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Options for Mitigating Green House Gas Emission from Rice Fields - A Review

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Abstract

Climate change poses a serious threat to global food security, with rice cultivation emerging as both a contributor to and a victim of this crisis. This review article explores the mechanisms behind greenhouse gas emissions from rice fields, focusing on microbial processes such as methanogenesis and denitrification, and highlights the mitigation strategies that balance productivity with environmental sustainability. The study emphasizes that water and fertilizer management are pivotal levers for reducing emissions. Techniques like Alternate Wetting and Drying, mid-season drainage, and controlled irrigation have shown promise in cutting methane emissions by up to 90%, though they may increase nitrous oxide emissions, necessitating careful trade-off management. Fertilizer innovations including enhanced efficiency fertilizers, nitrification inhibitors, and nano fertilizers offer further avenues for emission reduction while improving nitrogen use efficiency. Beyond agronomic practices, the selection of rice cultivars such as low-emission, high-yielding, and genetically engineered varieties demonstrate significant potential in reducing methane and nitrous oxide emissions. Additionally, rice straw management through composting, biochar production, and avoiding open-field burning can drastically lower the carbon footprint of rice farming. Microbial innovations, such as inoculating rice with methane-oxidizing bacteria or using plant microbial fuel cells, further enhance mitigation efforts. Despite these advances, challenges remain in scaling these solutions due to socio-economic constraints, regional variability and farmer adoption barriers.

Keywords: Alternate wetting and drying (AWD), climate change (CC), rice and greenhouse gas (GHG), methane (CH_4), nitrous oxide (N_2O)

Introduction

The phenomenon of climate change (CC) presents a substantial risk, causing rise in global average temperature and resultant climate catastrophes worldwide (Jackson *et al.*, 2020), chiefly attributable to the augmented atmospheric concentrations of both natural and anthropogenic greenhouse gases (GHGs) including water vapour, ozone (O_3), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases, which collectively modulate atmospheric radiative forcing and influence Earth's temperature by preventing infrared radiation from escaping into space (Kumar, 2024; Patterson, 2012). The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) reiterated that the rapid warming of the climate system is indisputable, primarily driven by anthropogenic GHG emissions (IPCC, 2023) reaching a record high in 2023, the warmest year on record, with a global average temperature of 1.45°C (±0.12°C) above pre-industrial levels, surpassing the previous record by 0.17°C (Sandford *et al.*, 2024; WMO, 2023). From 2011 to 2020, the global temperature was 1.1°C higher than the pre-industrial period of 1850–1900. Boosted by the *El Nino* phenomenon, the period spanning from February 2023 to January 2024 marked the first instance where the global average temperature surged 0.64°C above the 1991–2020 average and 1.52°C above the 1850-1900 average (Copernicus Climate Change Service, 2024). Moreover, the mean surface temperatures are anticipated to increase by 2.2°C to 3.5°C by mid-century without effective measures to mitigate global warming (IPCC, 2023). The consequences of CC, such as rising temperatures, heat waves, sea level rise, altered precipitation, prolonged droughts, severe storms, and poor air quality, are both observed and anticipated shortly (Sonwani and Saxena, 2022). Projections indicate that the adverse effects of CC will continue to worsen (Dhillon and Sohu, 2024).

Agriculture is the pivotal economic sector accountable for ensuring both food security and nutritional adequacy. Nevertheless, it exerts direct or indirect influence on the phenomenon of global climate alteration through the release of three of the major six GHGs *viz.*, CO_2, CH_4, and N_2O (Panchasara *et al.*, 2021), whereby agricultural soils serve as both source and sink of these gases across nearly all terrestrial ecosystems (Basheer *et al.*, 2024). These gases are integral to regulating the radiative balance by their capacity to absorb and emit specific infrared radiation reflecting from the terrestrial surface. Apart from being a dynamic GHG, CH_4 influences atmospheric oxidation by regulating tropospheric hydroxyl radical levels (Holmes, 2018; Tian *et al.*, 2020), whereas N_2O contributes to the stratospheric ozone depletion (Ravishankara *et al.*, 2009). Likewise, CO_2 also largely contributes to global CC, accounting for over half of the total greenhouse effect (Liu *et al.*, 2013). Additionally, CC is concurrently engendering significant challenges for global agricultural productivity, resulting in elevated food prices (Fahad *et al.*, 2022). Agriculture sector bears the primary responsibility for non-CO_2 emissions, notably CH_4 and N_2O, with their respective global warming potentials (GWPs) being 28 and 273 times greater than that of CO_2, over a century (IPCC, 2023). Agriculture accounts for approximately 50% and 60% of global CH_4 and N_2O emissions, respectively, accounting for approximately 10% to 12% of total anthropogenic GHG emissions (Xu *et al.*, 2016). The emanation of CH_4 from this sector is predominantly from activities such as livestock husbandry (enteric fermentation and manure handling) and the cultivation of rice. N_2O is predominantly released as a result of the utilization of nitrogenous fertilizers on agricultural lands. By 2023, key GHG concentrations have risen significantly from pre-industrial levels, with CO_2 increasing by about 50% from 280 to 420 ppm, CH_4 by 176% from 700 to 1934 ppb, and N_2O by 25% from 270 to 336.9 ppb (EEA, 2025), corroborating the World Meteorological Organization's Greenhouse Gas Bulletin which recorded CO_2 at 415.7 ppm, CH_4 at 1908 ppb, and N_2O at 334.0 ppb in 2021, indicating 149%, 262%, and 124% of pre-industrial levels, respectively.

Rice production is identified as a crucial sector of global agriculture that serves as the primary staple sustenance for over half the global population particularly concentrated in regions such as Asia, Sub-Saharan Africa, and South America, with cultivation spanning approximately 11% of the world's total arable land (USDA, 2023). In the 2023 crop year, global rice cultivation spanned approximately 168 million hectares, with India and China as the foremost producers; India's paddy rice output reached over 206.7 million metric tons (MMT), while China's slightly surpassed 206 MMT, culminating in a total rice production of 537.72 MMT for the 2024 marketing year (Shahbandeh, 2025). Projections indicate an anticipated rise in global rice consumption from 480 million tons in 2014 to close to 550 million tons by 2030 (Yuan *et al.*, 2021). However, the carbon footprint of rice production is substantial, with global emissions of 2430 kg CO_2 eq per megagram of grain in 2020 projected to rise due to rising consumption despite of burgeoning population. This makes rice a major contributor to global warming, particularly in Southeast, South, and East Asia (Abdo *et al.*, 2024). Conversely, rice production is also severely impacted by CC, with forecasts suggesting a potential 51% reduction in cultivation due to factors such as altered rainfall patterns, increased temperatures, and extreme weather events (Hussain *et al.*, 2020). Rising temperatures devastate rice yields, with every 1°C increase in minimum temperature causing 7% to 10% drop during critical growth phases such as reproduction (Fahad *et al.*, 2019; Peng *et al.*, 2004; Saxena and Kumar, 2022; Sanadya *et al.*, 2024; Umarani *et al.*, 2020) with 3.2 % drop in rice yields (Zhao *et al.*, 2017). Therefore, rice cultivation is a major concern to the scientific community and a considerable threat to sustainable agriculture. Furthermore, the attainment of the climate objective to confine global temperature rise to well below 2°C (3.6°F) with an ideal target of 1.5°C (2.7°F) above pre-industrial levels as highlighted in the Paris Climate Agreement (UNFCC, 2015) necessitates substantial reductions in GHGs across all agricultural sectors by 2030, with specific emphasis on the rice sector. This requires a "win-win" rice production strategy which can boost yield while reducing emissions.

