 kg ha^{-1}	AWD maximised the GWP of rice crops, but caution must be exercised while implementing this water-saving strategy.	Bologna, Italy (2013)
Linquist et al. (2015)	Dewitt silt loam	Crop rotation: rice–rice (RR) and rice-soybean (RS) Water management: CF, AWD/40F (flood), AWD/60, and AWD/40	NPK	CH_4: 2 kg ha^{-1} d^{-1}; N_2O: 100 g ha^{-1} d^{-1}	The flooded control treatment had the greatest GWP of 347 kg CO_2 eq Mg^{-1} (average across years and locations).	Stuttgart, USA (2013)

Abbreviations: AWD, alternate wetting and drying; GWP, global warming potential.

farmers to receive training on best practices and access to suitable fertiliser options. Surveys in Malaysia indicate that many farmers are unaware of slow-release fertilisers and their benefits, which emphasises the need for educational programs to enhance adoption (Adnan et al., 2020).

3.3.1 | Selecting fertiliser & other amendments

The choice of fertiliser significantly impacts GHG emissions in rice fields, playing a crucial role in balancing emissions of N_2O, CO_2, and CH_4. Approximately 75% of N_2O emissions from agricultural soils result from nitrogenous fertiliser applications, making careful selection essential for effective mitigation (Mohanty et al., 2017). The biochemical effects of nitrogenous fertilisers on GHG emissions are complex, particularly with ammonium-based fertilisers, which can stimulate methanotrophic activity and enhance methane oxidation. High concentrations of soil ammonium-N are key to reducing overall methane emissions (Hussain et al., 2015). Yagi et al. (2020) demonstrated that fertilisers containing sulphates, such as ammonium sulphate or phosphogypsum, can effectively reduce CH_4 emissions in rice fields. Their trials showed a consistent reduction in CH_4 emissions due to sulphate-induced modulation of methanogenesis, with effect sizes ranging from 0.31 to 0.76. This suggests that using these fertilisers contributes to methane mitigation. Conversely, Zhao et al. (2015) found that using urea alone led to higher nitrogen loading rates and GHG emissions, indicating that excessive nitrogen can exacerbate emissions. This aligns with Yagi et al. (2020) findings, emphasising the importance of evaluating fertiliser impacts holistically. Interestingly, Ku et al. (2017) noted that applying urea under AWD conditions can reduce GHG emissions without compromising yield in tropical regions. This indicates that specific fertiliser application practices, such as using urea in AWD, can effectively mitigate emissions while maintaining productivity. Nasrullah et al. (2022) highlighted the emissions associated with synthetic nitrogen manufacturing during top dressing (TD) compared to deep placement (DP), finding that TD methods resulted in higher GHG emissions, particularly CO_2, when scaled to yield and area. The contributions of Yagi et al. (2020), Zhao et al. (2015), Ku et al. (2017), and Nasrullah et al. (2022) collectively underscore the intricate relationship between nitrogenous fertilisation and GHG emissions. Mechanistically, sulphate-induced reduction of methanogenesis, as described by Yagi et al. (2020), interacts with nitrogen availability and microbial communities explored by Zhao et al. (2015). Ku et al. (2017) and Nasrullah et al. (2022) further clarify how specific application practices influence emissions dynamics. Future research should focus on the biochemical and microbial mechanisms underlying sulphate-induced CH_4 reduction. Understanding the interplay between nitrogen availability, soil biota, and emissions will provide valuable insights for refining fertiliser strategies. The synergy of specific application techniques holds promise for developing nuanced approaches to GHG mitigation.

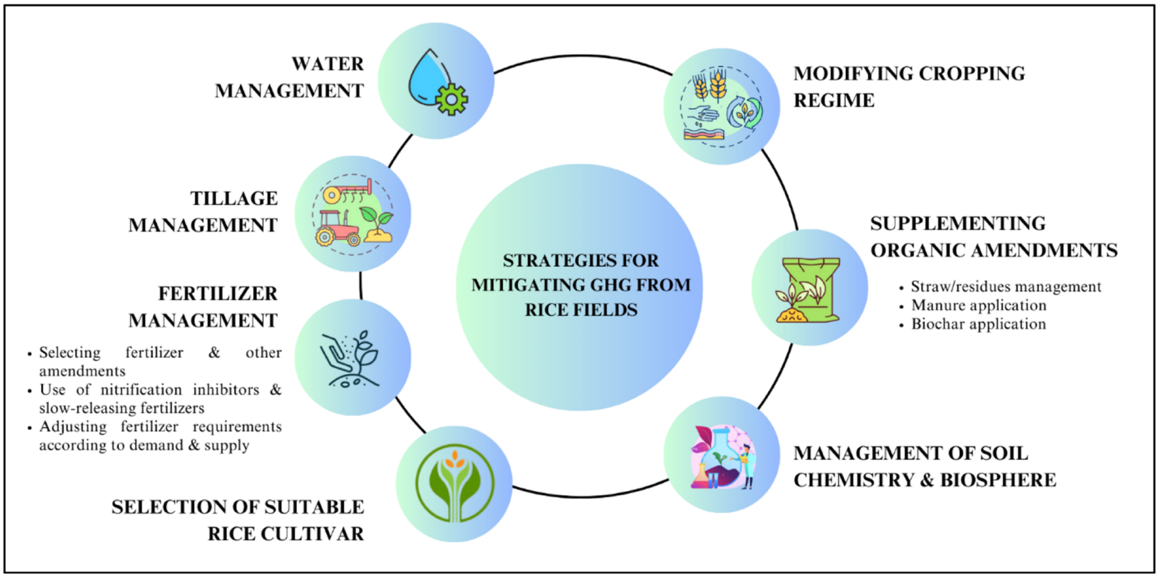

FIGURE 5 Agronomic management strategies for mitigating GHGs emissions from rice fields. GHGs, greenhouse gases.

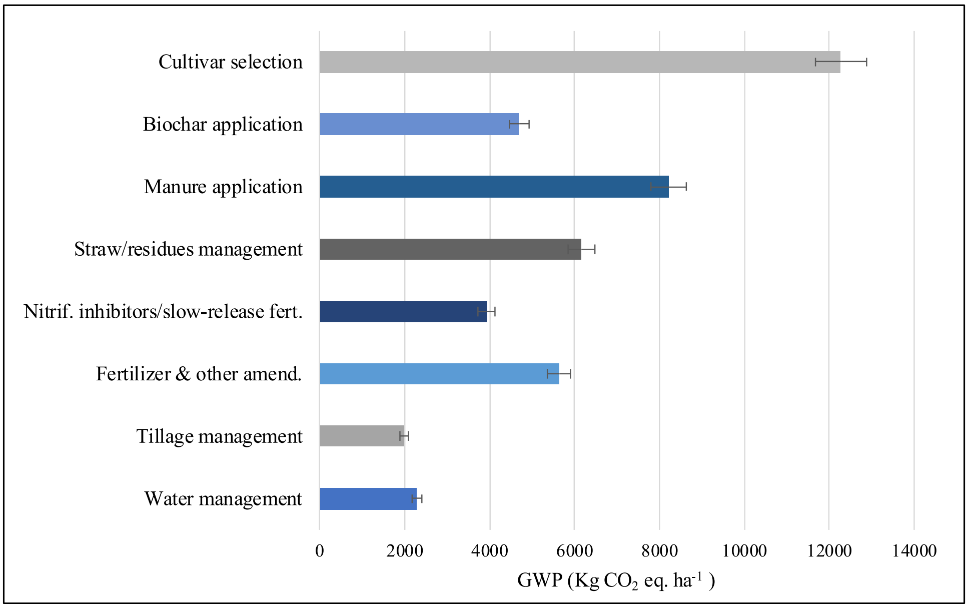

FIGURE 6 Bar graph illustrating the mean global warming potential (GWP) calculated from articles selected through the PRISMA selection process. GWP was calculated using the formula: GWP = CH_4 emission × 23 + N_2O emission × 296 + CO_2 emission.