Mechanism of greenhouse gas emissions from rice fields

Agricultural soils assume an imperative function in the release of GHGs, specifically CH_4, N_2O, and CO_2 through intricate interactions involving soil flora and microorganisms. In rice-cropping systems, direct emissions include CH_4 from inundated paddy fields, N_2O from nitrogen-based fertilizer application, and CO_2 emissions from plant rhizosphere and soil microbial respiration. Whereas, indirect emissions result from rice production, storage, consumption, waste chains and transportation of agricultural input production such as human inputs, fertilizers, fuel consumption, and pest and weed control (Ji *et al.*, 2024). Rice cultivation is the third most significant contributor to non CO_2 GHG emissions within the agricultural domain, trailing behind livestock and various forms of croplands on a global scale (Trang *et al.*, 2022). The traditional practice of paddy farming with inundated condition, wherein organic matter undergoes anoxic decomposition release of CH_4 by the process of methanogenesis, whereas, in aerobic soil, decomposition occurs in the presence of oxygen with the release of CO_2 (Gupta *et al.*, 2021). N_2O emissions arise from microbial N transformations through the processes of soil nitrification and denitrification, both of which can co-exist in flooded rice soils, and also by the heterotrophic reduction of nitrate-nitrogen to ammonium (Bhattacharyya *et al.*, 2013; Kuypers *et al.*, 2018).

Methanogenesis, methanotrophy and methane emission from rice paddies

CH_4 is the second most crucial GHG after CO_2 in terms of GWP, predominantly released from inundated rice paddies (Conrad, 2007), characterized by high radiative efficiency with shorter lifespan than CO_2. It exhibits high and moderate GWPs, respectively, over short and longer timescales (Balcombe *et al.*, 2018). Its atmospheric concentration has surged from preindustrial benchmark of 722 ppb (Wang *et al.*, 2017), contributing almost one quarter of the cumulative radiative forcings for CO_2, CH_4, and N_2O combined since 1750 (Etminan *et al.*, 2016), while global CH_4 emissions have consistently risen (Lamb *et al.*, 2021). With rice cultivation and livestock contributing to a current concentration of 1,895 ppb (Feng *et al.*, 2023), annual global emissions from rice fields were estimated at 27 ± 6 Tg, and predictions indicate persistent or increasing emissions in the future (Wang *et al.*, 2023). Christensen (2024) reported that wetland emissions, especially CH_4 concentrations, are rising faster than ever in the atmosphere. According to Maraseni *et al.,* (2018), rice cultivation is responsible for over 10 % of global CH_4 emissions, particularly in Southeast Asia, one of the world's major rice bowls, where it is accountable for 25% to 33 % of the region's emissions (Umali-Deininger, 2022). Linquist *et al.,* (2012b) reported the GWP of rice cultivation to be 2.7 and 5.7 times greater than that of maize and wheat systems, respectively, with CH_4 specifically accounting for over 90% of rice system's GWP. Recent reports have shown that the highest CH_4 emissions occur from the tillering to flowering stage in rice (Islam *et al.*, 2022b; Mallareddy *et al.*, 2023). Emission of CH_4 from paddy soils largely depends on the production and oxidation rates, mainly governed by methanogen and methanotroph population dynamics in the system, ultimately determining the net CH_4 emission from the rice fields (Fazli *et al.*, 2013).

Methanogenesis or CH_4 production, which necessitates anoxic conditions and low redox potential ($E_h < -150$ mV), is facilitated by anaerobic obligate bacteriae/archae referred to as methanogens (Penning and Conrad, 2007). They use fermentation products from microbial decomposition of plant matter and root exudates; with three biochemical pathways, namely hydrogenotrophic, acetoclastic, and methylotrophic, primarily producing CH_4 from acetate (Malyan *et al.*, 2016a). The CH_4 produced is either released into the atmosphere through three mechanisms, *viz.*, (i) diffusion loss of dissolved CH_4 across the water-air and soil-water interfaces, (ii) ebullition loss by the release of gas bubbles, and (iii) Plant-mediated transport (PMT) - transport into the roots by diffusion and conversion to CH_4 gas within the aerenchyma and cortex of rice plants, followed by concurrent release to the atmosphere through stomata; or, it may undergo methanotrophy. In the rice-growing season, nearly 80 to 90% CH_4 produced in the soil is released by PMT, facilitated by specialized aerenchyma structures that provide oxygen for respiration and CH_4 for transport (Xie and Li, 2002). Additionally, it is observed that 90% of the CH_4 produced in rice soils escapes primarily through micropores in the leaf sheath of the lower leaf position, whereas the leaf blade stomata serve as the secondary site of emission (Islam *et al.*, 2020b). Furthermore, CH_4 may undergo biological oxidation by aerobic and anaerobic methanotrophs, referred to as methanotrophy (Conrad, 2007; Nazaries *et al.,* 2013), wherein aerobic oxidation transforms CH_4 to CO_2 by sequential enzyme activity, utilizing oxygen as an electron acceptor, mediated by CH_4 monooxygenases that can also oxidize substrates such as acetate, ethanol, malate, succinate, and pyruvate. On the other hand, anaerobic methanotrophy or sulphate-dependent CH_4 oxidation is accomplished through physical combination of anaerobic methanotrophic archaea and sulphate-reducing bacteria using sulphate as an electron acceptor, facilitated by metals like iron and manganese (Chowdhary and Dick 2013; Nazaries *et al.*, 2013; Malyan *et al.*, 2016a). However, methanotrophy is limited by rapid ebullition, which reduces the likelihood of CH_4 oxidation.

Nitrous oxide production and emission from rice fields

N_2O is a leading anthropogenic GHG and plays a key role in stratospheric ozone depletion. Agriculture sector is the largest source of N_2O among all the anthropogenic contributors (Reay *et al.*, 2012), particularly due to the significant share of water and N-based fertilizers usage in rice cultivation (Zhao *et al.,* 2019; Jiang *et al.,* 2019). Hence, the likelihood of increased global N_2O emissions from rice fields in the future is markedly elevated (Ussiri and Lal*,* 2012). N_2O is generated through microbial nitrogen transformations in soils, which has been related to two biological processes, *viz.,* (i) Nitrification of ammonium (NH_4^+) under aerobic conditions leading to the loss of N as N_2O, and (ii) Denitrification - the reduction of NO_3^- to N_2O and, ultimately, N_2 gas under anaerobic conditions. It is produced in rice soils after intermittent flooding during the transition from wet to dry soil conditions. N_2O emissions from traditional flooded paddy fields, with 100 % water-filled pore space are minimal, because nitrification cannot occur due to anaerobic conditions, which also precludes denitrification due to the lack of NO_3^- in the soil (Qin *et al.*, 2010), as the NO_3^- gets reduced to NH_4^+ under such anaerobic condition. When N-based fertilizer is applied to the paddy fields, within the oxidized layer at the water-soil interface, the NH_4^+-N gets nitrified to NO_3^-, facilitated by ammonia oxidising bacteria (AOB) and archaea (AOA), with the latter being predominantly accountable for the process (Ahmed *et al.*, 2023). The NO_3^- thus formed in the oxidized layer moves to the reduced layer, where anaerobic bacteria denitrify it, producing N_2O as an intermediary compound (Van Spanning *et al.*, 2005; Xing *et al.,* 2002; Xing *et al.,* 2009). As N_2O is water-soluble, in flooded soils, rice roots absorb and transmit it through leaves *via* the transpiration stream, while it mainly diffuses to the soil surfaces in the absence of flood water.

Carbon dioxide production and emissions from rice fields

Rice paddies emit less CO_2 compared to CH_4 and N_2O, stemming from biotic and abiotic processes, but are often overlooked in studies due to maintained soil organic matter (SOM). The generation and release of CO_2 are contingent upon soil dynamics, prevailing environmental conditions, and the SOM characteristics. Microbial decomposition of reintroduced organic matter drives soil carbon mineralization, making it a key process in the release of CO_2 from soils (Hossain *et al.*, 2017; Mohanty *et al.*, 2017; Rahman, 2013). Anaerobic condition in inundated paddies limits carbon oxidation, thereby accumulates soil organic carbon and results in lower CO_2 emissions while promoting methanogenesis. At the surface level of the soil, CO_2 is liberated through the respiration of roots alongside various forms of flora and fauna (Hossain *et al.,* 2017). Observations indicate that CO_2 flux in rice paddies vary throughout the growth cycle, peaking during flowering due to heightened photosynthesis, while nocturnal emissions are primarily respiration-driven (Wang *et al.*, 2024). Ebullition contributes 13-35 % of CO_2, modulated by the content of crop residue and litter, root activities, and microbial processes that transform the soil carbon reservoirs into CO_2 through the action of soil microorganisms. Additionally, practices like urea application, residue incineration particularly the in-field burning of rice straw, and tillage methodologies enhances CO_2 emissions in rice cultivation (Ngo *et al.*, 2018; Rahman *et al.*, 2017). Urea fertilizer in the presence of water and urease enzyme gets converted to ammonium (NH_4^+), hydroxide (OH^-) and bicarbonate (HCO_3), with the latter ultimately evolving into CO_2 and water (Hussain *et al.,* 2015). However, albeit low efficiency of CO_2 assimilation due to photorespiration, rising atmospheric CO_2 concentrations stimulate photosynthesis and productivity of C3 plants such as rice, a phenomenon known as the CO_2 fertilization effect.

Strategies to prevent rice from warming the planet

Field studies have shown that the changes in crop genetics and selecting suitable cultivar, tillage practices, cropping regime, proper management of irrigation, fertilizer use, use of nitrification inhibitors, crop residue management *etc*., have a significant influence on GHG emissions from rice (Gupta *et al.*, 2021; Yadav *et al.*, 2024; Wassmann *et al.*, 2000), which in turn influence the biogeochemical processes of C and N in the soil (Islam *et al.*, 2020a). Alleviating GHGs emission from agriculture can be achieved by sequestering C in soil and reducing emissions of CH_4 and N_2O from soil through changes in land-use management (Pathak *et al.*, 2014). Such options are important not solely for global warming mitigation but also for improving soil health and fertility, along with optimal yield and curtailing emissions; essentially a win-win sustainable scenario. As major emission-curtailing factors are water regimes and fertilizer management practices, implementing targeted agro-technologies and management practices is crucial for mitigating GHG emissions in rice cultivation.

(A) Reducing GHG emissions while saving water

1. Irrigation and drainage management

Rice, a water-guzzling crop cultivated mostly through suboptimal irrigation methods, suffers from low water efficiency and significant environmental repercussions. Research indicates that water stress, especially, drought adversely affects rice productivity, with yield reductions ranging from 21% to 52% across various cultivars under stress conditions (Hussain *et al.*, 2022). Paddy fields exhibit a comparatively lower level of CO_2 emissions in relation to CH_4 and

N_2O, attributable to the suboptimal conditions for C oxidation of inundated paddy soils. The process of ebullition accounts for approximately 13–35% of CO_2 and 94–97% of CH_4 emissions (Hussain *et al.*, 2015). Rice paddies predominantly contribute to CH_4 emissions; however, under flooded conditions, they also emit N_2O, although to a lesser extent, due to the denitrification process favoured in anaerobic environment (Pittelkow *et al.*, 2013). On the other hand, N_2O emissions experience a substantial increase under conditions of continuous inundation and cycles of drainage which enhances nitrification. Consequently, rice cultivation presents a notable trade-off between CH_4 and N_2O emissions, with the generation of both the gases being significantly affected by the availability of water within the root zone of the crop. Nonetheless, rice production is currently confronted with considerable challenges, including the scarcity of irrigation water, labour shortages, and high GHG emissions from traditional continuous flooding (CF) of rice fields, sometimes over 90% CH_4 emissions than non-flooded practices (Sanchis *et al.*, 2012).

The irrigation patterns employed throughout the rice cultivation process can exert a profound influence on GHG emissions due to their regulation of soil microbial activity and the availability of substrates for non CO_2 emissions. Variations in soil moisture resulting from irrigation directly affect soil redox potential, which can significantly regulate the rates of release and consumption of GHGs (Wang *et al.*, 2017). Numerous studies have underscored the efficacy of diverse water management strategies including alternate wetting and drying (AWD), controlled irrigation (CI), mid-season drainage (MSD) in diminishing CH_4 and N_2O emissions originating from rice fields. In Eastern India, hydrologic variability exerts a considerable influence on GHG emissions, with variables such as the duration of flooding and interactions with crop residues and nitrogen management serving as pivotal determinants (Arenas-Calle *et al.*, 2024).