3.3.2 | Adjusting fertiliser requirements according to demand & supply

The interplay between crop productivity and GHG mitigation can be optimised through precision fertilisation strategies that align nitrogen and phosphorus levels with crop needs. Despite the use of advanced techniques, approximately 48% of applied nitrogen is released into the atmosphere as gaseous nitrogen (Hussain et al., 2015). In cases where phosphorus deficiency limits efficient nitrogen utilisation and reduces yields, increasing nitrogen fertiliser rates alongside phosphorus application can be effective without causing nitrate-N accumulation. Proper phosphorus application not only boosts yields and financial returns but also lowers soil nitrate-N levels, thereby minimising environmental nitrogen losses (Snyder et al., 2009). Additionally, splitting nitrogen applications and utilising tools such as colour charts or photometers to assess crop nitrogen needs based on leaf colour can enhance nitrogen utilisation efficiency (Wassmann et al., 2004). Liang et al. (2017) demonstrated that the timely application of nitrogen at the appropriate rate improves nitrogen use efficiency (NUE) and reduces nitrogen losses. When combined with the AWD irrigation technique, this approach achieved significant reductions in NGWP and nitrogen losses—specifically, reductions of

13.6% and 26.3%, respectively, under varying wet and dry irrigation regimes. Zhong et al. (2016) confirmed these findings, showing that applying 225 kg N/ha of the appropriate nitrogen fertiliser resulted in lower yield-scaled emissions of 3.69 and 2.23 kg CO_2-eq/kg rice yield. These results indicate that proper timing and dosage of nitrogen application not only enhance NUE but also contribute to lower GHG emissions per unit of rice yield. Liang et al. (2017) and Zhong et al. (2016) further illustrate how the timing, dosage, and irrigation practices intricately influence emissions dynamics. Future research should explore the biochemical processes underlying phosphorus-mediated nitrogen utilisation and the molecular mechanisms that drive nutrient synergy. Understanding how nitrogen absorption changes over time and the role of microbial communities can provide new insights into emissions dynamics. Conducting rigorous field-scale experiments could help translate these findings into practical solutions.

3.3.3 | Use of nitrification inhibitors/slow-releasing fertilisers

The strategic use of nitrification inhibitors and slow-releasing fertilisers represents a significant advancement in reducing GHG emissions from rice fields. Nitrification inhibitors, which vary in effectiveness depending on soil type, moisture, organic matter, pH, and temperature, can disrupt the activity of nitrifying bacteria, methane oxidisers, and methanogens (Wang et al., 2021). In contrast to soluble fertilisers containing inhibitors, controlled-release fertilisers function by specifically inhibiting certain bacteria involved in nitrogen conversion. Urease inhibitors temporarily halt the enzymatic degradation of urea, directly affecting the urease enzyme (Snyder et al., 2009). Research shows that the encapsulation of calcium carbide (ECC), which gradually releases acetylene in the soil, can increase rice yields while decreasing methane emissions (Hussain et al., 2015). Guo et al. (2019) found that polymer-coated urea (PCU), including sulphur-coated urea (SCU), reduced GWP by 21.1% and GHG intensity (GHGI) by 31.7%. Nitrapyrin-coated urea showed even greater reductions of 34.3% in GWP and 44.4% in GHGI, underscoring the efficacy of these treatments in mitigating agricultural emissions. Li et al. (2018) highlighted the effectiveness of combining nitrapyrin-urea with hydroquinone (NU + HQ), which not only limits the formation of inefficient tillers but also enhances nitrogen release patterns beneficial for methane utilisation. Dawar et al. (2021) reported that combining urea with biochar (BC) and biochar plus urea inhibitors (BC + UI) led to reductions in soil NH_3 emissions by 27% and 69%, respectively, while also improving grain yield by 13% and shoot biomass by 24%. In addition to synthetic inhibitors, plant-derived substances such as neem oil, neem cake, and Karanja seed extract have shown potential as natural nitrification inhibitors, reducing nitrogen losses and GHG emissions (Gupta et al., 2021). Moreover, Saud, Wang, et al. (2022) documented significant reductions in N_2O emissions (up to 90%) using biological nitrification inhibitors (BNIs) derived from rice cultivars *Oryza sativa* L. cv. Sabana 6 and cv. Toyo. These findings align with previous research, highlighting the critical role of inhibitors and slow-releasing fertilisers in mitigating GHG emissions. Future exploration should focus on understanding the biochemical interactions between these inhibitors and microbial dynamics. Additionally, investigating the mechanisms underlying nitrogen utilisation and the role of plant-derived substances can reveal new insights.

3.4 | Supplementing organic amendments

Organic amendments play a crucial role in influencing GHG emissions from rice fields. Generally, adding organic materials, such as manure and straw, tends to increase CH_4 emissions. The extent of this increase is influenced by factors such as the quantity, quality, and timing of the organic material applied (Hussain et al., 2015). Organic matter in rice fields comes from various sources, including by-products of rice cultivation like sloughed-off root cells, exudates, manure, and crop residues. The introduction of organic carbon (OC) into the soil is a primary driver of methane production, whether from organic fertilisers or the decomposition of agricultural residues (Win et al., 2021). Raton et al. (2021) noted that plant-soil interactions are affected by climate conditions alongside GHG emissions and OC levels. One potential strategy to mitigate CH_4 emissions is to limit the incorporation of straw and crop residues into the soil, as proposed by Yagi et al. (2020). A study in Vietnam demonstrated that minimal tillage combined with reduced straw incorporation led to a reduction in CH_4 and CO_2 emissions without significantly affecting rice yields (Dung et al., 2022). However, challenges remain in convincing farmers to change their practices, as many view the incorporation of straw as beneficial for soil health.

3.4.1 | Straw/residues management

Managing straw and residues in rice fields as a GHG mitigation strategy involves intricate biochemical and ecological dynamics. In continuously flooded lowland rice systems, N_2O emissions generally remain unaffected by residue management practices (Bhattacharyya and Barman, 2017). However, Belenguer-Manzanedo et al. (2022) found that delaying straw incorporation and preventing winter flooding can significantly reduce CH_4 and CO_2 emissions during the post-harvest season and subsequent cultivation periods. This effect is attributed to changes in microbial communities and nutrient availability, which suppress methane-generating pathways and CO_2 efflux. Methanogens thrive in anaerobic conditions created by waterlogged soils, especially when straw is incorporated, leading to increased CH_4 emissions (Kotsyurbenko et al., 2019). Conversely, nitrifiers can enhance N_2O emissions when nitrogen-rich fertilisers are used with residues, as aerobic conditions favour their activity (Hui et al., 2024). Liu et al. (2016) suggested that combining NPK fertiliser with rice straw strip mulching and green manuring can greatly enhance soil organic carbon (OC) sequestration, achieving a 103% increase in sequestration rates and a 27% reduction in NGWP. This synergy between straw carbon influx and nutrient-driven microbial activity promotes accelerated OC sequestration and emissions reduction. Bhattacharyya et al. (2012) further emphasised the role of inorganic fertilisers in conjunction with rice straw for efficient OC sequestration and increased grain yields, with a notable sequestration of 1.39 Mg ha^{-1} of OC. These findings collectively highlight the importance of managing crop residues in guiding GHG mitigation. The studies by Belenguer-Manzanedo et al. (2022), Liu et al. (2016), and Bhattacharyya et al. (2012) serve as foundational insights into the biochemical dynamics influencing emissions pathways. Future research should focus on the temporal adjustments of microbial communities during delayed straw incorporation, as well as the mechanisms linking nutrients, carbon influx, and microbial interactions to enhance OC storage.