The AWD irrigation system, developed by the International Rice Research Institute (IRRI) represents a promising, water-saving, and economically viable environmentally benign technique that entails intermittent drying and re-flooding of rice fields. It effectively reduces GHG emissions by 45-90%, enhances water utilization and sustains grain output by promoting non-flooded days throughout the crop cycle (Das *et al.*, 2016; Ogawa *et al.*, 2022). Global freshwater scarcity, labour shortages, and high GHG emissions from traditional continuous flooding (CF) of rice fields are driving the adoption of the AWD irrigation system (Lampayan *et al*., 2015). Conversely, AWD irrigation fosters an ideal environment for nitrification and ensuing denitrification upon re-hydration, which may emit N_2O gas (Jiang *et al.*, 2019). Consequently, a trade-off relationship between CH_4 and N_2O emissions has been identified through water management (Islam *et al.*, 2020b; Islam *et al.*, 2022a). While AWD decreases CH_2 emissions by up to 73% in certain conditions, with sustained rice yields comparable to CF systems (Prangbang *et al.*, 2020; Sander *et al.*, 2020) by enhanced diffusion of atmospheric oxygen into soil, it may also elevate N_2O emissions by 44% (Zhao *et al.*, 2024) due to increased nitrification of NH_4^+ during the dry episode and the subsequent denitrification of NO_3^- during re-wetting of dry soil; however, it still reduces total GHG emissions from rice fields mainly due to reduced CH_4 emissions. Furthermore, lysimeter studies by Phungern *et al.,* (2023) reported reduction of 55.6% for lowland and 59.6% for upland cultivars in GWP for AWD over CF practices, despite an increase in N_2O emissions attributable to higher dissolved oxygen levels. AWD can consistently reduce the amount of soil available P (Adhikary *et al.*, 2023), thereby boosts arbuscular mycorrhizal fungi (AMF) that help plants absorb nitrogen, leaving less for N_2O production and lowering emissions (Storer *et al.*, 2018). A thorough investigation by Aung *et al.,* (2018) further suggested that early-season AWD could effectively lower GHG emissions in contexts where the full-scale implementation of AWD is impractical, achieving CH_4 reductions up to 51.5% in the dry season and 20.1% in the wet season. However, full-AWD practices resulted in a

52.8% to 61.4% reduction compared to CI (controlled irrigation), significantly decreasing CH_4 emissions in the dry season and also reducing early season emissions in the following wet season. AWD and CI have demonstrated significant potential for mitigating CH_4 emissions by approximately 51.6% to 60.5% and reduce nutrient losses while maintaining rice yields (Lee *et al.*, 2023b; Zhao *et al.*, 2024). Additionally, CI and AWD practices effectively decrease N losses, particularly when soil desaturation occurs before re-irrigation, which is crucial for minimizing NO_3^- leaching (Gbedourorou *et al.*, 2024).

MSD (mid-season drainage) in flooded rice systems slashes seasonal CH_4 emissions by an impressive 20-77% averaging at 52% reduction, while the accompanying rise in N_2O emissions contributes only 3% to overall GWP (Perry *et al.*, 2024). In Japan, MSD is widely employed to augment rice yields and conserve water, and its application in areas characterized by high CH_4 emitting soils can lead to a significant reduction in national CH_4 emission estimates (Leon *et al.*, 2017). Liu *et al.,* (2019a), in a meta-analysis focused on MSD, reported 47% reductions in GWP. A global meta-analysis by Wu *et al.*, (2022) revealed that drainage in rice cultivation reduced CH_4 emissions by 57.8%, increased N_2O emissions by 149.9%, and CO_2 emissions by 27.7%, with negligible impact on yield (+0.3%), ultimately decreasing the GWP index by 57.7%.

Furthermore, studies indicate that while CF generally leads to lower N_2O emissions, the implementation of intermittent flooding can paradoxically increase N_2O emissions significantly, sometimes up to three times higher than those from CF fields (Akiyama *et al.*, 2005; Kritee *et al.*, 2018). The adoption of CI methods, such as controlled intermittent flooding (CIF), helps reduce emissions while enhancing water-use-efficiency (Rajasekar and Selvi, 2022). Intermittent wetting and drying (IWD) can lower CH_4 emissions without reducing yields, as observed in the Brahmaputra valley (Rajbonshi *et al.*, 2024). Additionally, the management of fallow periods between rice crops, including practices such as soil drying and aerobic tillage, can impact CH_4 and N_2O emissions, with soil drying treatments resulting in elevated N_2O emissions due to the accumulation of NO_3^- (Sander *et al.*, 2018). Collectively, these studies emphasize the critical importance of tailored water management practices that take into account local hydrologic conditions, soil types, and socio-economic factors to effectively mitigate GHG emissions in rice cultivation.

2. Alternate rice production systems

The conventional wetland rice cultivation methods of puddled transplanted rice (PTR) are both water-intensive and labour-demanding, necessitating the development of water-efficient rice production systems that enhance water productivity in light of the impending water crisis. Soil puddling induces oxygen-deficient conditions that intensify GHG release and nitrogen depletion, ultimately amplifying the environmental footprint of rice cultivation. The choice of rice establishment method, such as transplanted rice versus direct seeding, also affects emissions, with transplanted rice generally producing higher GHG emissions across various fertilizer methods (Tin *et al.*, 2022). However, Moe *et al.,* (2024) found lower GHG emissions in transplanting compared to broadcasting method, without reducing grain yield. Advanced resource conservation methodologies such as direct seeded rice (DSR), system of rice intensification (SRI), and aerobic rice present opportunities to optimize water utilization with reduced environmental footprint and enhanced productivity (Mallareddy *et al.*, 2023; Sultan *et al.*, 2024).

DSR is increasingly favoured over traditional PTR methods, offering benefits like reduced water use, lower labour costs, early crop maturity, and decreased GHG outputs, particularly CH_4 and N_2O, making it environmentally and economically appealing (Mishra *et al.*, 2023). The DSR technique involves sowing pre-germinated seeds in puddled soil (wet-DSR), standing water (water seeding), or dry seeding on a prepared seedbed (dry-DSR), while significantly lowering input needs, conserving 12–35% of water and labour, and curbing methane emissions by up to 90%. (Singh *et al.*, 2024).

The SRI methodology, which integrates practices such as AWD, has been widely adopted and is recognized for its substantial reduction in CH_4 emissions (Uphoff, 2024) 885, with research suggesting a reduction of approximately 35-41% in GHG emissions per hectare relative to traditional methods, while, also enhancing yields by approximately 66%, further decreasing emissions per kilogram of rice produced and lowering production costs, making it a more attractive option for farmers (Dahlgreen and Parr, 2023; Dahlgreen and Parr, 2024). Additionally, SRI practices enhance soil C sequestration and lessen the reliance on chemical inputs, thereby contributing to environmental sustainability and CC mitigation (Hoang *et al.*, 2021). The practice also reduced CH_4 and CO_2 emissions by 59.8% and 20.1% compared to conventional practice, while emitting a small amount of N_2O (up to 0.0002 kg ha^{-1}), which was not detected in conventional methods, and achieved greater grains output with lower seasonal GWP and greenhouse gas emission intensity (GHGI) when coupled with 90 $kgNha^{-1}$ (Mboyerwa *et al.*, 2022).

Aerobic rice, which is cultivated in non-flooded, well-drained soils, not only significantly reduces water consumption and GHG emissions but also enhances water productivity compared to flooded rice, positioning it as a sustainable alternative to traditional methods, although challenges in achieving potential yields remain (George, 2018) Aerobic rice showed better GHG reduction, with CH_4 emissions nearly halved compared to flooded rice (Jinsy, 2014). Furthermore, a study by Ramesh and Rathika (2020) revealed that while transplanted rice exhibited higher CH_4 emissions, aerobic and drip-irrigated rice displayed markedly lower GHG outputs and improved water productivity. The aerobic rice system demonstrated notable environmental benefits, reducing the carbon footprint of rice production by 14.6 and 19.3% over shallow lowland rice and rice intensification systems, respectively (Dash *et al.*, 2023).