3.4.2 | Manure applications

Numerous field experiments have explored the effects of organic amendments on GHG emissions, particularly CH_4. Notably, there are significant differences in GHG emissions between fresh and fermented materials. In rice fields, the addition of organic materials, such as manure and straw, can influence GHG emissions, with the timing and quality of application being crucial for their effectiveness (Hussain et al., 2015). Gupta et al. (2021) found that applying precomposted manures to rice soil can significantly reduce methane emissions, suggesting that this approach may be an effective strategy for mitigating CH_4 in rice cultivation. Conversely, Bhattacharyya et al. (2013) reported that the use of FYM in combination with chemical fertilisers (NPK) can lead to increased methane emissions, particularly in year-round cropping systems. The application of both chemical fertilisers and manure can stimulate carbon mineralisation, resulting in elevated methane emissions under submerged conditions, partly due to increased activity of methanogens in anaerobic zones. This underscores the importance of considering the combined effects of various fertilisers on methane emissions in rice fields. Snyder et al. (2009) further dissected the relationship between manure application, organic matter content, and N_2O emissions. Their findings revealed that the interaction of manure type, quality, and soil conditions can significantly influence N_2O emissions. In low organic matter soils, supplementing with manure can increase N_2O emissions compared to mineral fertilisers, likely due to processes such as substrate priming and the enhanced activity of nitrifiers under aerobic conditions. Mohanty et al. (2017) identified a positive correlation between water-soluble carbon and microbial biomass carbon in the soil with methane emissions. This biochemical surge potentially enhances microbial activity, creating pathways for increased methane production. These insights align with previous studies, highlighting the critical role of microbial metabolism in shaping emissions dynamics. The collective findings from Gupta et al. (2021), Bhattacharyya et al. (2013), Snyder et al. (2009), and Mohanty et al. (2017) provide a foundational understanding of the complex biochemical processes influencing emissions pathways. A deeper exploration of pre-composting, microbial interactions, and methane reduction is warranted. Investigating the interactions between organic and inorganic components across various soil conditions could yield valuable insights.

3.4.3 | Biochar application

The application of biochar is increasingly recognised for its potential to enhance soil OC and significantly reduce GHG emissions, particularly CH_4 and N_2O (Hussain et al., 2015; Yagi et al., 2020). Recent interest in biochar as a soil amendment has surged due to its dual benefits: mitigating GHG emissions while improving crop yields. However, previous studies have reported mixed results regarding the impact of biochar on GHG emissions (Qin et al., 2016). Gupta et al. (2021) and Yagi et al. (2020) found that the addition of biochar derived from rice straw at rates of 20 and 40 t/ha progressively reduced CH_4 emissions by 29.7% and 15.6%, respectively. These studies also noted increased rice production, suggesting that biochar application can enhance both environmental sustainability and agricultural productivity. Similarly, Dawar et al. (2021) reported that applying 5 Mg ha^{-1} or 10 Mg ha^{-1} of biochar in urea-amended soils significantly reduced total N_2O emissions by 27% and 35%, respectively, compared to urea alone. The enhanced retention of NH_4^+ is believed to be a key mechanism for these reductions, as it constrains nitrification processes and limits N_2O emissions from nitrifiers. Qin et al. (2016) also observed significant decreases in CH_4 emissions with biochar application at rates of 5, 10, and 20 t/ha, resulting in reductions of 20.88%, 17.79%, and 39.85%, respectively, compared to controls. These reductions are attributed to several factors, including increased soil pH, enhanced adsorption of methane to soil surfaces, and a rise in methanotrophic bacterial populations. Furthermore, Bo et al. (2023) highlighted that biochar produced at high pyrolysis temperatures can effectively adsorb dissolved organic carbon, a critical substrate for methanogenic microorganisms. This adsorption reduces the substrate available for CH_4 production, further supporting biochar's role in GHG mitigation. Additionally, while biochar can improve conditions that inhibit methanogenesis, it may also enhance nitrifier activity under aerobic conditions, potentially increasing N_2O emissions if not managed properly. Bamagoos et al. (2021) found that combining biochar with phosphorus fertilisation resulted in a 7% increase in rice grain yield compared to the control, even under high-temperature stress. In summary, the application of biochar presents a promising strategy for reducing GHG emissions in rice cultivation while simultaneously improving crop yields.

3.5 | Selection of suitable rice cultivar

In the context of increasing GHG concentrations and various abiotic stresses, selecting appropriate rice cultivars becomes a critical strategy for sustainable agriculture. Prominent abiotic stresses—such as drought, heat, cold, and salinity—trigger a range of morphological, physiological, biochemical, and molecular responses that significantly affect plant growth, development, and productivity (Fahad et al., 2022). Variations in CH_4 emissions among rice cultivars are influenced by factors such as rhizospheric oxidation potential, root exudates, and the plant's ability to transport CH_4 through aerenchyma tissue (Gupta et al., 2021; Hussain et al., 2015; Linquist et al., 2018; Win et al., 2021). Notably, research by Chirinda et al. (2018) and Zheng et al. (2014) indicates that yield-scaled GWP is significantly higher in Indica rice varieties compared to Japonica varieties. This highlights the importance of considering rice races in evaluating GHG emissions in rice production systems. Recently, there has been increased interest in “aerobic rice”, which includes drought-resistant, high-yielding varieties. For example, Hanyou 73 (HY73), an Indica hybrid, is recognised for its tolerance to drought and flooding (Zhang et al., 2021). Furthermore, Saud, Shi, et al. (2022) demonstrated that overexpressing DREB1A and OsPIL1 in transgenic rice can enhance drought resistance without the growth stunting typically associated with such traits. This suggests that genetic modification could be an effective approach to developing drought-resistant rice varieties. Fahad et al. (2015) noted that phytohormones play dual roles in seed germination and subsequent plant growth, influencing how rice responds to various stressors. Recent studies have focused on developing improved drought-resistant cultivars, such as Hanyou 3, HY3, IR64, and IR50, which have shown resilience under drought conditions while potentially mitigating CH_4 emissions (Win et al., 2021; Xu et al., 2015; Xu et al., 2016; Yagi et al., 2020). The research conducted by Chirinda et al. (2018), Zheng et al. (2014), Saud, Shi, et al. (2022), Fahad et al. (2015), Win et al. (2021), Xu et al. (2015), Xu et al. (2016), and Yagi et al. (2020) provides a solid foundation for selecting these rice varieties. Understanding genetic variations and the role of plant hormones offers valuable insights into how rice adapts to adverse conditions. Identifying optimal matches between rice cultivars and diverse farming environments remains a significant challenge, necessitating further investigation into the long-term performance and emission impacts of these varieties.

3.6 | Modifying cropping regime

Direct-seeded rice (DSR) has emerged as a promising alternative to conventional transplanted rice (PTR), particularly for its potential to mitigate GHG emissions and adapt to diverse climate challenges (Hussain et al., 2015). Research by Yagi et al. (2020) indicates that direct seeding significantly reduces CH_4 emissions compared to traditional transplanting. This reduction is attributed to altered flooding patterns in DSR, which disrupt the anaerobic conditions conducive to methane production, creating oxygen-rich environments that inhibit methanogenesis. The System of Rice Intensification is another effective strategy, demonstrating reductions in GWP while conserving water without sacrificing yields (Hasanah et al., 2019; Jain et al., 2014). This balance can be linked to enhanced root growth and more efficient water use, leading to lower GHG emissions. Conversely, Linquist et al. (2015) found that a rice-rice (RR) rotation resulted in higher cumulative emissions of CH_4 and N_2O compared to a rice-soybean (RS) rotation, highlighting how crop rotation practices can influence GHG emissions. In terms of environmental impacts, Zhou et al. (2022) reported that the ratoon rice (RR) system consistently had lower carbon, nitrogen, and water footprints compared to the double-rice (DR) system. This difference is primarily due to the higher irrigation requirements of the DR system, which contributes to a larger blue carbon footprint. Gupta et al. (2016) found that adopting a Zero Tillage-Wheat-Rice (ZTW + DSR) system significantly reduced GHGI. This approach protects soil structure and microbial ecosystems by minimising soil disturbance, creating conditions less favourable for GHG production. The findings of Yagi et al. (2020), Hasanah et al. (2019), Jain et al. (2014), Linquist et al. (2015), Zhou et al. (2022), and Gupta et al. (2016) collectively highlight strategies that balance emissions reduction with agronomic sustainability. Further investigation into the mechanistic understanding of emissions dynamics across different cropping regimes presents an opportunity for deeper insights.