In Vietnam the package of improved cultivation techniques known as "1 Must-do, 5 Reductions" (1M5R) integrating AWD alongside other advanced techniques can save up to 11 tons of CO_2 equivalent per hectare annually compared to conventional farming. The approach promotes the use of certified seed and must achieve '5 reductions' in seed rate, fertilizer rate (nitrogen), pesticide rate, water consumption through AWD irrigation, and post-harvest losses as a means to improve the overall sustainability of rice production (IRRI, 2024).

(B) GHG mitigation through fertilizer management

The on-going challenge of improper and non-judicious fertilizer application in agriculture has elicited significant concern. Rice represented 15% of global fertilizer use among the top three cereals (maize, wheat, and rice), with cereals overall accounting for 59% of nitrogen fertilizer consumption. Rice received approximately 16%, 13%, and 12% of the 59% N, 49 % P_2O_5, and 39 % K_2O used by the cereals, respectively (IFA, 2022). Nitrogen fertilization constitutes one of the strategies employed to improve crop yield and sustain soil fertility, though it significantly stimulates N_2O, CH_4 and CO_2 emissions, contributing to enhanced global warming (Menegat *et al.*, 2022). Methane fluxes are highly dependent on carbon availability, which is derived from the application of fertilizers, dead plant tissues, and organic exudates (Bhatia *et al.*, 2005). Nitrogen fertilizer's impact on CH_4 emissions from rice fields is complex, influencing production, oxidation, and transport processes. It can either increase emissions by promoting rice growth and substrate C supply for methanogens or decrease emissions by enhancing CH_4 oxidation by stimulating growth of methanotrophs (Chen *et al.*, 2024). However, the net effect depends on nitrogen source and agronomic practices. Specifically, N fertilization enhances methanogen activity and accelerates organic matter decomposition, significantly increasing CH_4

emissions in acidic soils. Furthermore, approximately three-quarters of N_2O emissions from agricultural soils is from application of nitrogenous fertlizers, which enhances soil microbial activity, thus necessitating meticulous selection for effective mitigation strategies (Mohanty *et al.*, 2017). Additionally, rice plants themselves may contribute to N_2O emissions through a proposed mitochondrial pathway under hypoxic conditions, suggesting dual sources of N_2O in paddies *i.e.,* soil microorganisms and the plants (Timilsina *et al.*, 2020). However, research indicates that only 30-40% of the applied N is effectively absorbed by rice plants, while 60-70% is lost through processes such as ammonia volatilization, denitrification, surface runoff and NO_3^- leaching (Galloway *et al.*, 2003), necessitating improved nitrogen management strategies to enhance nitrogen use efficiency and eventually alleviate GHG emissions.

The effective management of fertilizers has a substantial effect on the reduction of the emissions of N_2O and CH_4, as it is largely affected by the type, rate, mode, timing, and method of fertilizer-N application. Enhancing nitrogen efficiency potentially mitigates N_2O emissions and residual NO_3^- in soil, while the 4R nutrient management approach *viz.*, right source, right time, right rate, and right placement successfully alleviates GHG emissions. Furthermore, promising results have been observed from sophisticated fertilizer management strategies designed to diminish GHG emissions from rice paddies, including the utilization of enhanced efficiency nitrogen fertilizers (EENFs), plant need-based application using leaf colour chart (LCC), precise incorporation into soil, tailored application rates and timings, and the avoidance of excessive use.

The type and amount of fertilizer material used can significantly affect soil microbial activity, thereby altering CH_4 and N_2O emissions. Researchers concluded after a meta-analysis of 155 studies that N fertilizer enhances CH_4 emissions, and the stimulatory effect of urea is more pronounced (2–3 times higher) than that of ammonium sulphate (AMS) (Banger *et al.*, 2012). Elevated levels of NH_4^+N in soil can significantly curb overall CH_4 emissions (Hussain *et al.*, 2015). Urea application enhances the soil NH_4^+N, and due to the structural parallels between CH_4 and NH_4^+ ion (Schimel, 2000), methanotrophs preferentially bind to NH_4^+; therefore limits methanotrophy, ultimately leading to increased CH_4 emission from soil (Malyan *et al.*, 2016a). On the other hand, AMS suppressed methanogens in rice soils. AMS application has been demonstrated to lower CH_4 emissions by 42% to 60% through the promotion of methanotrophic bacteria that oxidize CH_4. This is because the sulphate (SO_4^-) ions present in AMS can inhibit CH_4 production by fostering competition for resources between methanogens and sulphate-reducing bacteria. Ali *et al.,* (2012) and Malyan *et al.,* (2016b) observed 15% - 21% reduction in total seasonal CH_4 flux by AMS over urea. Applying phosphorus (P) and potassium (K) fertilizers reduces CH_4 emissions from rice fields, likely by promoting plant aerenchyma development and stimulating methanotrophic bacteria. Although N fertilizer increases CH_4 emissions, combining N, P, and K lowers the CH_4-to-grain yield ratio significantly (Datta *et al.*, 2013). Additionally, Slameto *et al.,* (2024) reported that combined application of NPKS fertilizer with manure fertilizer substantially increased rice yield while reduced CH_4 emissions and GWP values compared to alternative fertilizer formulations. Long-term P fertilizer input reduces CH_4 emissions in rice fields, mainly by improving CH_4 oxidation (Zhu *et al.*, 2022), which highlights the need for judicious P management to increase rice yield while reducing CH_4 emissions. Research by Kang *et al.,* (2024) suggest that the application of silicate fertilizer containing 2.5 % iron slag, particularly those enriched with electron acceptors such as oxidized iron (Fe^{3+}), show promise in reducing CH_4 emissions without compromising rice grain yield or soil characteristics. However, the dynamics of N_2O were questionable. Since the reduced iron (Fe^{2+}) can react as an electron donor, iron slag-based silicate fertilizer application might suppress N_2O emissions by progressing N_2O into N_2 gas during the denitrification process. In the Korean rice paddy, iron slag–based silicate fertilizer, enriched with Fe^{3+}, suppressed seasonal CH_4 emissions by 36–38 % through competition for electrons under anaerobic conditions, while reduces seasonal N_2O emissions by 49–56 % by donating electrons to drive denitrification toward N_2O gas rather than N_2O. It cuts net GWP by 37–40 %, and boosts grain yield by 22–25 % at an optimal soil SiO_2 level of ~183 mg/kg (Galgo *et al.*, 2024).

Microbial processes involved in N_2O production are typically related to the amount of N available in the soil, highlighting N fertilizer rate as the key determinant for N_2O emissions. Meta-analyses by Linquist *et al.,* (2012a) and Zheng *et al.,* (2014) revealed that unlike CH_4 emissions, which rise under low-to-moderate N levels but decline with excessive N, N_2O emissions increase with higher nitrogen input. Notably, at optimal application rate of 150-200 kg N ha^{-1}, yield benefits of nitrogen fertilization surpassed its GWP impact (Zheng *et al.*, 2014). Zhong *et al.,* (2016) reported the same trend with N_2O emissions and N-fertilizer rates, peaking at reproductive phase of rice growth, and suggested 225 kg N/ha as optimal. Regardless of N fertiliser type and biochar rates, increasing N rates increased rice yield and N_2O emissions (Iboko *et al.*, 2023). Thus, decreasing N input in rice soils is a promising strategy to mitigate GHG emissions, particularly N_2O. This is because lower N inputs enhance competition between plants and soil microbes, leading to improved N assimilation by plants and hence reduced N_2O emissions. However, applying less than the optimal amount can deplete SOC and reduce soil productivity.

Enhanced efficiency nitrogen fertilizers (EENFs) such as polymer-coated slow or control release fertilizer (S/CRF) and common N-fertilizer combined with nitrification inhibitor (NI), urease inhibitor (UI), and double inhibitors of UI + NI (DI) are designed to optimize nitrogen use by crops, reducing environmental losses. EENFs reduce CH_4 emissions by boosting oxidation and cut N_2O emissions by limiting N availability for nitrification and denitrification processes (Qian *et al.*, 2023). Compared to conventional N fertilizer, EENFs significantly reduced CH_4 emission by 16.2% and increased rice yield by 7.3%, leading to a 21.7% decline in yield-scaled N_2O emissions (Yang *et al.*, 2022). They further found that Nitrapyrin, DMPP (3, 4-dimethylpyrazole phosphate), and HQ (Hydroquinone) + Nitrapyrin were more effective in reducing CH_4 emissions, while HQ alone had less impact on rice yield than other EENFs. According to Shakoor *et al.,* (2018), N_2O emissions peaked with conventional fertilizer applications, while optimized and slow-release fertilizers reduced emissions by up to 21% in rice-wheat cropping system. Kuchi *et al.,* (2024) reported that coating urea with urease inhibitors conserves 20-25% N and ensures slow, gradual release throughout the crop growth, helping reduce pollution in soil, water, and the environment. Additionally, plant-derived materials such as neem cake, neem oil, and karanja seed extract are potential NIs (Gupta *et al.*, 2021). Biological nitrification inhibitors (BNIs) enhance nitrogen utilisation efficiency, reduce leaching, lower N_2O emissions and boost crop yields. Studies have proved that application of BNIs can decrease N_2O emissions by up to 90% compared to non-BNI producing plants (Saud *et al.*, 2022). Improved rice quality indices have also been observed, indicating that BNIs not only mitigate emissions but also enhance agricultural productivity, with 15.45% yield increase when BNIs are applied alongside conventional fertilizer (Huang *et al.*, 2023). Compounds such as syringic acid derived from rice root exudates inhibit *Nitrosomonas* strains leading to improved nitrogen utilization, and significant reductions in N_2O emissions by 69.1-79.3% in paddy soils and by 40.8%-46.4% from red soil, respectively (Lu *et al.*, 2022). They further found that the nitrification inhibitory efficacy of syringic acid was strongest in acidic red soil, followed by weakly acidic paddy soil, with no significant effect in an alkaline calcareous soil. Additionally, syringic acid addition possessed dual inhibition of both AOA and AOB abundance in paddy and red soil, linked to soil NH_4^+ and dissolved organic carbon.

Nano-fertilizer technology presents a viable approach to reduce agricultural emissions and mitigates climate change through controlled or slow-release of the nutrients (Saraiva *et al.*, 2023; Srivastava *et al.*, 2023). A greenhouse study by Mohanraj *et al.,* (2017) showed that nano-zeolite fertilizers containing NO_3^-N and NH_4^+N facilitate prolonged nutrient release, extending availability up to 11.6 and 20 days, respectively. They further found that while NH_4^+based nano-fertilizer reduced N_2O emissions, NO_2^- based nano-fertilizers decreased CH_4 emissions compared to conventional methods, showcasing enhanced nitrogen management and environmental benefit. Additionally, applying 75 kg N/ha through urea along with three nano-urea foliar sprays at 20, 40 and 60 days after transplanting halved CH_4 and N_2O emissions compared to 150 kg N/ha through urea in conventional split application, while maintaining or boosting yields (Anushka *et al.*, 2024). Moreover, Borah and Baruah (2016) assessed the impact of foliar application of plant growth hormones on CH_4 emission reduction from rice paddies. The results indicated that treatments with indole-3-acetic acid and kinetin (in 20 mg L^{-1} concentration) significantly decreased cumulative CH_4 emissions while enhancing grain productivity, thus presenting a viable approach for both emission regulation and economic yield improvement in rice cultivation.

Nitrogen topdressing in irrigated Eastern India rice fields can be guided by LCC (≥5) and soil plant analysis development (SPAD) or chlorophyll meter (≥37) thresholds, saving 20–47.5 kg N/ha over fixed-timing methods (Maiti *et al.*, 2004). Split application synchronize nutrient supply with crop demand and minimizes N losses to the environment, but show inconsistent effects on N_2O emissions over the course of a season depending on soil properties and water management (Slayden *et al.*, 2022). Typically, N_2O emissions spike shortly after fertilization due to heightened nitrification and denitrification (Gaihre *et al.*, 2020; Gogoi and Baruah, 2014; Shakoor *et al.*, 2018). Urea deep placement (UDP) significantly enhanced rice yield and nitrogen uptake by increasing panicle production per hill and improving nitrogen recovery efficiency (Gaihre *et al.*, 2020), aligning with earlier findings that reported 15%–20% yield gains and 25%–50% urea savings compared to broadcast urea due to targeted nitrogen placement in the root zone (Huda *et al.*, 2016; Islam *et al.*, 2018). However, further investigations are needed before endorsing deeper placement as a sustainable method farming practice as indicated by (Rychel *et al.*, 2020).

(C) Other Agronomic management practices

1. Tillage management

Soil tillage practices exert a considerable influence on GHG emissions during rice cultivation, by altering both the physicochemical and biological characteristics of the soil, thereby enhancing microbial production of CH_4 and N_2O (Oorts *et al.*, 2007). When considering GHGs collectively, soil tillage resulted in a 20 % increase in net global warming relative to NT, underscoring the CC mitigation potential inherent in a NT system. Conventional tillage practices, characterised by extensive soil disturbance, disrupts soil structure, leading to erosion, nutrient depletion, and reduced soil fertility over time. Contrastly, conservation tillage methods such as no-till (NT) and reduced tillage (RT) minimize soil disturbance, helping maintain structure, increase organic matter content, and improve moisture retention (Derpsch *et al.*, 2010). These practices enhance drought resilience and soil health, while lowering GHG emissions and boosting carbon sequestration, thereby supporting climate mitigation and long-term agricultural sustainability (Lal, 2018). In comparison to CT systems, the adoption of NT or RT practices markedly diminished the total GWP (by 6.6 %) linked to CH_4 and N_2O emissions, with NT showing greater mitigation effectiveness under crop rotation, straw removal, specific nitrogen application rates, and land-use conditions; while RT's impact varied widely, often increasing GHG emissions except in upland monoculture systems (Feng *et al.*, 2018). The consistent implementation of NT practices may enhance CH_4 oxidation and, in turn, reduce CH_4