3.7 | Management of soil chemistry & biosphere

Understanding enzymes and microbiological organisms is crucial for developing protocols that effectively modify soil chemistry, thereby influencing the characteristics of denitrifying bacteria and methanogens. This modification can significantly reduce GHG emissions, particularly N_2O and CH_4 (Gupta et al., 2021). Malyan et al. (2021) proposed that utilising *Methylobacterium oryzae* (MNL7), Azolla, and a combination of Azolla with Blue-Green Algae (BGA) can mitigate GHG emissions while increasing crop yield. Their findings suggest that these strategies can potentially reduce global warming risk by 15.2%–27.4%, concurrently enhancing agricultural productivity. Mechanistically, *Methylobacterium oryzae* has methane-oxidising capabilities, Azolla reduces N_2O emissions through nitrogen fixation, and the symbiotic relationship with BGA enhances the soil ecosystem. Wang et al. (2021) emphasised the need to minimise nitrifying bacteria activity in the rhizosphere to improve the nitrogen recovery rate from fertilisers. By reducing nitrogen losses from nitrification and denitrification processes, this approach can effectively redirect nitrogen toward plant nourishment and decrease its conversion to N_2O. This highlights the delicate balance involved in regulating nitrogen movement within the rhizosphere, suggesting that optimised fertiliser management can significantly reduce nitrogen-related GHG emissions while improving nutrient use efficiency. Recent research by Yulianingsih et al. (2021) further underscored the role of biofertilizers in reducing GHG emissions. Their study found that combining rice straw with biofertilizers led to reductions in CH_4, N_2O, and CO_2 emissions by 9.2%, 14.78%, and 27.68%, respectively, resulting in a decrease in GWP by 10.75%. Ramessh et al. (2022) confirmed that biofertilizers like Azolla and BGA significantly reduced methane emissions and enhanced soil organic carbon levels. Sun et al. (2021) reported that co-applying biochar with biofertilizers diminished ammonia volatilisation and overall GWP by 15.2%. The incorporation of biostimulants, such as methane-derived microbial biostimulants investigated by Kumar et al. (2024), has shown promise in enhancing crop yield while reducing GHG emissions. Pathak et al. (2024) reviewed the benefits of cyanobacterial and algal biofertilizers as plant growth stimulants, noting their positive effects on soil health and emissions reduction. Bashir et al. (2021) discussed how plant growth stimulators and biostimulants rich in nutrients and plant hormones can improve soil health and decrease GHG emissions. Integrating beneficial microorganisms and optimising fertiliser management can yield significant environmental and agronomic benefits. Hiis et al. (2024) introduced bioaugmentation with *Cloacibacterium sp*. strain CB-01, which consumes N_2O and releases N_2, achieving reductions of up to 95% in N_2O emissions when live bacteria were introduced alongside nitrogen fertilisers. This innovative approach demonstrated effectiveness across various soil types, showcasing the potential of microbial processes for large-scale GHG mitigation in agriculture. Similarly, Daniels (2022) advocated for regenerative practices in U.S. agriculture, such as improved manure and fertiliser management, which can lower GHG emissions by 40%–50%, particularly targeting reductions in methane and N_2O. Overall, strategies for managing soil are interconnected and resonate across various areas. Malyan et al. (2021) linked emissions reduction with improved agricultural productivity, envisioning a future that is both food-secure and ecologically balanced. Wang et al. (2021) explored the complexities of the rhizosphere, pointing toward efficient fertiliser management practices that benefit both environmental health and crop yields.

4 | PERSPECTIVES

As the global population continues to grow, the demand for staple crops like rice will intensify. This increased demand, coupled with the challenges posed by climate change, necessitates a reevaluation of rice cultivation practices. The future of rice farming must focus on sustainability, innovation, and resilience (Figure 7). We will need to produce more food on less land while using fewer resources. Significant advancements in agricultural technology will be required, including the development of high-yielding, stress-tolerant rice varieties.

Precision agriculture, which leverages data and technology to optimise inputs and maximise outputs, will play a crucial role in enhancing productivity. Additionally, integrating traditional knowledge with modern farming techniques will be essential in creating a more sustainable rice production system. Climate change is expected to have profound effects on rice production, with altered precipitation patterns, rising temperatures, and increased frequency of extreme weather events. These changes will likely shift to the geographic regions where rice can be grown and may reduce yields in some areas. Adaptation strategies, such as altering planting dates, adopting drought-resistant varieties, and improving irrigation efficiency, will be

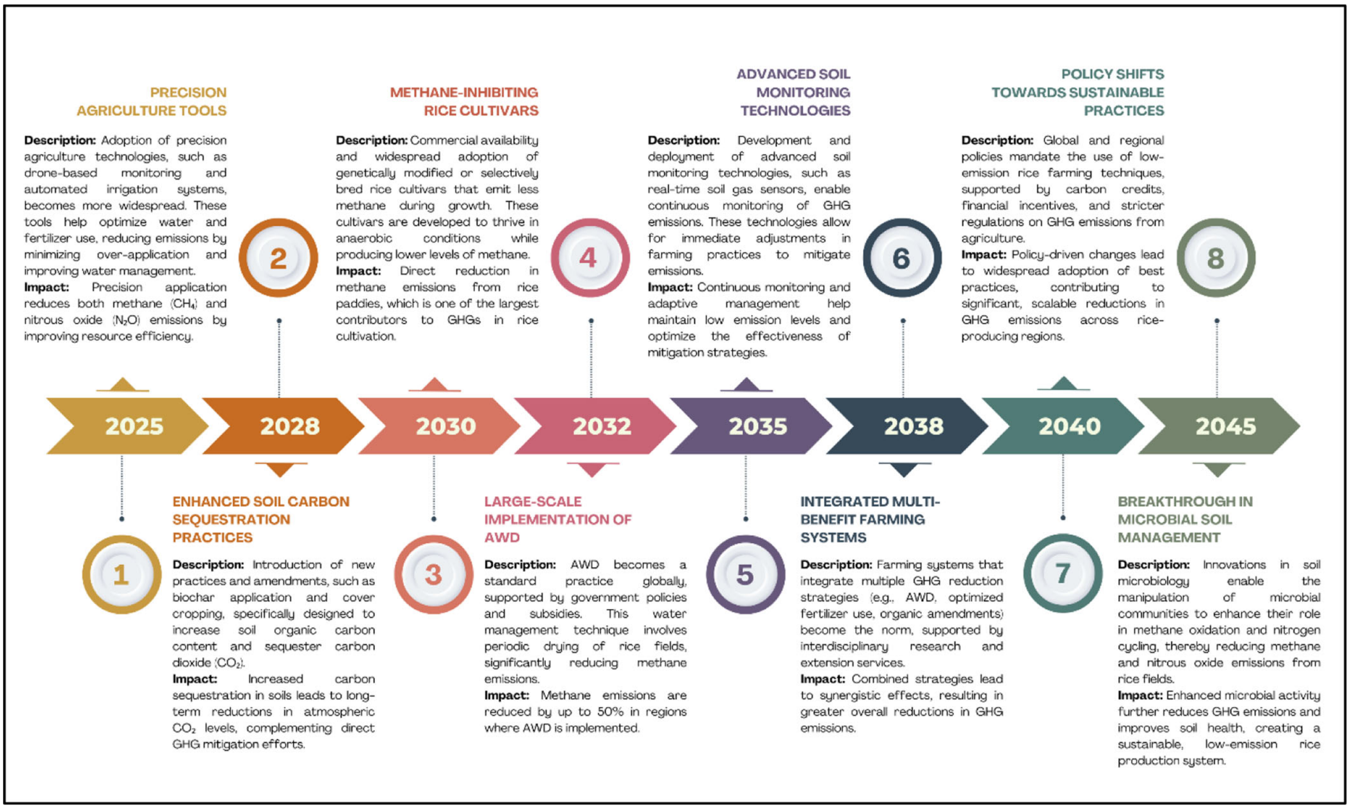

FIGURE 7 Future perspectives in GHGs emission reduction in rice cultivation. GHGs, greenhouse gas.

critical in ensuring that rice cultivation remains viable in the face of these challenges. As the demand for rice grows, so does the potential for increased GHG emissions. However, this trajectory is not inevitable.