emissions. Omonode *et al.,* (2007) articulated that NT practices limit CH_4 oxidation by compacting soil, thus reducing CH_4 uptake by rice soils. Moreover, research suggests that reducing tillage frequency in rice paddies could lead to diminished CH_4 emissions, attributable to an increase in soil bulk density under NT methodologies, which subsequently reduces soil porosity and ultimately lowers the decomposition rate of organic matter (Ahmad *et al*., 2009; Pandey *et al.*, 2012). However, some researchers contend that NT practices may intensify N_2O emissions from rice soils (Zhang *et al.*, 2011; Nyamadzawo *et al.*, 2013). Bordoloi *et al.,* (2019) reported that a 25% reduction in N fertilizer application rates significantly curbed N_2O emissions from CT and RT agricultural systems. Given the potential for carbon sequestration and CH_4 mitigation, NT practices possess the potential to counterbalance overall GHG emissions. NT cultivation emitted 16.5% less GHGs in terms of CO_2-equivalent compared to conventional tillage practices (Yadav *et al.*, 2020). The potential regulatory influence of RT on CH_4 oxidation may facilitate the mitigation of CH_4 emissions. The reduced GWP associated with NT or RT compared to CT practices in rice agricultural settings (Ahmad *et al.*, 2009) suggests that the implementation of RT could confer significant benefits for GHG mitigation and carbon-smart agricultural practices, warranting endorsement within rice-based cropping systems. Overall, NT or RT practices can mitigate GHG emissions and enhance carbon sequestration, although their effectiveness depends on specific tillage methods and other management practices (Feng *et al.*, 2018).

2. Selection of suitable rice cultivars

The selection of rice varieties that enhance resource use efficiency while minimizing GHG emissions is essential for improving yields and addressing CC and associated abiotic stresses. There exists inherent variability in plant morphology, metabolic processes, and gas transport capabilities among distinct rice cultivars, with traits such as reduced number of sterile tillers, the number of plant tillers, above- and below-ground biomass, root exudates and root aerenchyma, a shorter root system, smaller xylem vessels, an elevated rhizospheric oxidation potential, an optimized harvest index, and a reduced propensity for root excretion, in conjunction with timely maturation traits (Aulakh *et al.*, 2000; Aulakh *et al.*, 2001; Gupta *et al.*, 2021; Bharali *et al.*, 2017; Hussain *et al.*, 2015; Linquist *et al.*, 2018; Oo *et al.*, 2016; Rajendran *et al.*, 2024; Wang and Adachi, 2000; Win *et al.*, 2021) are optimally suited for the reduction of CH_4 emissions from rice soils, highlighting the potential for selective breeding to enhance sustainability in rice cultivation amid GHG concerns (Bhattacharyya *et al.*, 2012). A positive correlation between rice biomass and CH_4 flux has been documented (Khosa *et al.*, 2010; Lee *et al.*, 2023a; Su *et al.*, 2015) , although outcomes from varietal comparisons have been inconsistent (Jiang *et al.*, 2013; Qin *et al.*, 2014). Moreover, a comprehensive meta-analysis by Zheng *et al.,* (2014) demonstrated that while potentially having higher yields, *indica* cultivars display a markedly elevated GWP per unit of yield, measured at 1101.72 kg CO_2 equivalent per Mg, in contrast to 711.38 kg CO_2 equivalent per Mg for *japonica* cultivars. This disparity underscores the significance of considering rice races in alleviating GHG emissions in rice production systems.

Studies indicate that CH_4 emissions from various rice varieties can range significantly, with values reported between 157.05 to 470.73 kg ha^{-1} during the main season, while N_2O emissions were notably lower, peaking at 0.94 kg ha^{-1} (Yadav *et al.*, 2024). The fluctuations in these non-CO_2 emissions may be contingent upon the physiological and anatomical attributes of various rice cultivars. Rice plants are vital for the production, oxidation, and emission of CH_4, serving as the principal conduit for over 90% CH_4 gas stemming from soil to atmosphere. Rice plays a dual role in CH_4 dynamics *viz.*, i) it enhances emissions through pathways like aerenchyma, and substrates (rhizodeposition, providing 40% to 60% of the organic C) for methanogens from the booting stage onwards; ii) it suppresses emissions by facilitating oxygen pathways that inhibit methanogenesis or promote methanotrophy (Conrad, 2007; Yuan *et al.*, 2012).

Furthermore, the overall contribution of rice cultivation to global GHG emissions underscores the importance of adopting low-emission rice varieties and sustainable agricultural practices to balance food security with environmental sustainability (Chirinda *et al.*, 2018; Chen *et al.*, 2024; Yadav *et al.*, 2024). Recent efforts to mitigate emissions include the promotion of submergence-tolerant varieties, drought-tolerant aerobic rice, short-duration varieties, high-yielding hybrids, and transgenic lines tailored for reduced methanogenic activity. Short duration varieties have demonstrated significantly low CH_4 emissions and GWP while exhibited elevated cumulative N_2O emissions (Win *et al.*, 2021). Furthermore, high-yielding and drought-resistant rice varieties can lower GHG emissions by 3.7% to 21.5% through optimized agronomic practices (Ji *et al.*, 2024). Flood-tolerant rice like MTU 1184 may cut irrigation needs, and thereby may potentially influence CH_4 emissions, and stabilize yields in flood-prone areas (Charumathi *et al.*, 2024). Selecting varieties with physiological traits that correlate with lower CH_4 emissions, such as smaller xylem vessels, further supports this mitigation strategy (Bharali *et al.*, 2017). High-yielding short duration hybrids which can minimize the time fields remain flooded, are emerging as a transformative approach to reducing GHG emissions (Hosseiniyan Khatibi *et al.*, 2025). Research shows that hybrid rice can emit 19% less CH_4, often exhibit enhanced nitrogen-use efficiency, reducing nitrogen emissions associated with excessive fertilizer application, compared to traditional inbred varieties under similar conditions (IRRI, 2025).

Research indicates that specific rice varieties exhibit significant differences in CH_4 emissions due to their root microbiomes and genetic traits. For instance, low-methane emitting cultivars like CLXL745 have been shown to have reduced methanogenic activity compared to high-emitting varieties (Hu, 2023; Liechty *et al.*, 2020). The effect of rice varieties on CH_4 emissions depends significantly on the colonization of methanogenic bacteria in roots as documented in Heijing 5 variety (Hu *et al.*, 2023). Additionally, a 70% reduction in CH_4 emissions with sustained yields was achieved when Heijing 5 was hybridized with elite high-yielding varieties, due to improved carbon partitioning and enhanced sugar transporters that optimize above-ground carbon allocation and limited CH_4-promoting root exudates (Hu *et al.*, 2024).