As we look to the future of rice cultivation, the health of soil biological communities will be paramount for sustainable practices. Employing biological regulation strategies can enhance soil chemistry and microbial diversity, leading to improved rice production while simultaneously mitigating GHG emissions. By integrating beneficial microorganisms, such as nitrogen-fixing bacteria and methanogens, farmers can create a more resilient soil ecosystem. These organisms play vital roles in nutrient cycling and can help reduce GHG emissions through enhanced denitrification processes and improved nitrogen recovery from fertilisers. Additionally, practices such as cover cropping and the application of organic amendments can foster a thriving soil microbiome, further enhancing soil structure and fertility. Ultimately, prioritising soil biological health will contribute to a holistic approach in rice farming, promoting productivity, sustainability, and environmental stewardship.

Advances in precision agriculture, such as remote sensing, drones, and AI, offer opportunities to optimise water management, nutrient application, and pest control, further reducing emissions. Developing climate-resilient rice varieties through genetic engineering and genomic selection will be crucial in adapting to climate change. Integrated management practices, combining water-saving technologies with improved fertiliser and residue management, can synergistically cut emissions. Sustainable intensification—improving yield while minimising environmental impacts—along with conservation tillage and soil carbon sequestration, will be key to balancing food production with ecological sustainability. Policy and economic incentives, including subsidies, carbon markets, and certification schemes, are vital to promoting these practices. Education, capacity building, and global collaboration will ensure the successful adoption of these innovations and the development of tailored solutions for different regions. Looking ahead, the vision for a sustainable rice cultivation system involves a multifaceted approach that balances productivity with environmental stewardship. This includes promoting agroecological practices, enhancing biodiversity within rice fields, and fostering collaboration between scientists, farmers, and policymakers. In the long term, the success of rice cultivation will depend on our ability to innovate and adapt to changing conditions while minimising the environmental impact of production. As we navigate these challenges, ongoing research and adaptive strategies will be essential in ensuring that rice remains a cornerstone of global food security without compromising the health of our planet.

5 | CONCLUSION

The projected increase in population and rice demand in the future has raised significant concerns about stabilising GHG emissions to minimise the anticipated global climate change. In this comprehensive review, we synthesised existing data to identify suitable crop management practices in rice cultivation that can attenuate GHG emissions. While limitations in data availability prevented us from addressing all gases in each segment, we conducted a feasibility analysis and evaluated the potential of various practices based on their GWP, particularly focusing on CH_4 and N_2O emissions. Our findings demonstrate that implementing crop management interventions can effectively mitigate the impact of rice cultivation on global climate change. For instance, compared to traditional flooding irrigation, alternative practices such as AWD, DC, and flooding and mid-season drainage (CP) systems show mitigation potentials ranging from 34% to 38%, 9% to 39%, 7% to 47.1%, respectively, when considering CH_4, CO_2, and N_2O emissions. Shifting from CT to no-tillage NT and conservation tillage practices proves beneficial in GHG mitigation as these practices effectively reduce overall GHG emissions by 21% compared to traditional tillage practices. Proper management of straw through surface retention or mulching with a combination of NPK fertiliser reduces GHGs by 27%, as well as the conversion of biomass into biochar/compost instead of burning or incorporation, can offset GHG emissions in rice fields. The use of organic manures and optimised fertilisation techniques, such as deep placement, replacing urea with ammonium sulphate, and employing nitrification inhibitors, also offer efficient approaches to lower GHG emissions. Among different cropping regimes, DSR appears to be the most promising and environmentally friendly alternative to traditional transplanting (TPR), exhibiting lower GWP. Adopting these proposed mitigation options not only has the potential to sustain or improve rice productivity and input use efficiency but also contributes to addressing the challenges of food security. However, successful implementation of these practices requires addressing social, economic, educational, and political barriers. Future research should focus on verifying the effectiveness of these practices across diverse geographical zones and under varying circumstances to provide site-specific mitigation strategies. Integrating geographic information systems databases, yield, GHG emission models, and socioeconomic information can enhance decision-making processes. Additionally, establishing a standardised method for calculating GWP and considering factors beyond GHG emissions, such as cultural significance, ecosystem services, food security, and human health, are crucial in the context of global climate change and agriculture.

AUTHOR CONTRIBUTIONS

Shubh Pravat Singh Yadav: Conceptualisation; literature investigation; data curation; data interpretation; data visualisation; writing—original draft, review & editing. **Netra Prasad Ghimire**, **Prava Paudel**, **Dipesh Kumar Mehata**: Literature investigation; writing—original draft. **Sangita Bhujel**: Conceptualisation; writing—review; supervision.

ACKNOWLEDGEMENTS

The authors have nothing to report. This research did not receive any funding.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.

ORCID

Shubh Pravat Singh Yadav http://orcid.org/0000-0003-3987-5616
Netra Prasad Ghimire http://orcid.org/0000-0003-4604-9865
Prava Paudel http://orcid.org/0000-0002-1933-4540
Dipesh Kumar Mehata http://orcid.org/0000-0002-2942-9199

REFERENCES

Adnan N, Nordin SM, Anwar A. Transition pathways for Malaysian paddy farmers to sustainable agricultural practices: An integrated exhibiting tactics to adopt Green fertilizer. Land Use Policy. 2020;90:104255.

Al-Zahrani HS, Alharby HF, Fahad S. Antioxidative defense system, hormones, and metabolite accumulation in different plant parts of two contrasting rice cultivars as influenced by plant growth regulators under heat stress. Front Plant Sci. 2022;13:911846. https://doi.org/10.3389/fpls.2022.911846

Bamagoos A, Alharby H, Fahad S. Biochar coupling with phosphorus fertilization modifies antioxidant activity, osmolyte accumulation and reactive oxygen species synthesis in the leaves and xylem sap of rice cultivars under high-temperature stress. Physiol Mol Biol Plants. 2021;27(9):2083–100. https://doi.org/10.1007/s12298-021-01062-7

Bashir MA, Rehim A, Raza QUA, Raza HMA, Zhai L, Liu H, et al. Biostimulants as plant growth stimulators in modernized agriculture and environmental sustainability. Technol Agric. 2021;311:1–12. https://doi.org/10.5772/intechopen.98295

Bayer C, Costa FS, Pedroso GM, Zschornack T, Camargo ES, Lima MA, et al. Yield-scaled greenhouse gas emissions from flood irrigated rice under long-term conventional tillage and no-till systems in a humid subtropical climate. Field Crops Research. 2014;162:60–9. https://doi.org/10.1016/j.fcr.2014.03.015

Belenguer-Manzanedo M, Alcaraz C, Camacho A, Ibáñez C, Català-Forner M, Martínez-Eixarch M. Effect of post-harvest practices on greenhouse gas emissions in rice paddies: flooding regime and straw management. Plant Soil. 2022;474(1–2):77–98. https://doi.org/10.1007/s11104-021-05234-y

Bhattacharyya P, Barman D. Crop residue management and greenhouse gases emissions in tropical rice lands. In: Soil management and climate change: Effects on organic carbon, nitrogen dynamics, and greenhouse gas emissions. Cambridge, Massachusetts: Elsevier Inc; 2017. p. 323–35. https://doi.org/10.1016/B978-0-12-812128-3.00021-5

Bhattacharyya P, Nayak AK, Mohanty S, Tripathi R, Shahid M, Kumar A, et al. Greenhouse gas emission in relation to labile soil C, N pools and functional microbial diversity as influenced by 39 years long-term fertilizer management in tropical rice. Soil Tillage Res. 2013;129:93–105. https://doi.org/10.1016/j.still.2013.01.014

Bhattacharyya P, Roy KS, Neogi S, Adhya TK, Rao KS, Manna MC. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. Soil and Tillage Res. 2012;124:119–30. https://doi.org/10.1016/j.still.2012.05.015

Bo X, Zhang Z, Wang J, Guo S, Li Z, Lin H, et al. Benefits and limitations of biochar for climate-smart agriculture: A review and case study from China. Biochar. 2023;5:77. https://doi.org/10.1007/s42773-023-00279-x

Burney JA, Davis SJ, Lobell DB. Greenhouse gas mitigation by agricultural intensification. Proc Natl Acad Sci. 2010;107(26):12052–7. https://doi.org/10.1073/pnas.0914216107

Chirinda N, Arenas L, Katto M, Loaiza S, Correa F, Isthitani M, et al. Sustainable and low greenhouse gas emitting rice production in Latin America and the Caribbean: A review on the transition from ideality to reality. Sustainability. 2018;10(3):671. https://doi.org/10.3390/su10030671

Daniels TL. The potential of nature-based solutions to reduce greenhouse gas emissions from US agriculture. Socio-Ecol Pract Res. 2022;4:251–65. https://doi.org/10.1007/s42532-022-00120-y

Dawar K, Saif-ur-Rahman K, Fahad S, Alam SS, Khan SA, Dawar A, et al. Influence of variable biochar concentration on yield-scaled nitrous oxide emissions, wheat yield and nitrogen use efficiency. Sci Rep. 2021;11(1):16774. https://doi.org/10.1038/s41598-021-96309-4

Deng J, Harrison MT, Liu K, Ye J, Xiong X, Fahad S, et al. Integrated crop management practices improve grain yield and resource use efficiency of super hybrid rice. Front Plant Sci. 2022;13:1–12. https://doi.org/10.3389/fpls.2022.851562

Dung TV, Thu TA, Long VV, Da CT. Decomposition of rice straw residues and the emission of CO2, CH4 under paddy rice and crop rotation in the Vietnamese Mekong Delta region - A microcosm study. Plant, Soil Environ. 2022;68(1):29–35. https://doi.org/10.17221/304/2021-PSE

Fahad S, Adnan M, Saud SNL, editors. Climate change and ecosystems: Challenges to sustainable development. In: Footprints of climate variability on plant diversity. Boca Raton: CRC press; 2022.

Fahad S, Hussain S, Matloob A, Khan FA, Khaliq A, Saud S, et al. Phytohormones and plant responses to salinity stress: A review. Plant Growth Regul. 2015;75(2):391–404. https://doi.org/10.1007/s10725-014-0013-y

Gaihre YK, Singh U, Islam SMM, Huda A, Islam MR, Sanabria J, et al. Nitrous oxide and nitric oxide emissions and nitrogen use efficiency as affected by nitrogen placement in lowland rice fields. Nutr Cycl Agroecosyst. 2018;110(2):277–91. https://doi.org/10.1007/s10705-017-9897-z

Gaihre YK, Singh U, Islam SMM, Huda A, Islam MR, Satter MA, et al. Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. Geoderma. 2015;259–260:370–9. https://doi.org/10.1016/j.geoderma.2015.06.001

Van Groenigen KJ, Van Kessel C, Hungate BA. Increased greenhouse-gas intensity of rice production under future atmospheric conditions. Nat Clim Change. 2013;3(3):288–91. https://doi.org/10.1038/nclimate1712

Del Grosso SJ, Ojima DS, Parton WJ, Stehfest E, Heistemann M, DeAngelo B, et al. Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils. Glob Planet Change. 2009;67(1–2):44–50. https://doi.org/10.1016/j.gloplacha.2008.12.006

Guo C, Ren T, Li P, Wang B, Zou J, Hussain S, et al. Producing more grain yield of rice with less ammonia volatilization and greenhouse gases emission using slow/controlled-release urea. Environ Sci Pollut Res. 2019;26(3):2569–79. https://doi.org/10.1007/s11356-018-3792-2

Gupta DK, Bhatia A, Kumar A, Das TK, Jain N, Tomer R, et al. Mitigation of greenhouse gas emission from rice-wheat system of the Indo-Gangetic plains: Through tillage, irrigation and fertilizer management. Agric Ecosyst Environ. 2016;230:1–9. https://doi.org/10.1016/j.agee.2016.05.023

Gupta K, Kumar R, Baruah KK, Hazarika S, Karmakar S, Bordoloi N. Greenhouse gas emission from rice fields: a review from Indian context. Environ Sci Pollut Res. 2021;28(24):30551–72. https://doi.org/10.1007/s11356-021-13935-1

Hao Q, Jiang C, Chai X, Huang Z, Fan Z, Xie D, et al. Drainage, no-tillage and crop rotation decreases annual cumulative emissions of methane and nitrous oxide from a rice field in Southwest China. Agric Ecosyst Environ. 2016;233:270–81.

Hasanah NAI, Setiawan BI, Arif C, Widodo S, Uphoff N. Optimizing rice paddies' lower greenhouse gas emissions and higher yield with SRI management under varying water table levels. Paddy Water Environ. 2019;17(3):485–95. https://doi.org/10.1007/s10333-019-00744-z

Hiis EG, Vick SHW, Molstad L, Røsdal K, Jonassen KR, Winiwarter W, et al. Unlocking bacterial potential to reduce farmland N2O emissions. Nature. 2024;630:421–8. https://doi.org/10.1038/s41586-024-07464-3

Hoang TN, Minamikawa K, Tokida T, Wagai R, Tran TXP, Tran THD, et al. Higher rice grain yield and lower methane emission achieved by alternate wetting and drying in central Vietnam. Eur J Agron. 2023;151:126992.

Hui D, Ray A, Kasrija L, Christian J. Impacts of climate change and agricultural practices on nitrogen processes, genes, and soil nitrous oxide emissions: A quantitative review of meta-analyses. Agriculture. 2024;14(2):240. https://doi.org/10.3390/agriculture14020240

Hussain S, Peng S, Fahad S, Khaliq A, Huang J, Cui K, et al. Rice management interventions to mitigate greenhouse gas emissions: a review. Environ Sci Pollut Res. 2015;22(5):3342–60. https://doi.org/10.1007/s11356-014-3760-4

IPCC. Climate change 2007: impacts, adaptation and vulnerability. In: ML P, Canziani O, Palutikof J, Van der LindenP, Hanson C, editors. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. 541. Cambridge: Cambridge University Press; 2007. p. 81–2

Islam SMM, Gaihre YK, Biswas JC, Singh U, Ahmed MN, Sanabria J, et al. Nitrous oxide and nitric oxide emissions from lowland rice cultivation with urea deep placement and alternate wetting and drying irrigation. Sci Rep. 2018;8(1):17623. https://doi.org/10.1038/s41598-018-35939-7

Islam SMM, Gaihre YK, Islam MR, Ahmed MN, Akter M, Singh U, et al. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. J Environ Manage. 2022;307:114520. https://doi.org/10.1016/j.jenvman.2022.114520

Islam SMM, Gaihre YK, Islam MR, Akter M, Al Mahmud A, Singh U, et al. Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh. Sci Total Environ. 2020;734: 139382.

Jain N, Dubey R, Dubey DS, Singh J, Khanna M, Pathak H, et al. Mitigation of greenhouse gas emission with system of rice intensification in the Indo-Gangetic plains. Paddy Water Environ. 2014;12(3):355–63. https://doi.org/10.1007/s10333-013-0390-2

Jiang J, Trundle P, Ren J, Cheng YL, Lee CY, Huang YL, et al. A review on Kentucky bluegrass responses and tolerance to drought stress. In: Abiotic stress in plants. IntechOpen; 2010. p. 57–67. https://doi.org/10.1007/s12559-021-09926

Kasimir-Klemedtsson Å, Klemedtsson L, Berglund K, Martikainen P, Silvola J, Oenema O. Greenhouse gas emissions from farmed organic soils: A review. Soil Use Manage. 1997;13:245–50.

Khan A, Tan DKY, Munsif F, Afridi MZ, Shah F, Wei F, et al. Nitrogen nutrition in cotton and control strategies for greenhouse gas emissions: A review. Environ Sci Pollut Res. 2017;24(30):23471–87. https://doi.org/10.1007/s11356-017-0131-y

Kotsyurbenko OR, Glagolev MV, Merkel AY, Sabrekov AF, Terentieva IE. Methanogenesis in soils, wetlands, and peat. In: Stams A, Sousa D, editors. Biogenesis of hydrocarbons. Handbook of hydrocarbon and lipid microbiology. Cham: Springer; 2019. https://doi.org/10.1007/978-3-319-53114-4_9-1

Krüger M, Frenzel P, Conrad R. Microbial processes influencing methane emission from rice fields. Global Change Biol. 2001;7(1):49–63.

Ku HH, Hayashi K, Agbisit R, Villegas-Pangga G. Evaluation of fertilizer and water management effect on rice performance and greenhouse gas intensity in different seasonal weather of tropical climate. Sci Total Environ. 2017;601–602: 1254–62. https://doi.org/10.1016/j.scitotenv.2017.05.277

Kudo Y, Noborio K, Shimoozono N, Kurihara R. The effective water management practice for mitigating greenhouse gas emissions and maintaining rice yield in central Japan. Agric Ecosyst Environ. 2014;186:77–85. https://doi.org/10.1016/j.agee.2014.01.015

Kumar SR, David EM, Pavithra GJ, Sajith GK, Lesharadevi K, et al. Enabling greenhouse gas emission reduction while improving rice yield with a methane-derived microbial biostimulant. bioRxiv. 2024;13:584920. https://doi.org/10.1101/2024.03.13.584920

Lagomarsino A, Agnelli AE, Linquist B, Adviento-Borbe MA, Agnelli A, Gavina G, et al. Alternate wetting and drying of rice reduced CH4 emissions but triggered N2O peaks in a clayey soil of central Italy. Pedosphere. 2016;26(4):533–48. https://doi.org/10.1016/S1002-0160(15)60063-7

Lawrencia D, Wong SK, Low DYS, Goh BH, Goh JK, Ruktanonchai UR, et al. Controlled release fertilizers: A review on coating materials and mechanism of release. Plants. 2021;10(2):238. https://doi.org/10.3390/plants10020238

Li C, Salas W, DeAngelo B, Rose S. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next twenty years. J Environ Qual. 2006;35(4):1554–65. https://doi.org/10.2134/jeq.2005.0208

Li J, Li Y, Wan Y, Wang B, Waqas MA, Cai W, et al. Combination of modified nitrogen fertilizers and water saving irrigation can reduce greenhouse gas emissions and increase rice yield. Geoderma. 2018;315:1–10. https://doi.org/10.1016/j.geoderma.2017.11.033

Liang K, Zhong X, Huang N, Lampayan RM, Liu Y, Pan J, et al. Nitrogen losses and greenhouse gas emissions under different N and water management in a subtropical double-season rice cropping system. Sci Total Environ. 2017;609(3):46–57. https://doi.org/10.1016/j.scitotenv.2017.07.118

Linquist BA, Anders MM, Adviento-Borbe MAA, Chaney RL, Nalley LL, da Rosa EFF, et al. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Global Change Biol. 2015;21(1):407–17. https://doi.org/10.1111/gcb.12701

Linquist BA, Marcos M, Adviento-Borbe MA, Anders M, Harrell D, Linscombe S, et al. Greenhouse gas emissions and management practices that affect emissions in US rice systems. J Environ Qual. 2018;47(3):395–409. https://doi.org/10.2134/jeq.2017.11.0445

Liu W, Hussain S, Wu L, Qin Z, Li X, Lu J, et al. Greenhouse gas emissions, soil quality, and crop productivity from a mono-rice cultivation system as influenced by fallow season straw management. Environ Sci Pollut Res. 2016;23(1):315–28. https://doi.org/10.1007/s11356-015-5227-7

Malyan SK, Bhatia A, Tomer R, Harit RC, Jain N, Bhowmik A, et al. Mitigation of yield-scaled greenhouse gas emissions from irrigated rice through Azolla, Blue-Green algae, and plant growth–promoting bacteria. Environ Sci Pollut Res. 2021;28(37):51425–39. https://doi.org/10.1007/s11356-021-14210-z

Maneepitak S, Ullah H, Datta A, Shrestha RP, Shrestha S, Kachenchart B. Effects of water and rice straw management practices on water savings and greenhouse gas emissions from a double-rice paddy field in the Central Plain of Thailand. Eur J Agron. 2019;107:18–29. https://doi.org/10.1016/j.eja.2019.04.002

Maraseni TN, Deo RC, Qu J, Gentle P, Neupane PR. An international comparison of rice consumption behaviours and greenhouse gas emissions from rice production. J Clean Prod. 2018;172:2288–300. https://doi.org/10.1016/j.jclepro.2017.11.182

Maraseni TN, Mushtaq S, Maroulis J. Greenhouse gas emissions from rice farming inputs: A cross-country assessment. J Agric Sci. 2009; 147(2):117–26. https://doi.org/10.1017/S0021859608008411

Meijide A, Gruening C, Goded I, Seufert G, Cescatti A. Water management reduces greenhouse gas emissions in a Mediterranean rice paddy field. Agric Ecosyst Environ. 2017;238:168–78. https://doi.org/10.1016/j.agee.2016.08.017

Mohanty S, Swain CK, Sethi SK, Dalai PC, Bhattachrayya P, Kumar A, et al. Crop establishment and nitrogen management affect greenhouse gas emission and biological activity in tropical rice production. Ecol Eng. 2017;104:80–98. https://doi.org/10.1016/j.ecoleng.2017.03.014

Monaco F, Sali G, Ben Hassen M, Facchi A, Romani M, Valè G. Water management options for rice cultivation in a temperate area: A multi-objective model to explore economic and water saving results. Water. 2016;8(8):336. https://doi.org/10.3390/w8080336

Narrowe AB, Borton MA, Hoyt DW, Smith GJ, Daly RA, Angle JC, et al. Uncovering the diversity and activity of methylotrophic methanogens in freshwater wetland soils. mSystems. 2019;4(6):10–1128.

Nasrullah M, Liang L, Rizwanullah M, Yu X, Majrashi A, Alharby HF, et al. Estimating nitrogen use efficiency, profitability, and greenhouse gas emission using different methods of fertilization. Front Plant Sci. 2022;13:1–15. https://doi.org/10.3389/fpls.2022.869873

Nayak D, Saetnan E, Cheng K, Wang W, Koslowski F, Cheng YF, et al. Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. Agric Ecosyst Environ. 2015;209:108–24. https://doi.org/10.1016/j.agee.2015.04.035

Van Nguyen N, Ferrero A. Meeting the challenges of global rice production. Paddy Water Environ. 2006;4(1):1–9. https://doi.org/10.1007/s10333-005-0031-5

Pathak J, Jaiswal J, Shukla RK, Singh DK, Sinha RP. Algal biofertilizers as plant growth stimulants for sustainable agriculture. J Med Plants Stud. 2024;12(1):25–37. https://doi.org/10.22271/plants.2024.v12.i1a.1622

Peyron M, Bertora C, Pelissetti S, Said-Pullicino D, Celi L, Miniotti E, et al. Greenhouse gas emissions as affected by different water management practices in temperate rice paddies. Agric Ecosyst Environ. 2016;232:17–28. https://doi.org/10.1016/j.agee.2016.07.021

Qin X, Li Y, Wang H, Liu C, Li J, Wan Y, et al Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south China. Sci Total Environ. 2016;569–570: 1390–401. https://doi.org/10.1016/j.scitotenv.2016.06.222

Rahman MM, Yamamoto A. Methane cycling in paddy field: A global warming issue. In: Agrometeorology. IntechOpen; 2020. p. 1–22. https://doi.org/10.5772/intechopen.94200

Ramessh C, Singh D, Kannan P, Surya R. Evaluating the effect of biofertilizers in mitigating GHGs in puddled rice (*Oryza sativa*. L). J Cereal Res. 2022;14(Suppl 2):68–72. https://doi.org/10.25174/2582-2675/2022/125330

Raton FL, Fahad S, Sönmez O, Turan V, Adnan M, Saud S, et al., editor. Sustainable soil and land management and climate change. In Footprints of climate variability on plant diversity. First. Boca Raton: CRC Press; 2021.

Sass RL. CH4 emissions from rice agriculture. In: Good practice guidance and uncertainty management in national greenhouse gas inventories. Hayama: IPCC; 2000. p. 399. Rice agriculture breakout group: Janssen L, Yagi K, Denier van der Gon H, Lantin R. Reviews by Mosier A, Irving WN.

Saud S, Shi Z, Xiong L, Danish S, Datta R, Ahmad I, et al. Recognizing the basics of Phytochrome-Interacting factors in plants for abiotic stress tolerance. Plant Stress. 2022;3:100050. https://doi.org/10.1016/j.stress.2021.100050

Saud S, Wang D, Fahad S. Improved nitrogen use efficiency and greenhouse gas emissions in agricultural soils as producers of biological nitrification inhibitors. Front Plant Sci. 2022;13:854195. https://doi.org/10.3389/fpls.2022.854195

Shah AN, Iqbal J, Tanveer M, Yang G, Hassan W, Fahad S, et al. Nitrogen fertilization and conservation tillage: A review on growth, yield, and greenhouse gas emissions in cotton. Environ Sci Pollut Res. 2017;24(3):2261–72. https://doi.org/10.1007/s11356-016-7894-4

Simth P. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L, editors. Climate change: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2007.

Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric Ecosyst Environ. 2009;133(3–4):247–66. https://doi.org/10.1016/j.agee.2009.04.021

Van Spanning RJM, Delgado MJ, Richardson DJ. The nitrogen cycle: denitrification and its relationship to N2 fixation. In: Nitrogen fixation in agriculture, forestry, ecology, and the environment. Dordrecht: Springer Netherlands; 2005. p. 277–342.

Stams AJM, Teusink B, Sousa DZ. Ecophysiology of acetoclastic methanogens In: Stams AJM, Sousa DZ, editors. Handbook of hydrocarbon and lipid microbiology. Vol. 2, Biogenesis of hydrocarbons. Cham: Springer; 2019.

Sun H, Zhang Y, Yang Y, Chen Y, Jeyakumar P, Shao Q, et al. Effect of biofertilizer and wheat straw biochar application on nitrous oxide emission and ammonia volatilization from paddy soil. Environ Pollut. 2021;275:116640. https://doi.org/10.1016/j.envpol.2021.116640

Tran DH, Hoang TN, Tokida T, Tirol-Padre A, Minamikawa K. Impacts of alternate wetting and drying on greenhouse gas emission from paddy field in Central Vietnam. Soil Sci Plant Nutr. 2018;64(1):14–22.

Trinh MV, Tesfai M, Borrell A, Nagothu US, Bui TPL, Quynh VD, et al. Effect of organic, inorganic and slow-release urea fertilisers on CH 4 and N 2 O emissions from rice paddy fields. Paddy and Water Environment. 2017;15:317–30.

Vergé XPC, De Kimpe C, Desjardins RL. Agricultural production, greenhouse gas emissions and mitigation potential. Agricult Forest Meterol. 2007;142(2–4):255–69. https://doi.org/10.1016/j.agrformet.2006.06.011

Wang H, Zhang Y, Zhang Y, McDaniel MD, Sun L, Su W, et al. Water-saving irrigation is a 'win-win' management strategy in rice paddies – With both reduced greenhouse gas emissions and enhanced water use efficiency. Agricult Water Manag. 2020;228:105889. https://doi.org/10.1016/j.agwat.2019.105889

Wang X, Bai J, Xie T, Wang W, Zhang G, Yin S, et al. Effects of biological nitrification inhibitors on nitrogen use efficiency and greenhouse gas emissions in agricultural soils: A review. Ecotoxicol Environ Safety. 2021;220:112338. https://doi.org/10.1016/j.ecoenv.2021.112338

Wassmann R, Neue HU, Ladha JK, Aulakh MS. Mitigating greenhouse gas emissions from rice-wheat cropping systems in Asia. Environ, Dev Sustain. 2004;6:65–90.

Win EP, Win KK, Bellingrath-Kimura SD, Oo AZ. Influence of rice varieties, organic manure and water management on greenhouse gas emissions from paddy rice soils. PLoS One. 2021;16:e0253755. https://doi.org/10.1371/journal.pone.0253755

Wu C, Cui K, Wang W, Li Q, Fahad S, Hu Q, et al Heat-induced cytokinin transportation and degradation are associated with reduced panicle cytokinin expression and fewer spikelets per panicle in rice. Front Plant Sci. 2017;8:1–15. https://doi.org/10.3389/fpls.2017.00371

Wu C, Song Y, Qi B, Fahad S. Effects of asymmetric heat on grain quality during the panicle initiation stage in contrasting rice genotypes. J Plant Growth Regul. 2022;42:630–6. https://doi.org/10.1007/s00344-022-10598

Wu C, Tang S, Li G, Wang S, Fahad S, Ding Y. Roles of phytohormone changes in the grain yield of rice plants exposed to heat: A review. PeerJ. 2019;7:e7792. https://doi.org/10.7717/peerj.7792

Xia L, Xia Y, Li B, Wang J, Wang S, Zhou W, et al. Integrating agronomic practices to reduce greenhouse gas emissions while increasing the economic return in a rice-based cropping system. Agric Ecosyst

Environ. 2016;231:24–33. https://doi.org/10.1016/j.agee.2016.06.020

Xu Y, Ge J, Tian S, Li S, Nguy-Robertson AL, Zhan M, et al. Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. Sci Total Environ. 2015;505:1043–52. https://doi.org/10.1016/j.scitotenv.2014.10.073

Xu Y, Zhan M, Cao C, Tian S, Ge J, Li S, et al. Improved water management to reduce greenhouse gas emissions in no-till rapeseed-rice rotations in Central China. Agric Ecosyst Environ. 2016;221:87–98. https://doi.org/10.1016/j.agee.2016.01.021

Yagi K, Sriphirom P, Cha-un N, Fusuwankaya K, Chidthaisong A, Damen B, et al. Potential and promisingness of technical options for mitigating greenhouse gas emissions from rice cultivation in Southeast Asian countries. Soil Sci Plant Nutr. 2020;66(1):37–49. https://doi.org/10.1080/00380768.2019.1683890

Yulianingsih E, Pramono A, Setyanto p. Greenhouse gas emissions reduction and rice yield potential under bio-fertilizer application. IOP Conf Ser: Earth Environ Sci. 2021;648(1):012115. https://doi.org/10.1088/1755-1315/648/1/012115

Zhang X, Zhou S, Bi J, Sun H, Wang C, Zhang J. Drought-resistance rice variety with water-saving management reduces greenhouse gas emissions from paddies while maintaining rice yields. Agric Ecosyst Environ. 2021;320:107592. https://doi.org/10.1016/j.agee.2021.107592

Zhang ZS, Guo LJ, Liu TQ, Li CF, Cao CG. Effects of tillage practices and straw returning methods on greenhouse gas emissions and net ecosystem economic budget in rice-wheat cropping systems in central China. Atmos Environ. 2015;122:636–44. https://doi.org/10.1016/j.atmosenv.2015.09.065

Zhao Z, Yue Y, Sha Z, Li C, Deng J, Zhang H, et al. Assessing impacts of alternative fertilizer management practices on both nitrogen loading and greenhouse gas emissions in rice cultivation. Atmos Environ. 2015;119:393–401. https://doi.org/10.1016/j.atmosenv.2015.08.060

Zheng H, Huang H, Yao L, Liu J, He H, Tang J. Impacts of rice varieties and management on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. Biogeosciences. 2014;11(13):3685–93. https://doi.org/10.5194/bg-11-3685-2014

Zhong Y, Wang X, Yang J, Zhao X, Ye X. Exploring a suitable nitrogen fertilizer rate to reduce greenhouse gas emissions and ensure rice yields in paddy fields. Sci Total Environ. 2016;565:420–6. https://doi.org/10.1016/j.scitotenv.2016.04.167

Zhou Y, Liu K, Harrison MT, Fahad S, Gong S, Zhu B, et al. Shifting rice cropping systems mitigates ecological footprints and enhances grain yield in central China. Front Plant Sci. 2022;13:1–12. https://doi.org/10.3389/fpls.2022.895402

How to cite this article: Yadav SPS, Ghimire NP, Paudel P, Mehata DK, Bhujel S. Advancing effective methods for mitigating greenhouse gas emissions from rice (*Oryza sativa* L.) fields. J Sustain Agric Environ. 2024;3:e70012. https://doi.org/10.1002/sae2.70012