Notably, the cultivar Cliangyouhuazhan (CLYHZ) demonstrated high yield alongside the lowest GWP and GHGI in ratoon rice systems, making it a promising option for reducing CH_4 emissions (Zhang *et al.*, 2024). Genetically engineered rice varieties have shown significant potential in mitigating both CH_4 and N_2O emissions from paddy fields. For instance, transgenic lines with overexpressed nitrate transporters have demonstrated reductions in CH_4 emissions by up to 60% and also reduced total cumulative N_2O compared to their wild types, attributed to decreased root aerenchyma formation and lower methanogen populations in the rhizosphere (Iqbal *et al.*, 2023). India has launched two genome-edited rice varieties, ‘Kamala’ (DRR Dhan 100) and ‘Pusa DST Rice 1’, using Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas) technology. These offer higher yields, climate resilience, and reduced environmental impact, marking a breakthrough in sustainable agriculture (GOI, 2025). Additionally, rice varieties engineered for enhanced root traits, such as gas-tight barriers, facilitate better oxygen diffusion, promoting CH_4 oxidation and nitrification, which further reduces GHG emissions (Jiménez and Pedersen, 2023). Breeding rice to channel more photosynthates to grains instead of roots can cut CH_4 emissions and boost yields (Das and Kim, 2024). A genetically modified rice strain with increased starch content has been linked to lower methanogen levels, thereby contributing to reduced CH_4 emissions (Bodelier, 2015). The root development of a particular rice variety may influence the sequestration of SOC within the soil matrix. Furthermore, this aspect affects microbial activity by providing the carbon sources requisite for the processes of nitrification and denitrification (Borah and Baruah, 2016). Additionally, both qualitative and quantitative modifications in the profile of root exudates among various rice cultivars can significantly alter the rate of CH_4 production (Jia *et al.*, 2002). Varietal selection, along with irrigation management techniques such as AWD, can further mitigate CH_4 emissions (Asch *et al.*, 2023). According to Pramono *et al.,* (2020), the low-emission cultivar Inpari 32 when paired with AWD techniques, achieved a 46% reduction in CH_4 emissions.

3. Rice straw/residues management

Globally, the annual rice straw output ranges between 800 and 1,000 million tonnes, with 600 to 800 million tonnes, primarily from Asia (IRRI, 2018). The straw-to-paddy ratio varies significantly, ranging from 1.0 to 4.3 (Nguyen *et al.,* 2016; Zafar, 2015). Anaerobic decomposition of paddy straw and crop residue under CF conditions is a major contributor of CH_4 emissions from lowland rice fields (Liu *et al.*, 2014). Consequently, managing rice straw emerges as a critical consideration in the effort to regulate GHG emissions associated with lowland rice cultivation. Moreover, the effective management of straw is integral to the functioning of global carbon cycles, particularly through the sequestration of soil organic carbon (SOC).

Off-field practices such as composting, compost application, and bioenergy production offer greater mitigation potential than in-field practices. Proper straw management via surface retention/mulching or converting it into biochar or compost rather than burning or incorporation showed potential to curtail GHG discharges from rice soils (Bhattacharyya and Barman, 2018; Hussain *et al.,* 2015). Composting can mitigate emissions associated with fresh straw, livestock manure, and fertilizers (Gummert *et al.,* 2020). Combining biochar and compost can further enhance mitigation (Allen *et al.,* 2020), while avoiding straw burning, and adopting late incorporation can further reduce GHG potential. These methods have been shown to reduce net GWP by up to 206% compared to conventional practices (Belenguer-Manzanedo *et al.,* 2022). The development of alternative uses for rice straw can foster sustainable value chains, benefiting rural communities while addressing environmental concerns (Prateep Na Talang *et al.,* 2024).

In-field practices

a) Open-field burning – pile burning and spread burning

Rice straw burning is preferred over residue management due to several interrelated factors, including time constraints, short window for sowing of subsequent crops (Parihar *et al.,* 2023; Zaidi *et al.,* 2021), lack of awareness about alternative residue management techniques (Kumar *et al.,* 2023a; Muliarta *et al.,* 2022; Sharma and Bhattu, 2015), and insufficient technological support. The high costs and limited access to alternative technologies further perpetuate this reliance on burning (Shyamsundar *et al.,* 2019). Burning 1 kg of dry rice straw emits 700-4100 mg CH_4, 19-57 mg N_2O, and about 7300 kg CO_2-equivalent per hectare (Bhattacharyya *et al.,* 2021). Studies suggest that the gross GHG emissions, excluding CO_2 as it is net neutral due to photosynthesis in the IPCC guidelines, from burning are up to 98% lower than those from fresh straw incorporation in flooded soils (Van Hung *et al.,* 2020). When CO_2 is included, combustion causes 90% carbon loss, reducing soil carbon sequestration potential of fresh straw incorporation (Chen *et al.,* 2019). When this is accounted for, the net GWP from burning aligns closely with that of complete fresh straw incorporation (Lu *et al.,* 2010). Despite the established negative long-term impacts of straw incineration on soil quality, SOC sequestration and air quality, intensive rice farmers still prefer burning rice straw for its costeffectiveness, reduced weed and disease carryover, and ease of tillage. Additionally, rice straw is less nutritious as fodder due to its silica content, making it less desirable for livestock feed. Thus, open-field burning remains the preferred method for farmers over residue management.

b) Incorporation

Studies indicate that while straw incorporation generally improves SOC levels, it can significantly elevate CH_4 emissions, particularly when applied at inappropriate times or methods, especially before rice transplanting in spring, leading to a potential 120% rise in CH_4 flux compared to no straw application (Song *et al.*, 2019). Conversely, autumn incorporation with soil mixing can reduce CH_4 emissions by 24-43% (Song *et al.*, 2019). Furthermore, while long-term (5 years) straw incorporation tends to lower N_2O emissions by up to 73.1% compared to one-year incorporation, it may also elevate CH_4 emissions by over 100% particularly during tillering stage, necessitating careful management to balance productivity with environmental impacts (Huang *et al.*, 2022). Effective strategies, such as controlled irrigation combined with multi-year straw incorporation, can optimize yields while minimizing GHG emissions (Huang *et al.*, 2022). Therefore, the timing and method of straw incorporation are critical for achieving sustainable rice production and effective GHG management (Danso *et al.*, 2023; Vijayaprabhakar *et al.*, 2021). Nevertheless, the slow decomposition rate of rice straw due to high contents of recalcitrant components (12% Ca, 16% silica and 6%–7% lignin), low N content (< 1.0%), and high C/N ratio (Yadvinder-Singh *et al.*, 2005) leads some farmers to forgo its soil incorporation, particularly in intensive cropping systems with a three-week interlude. As a result, scientists have initiated research aimed at accelerating the decomposition of rice straw. Thailand promotes ploughing harvested paddy into soil with additives to speed up rice straw degradation. Yet, farmers hesitate due to the method's time demands and expensive machinery (Oanh, 2021).

Off-field practices

c) Composting

Straw composting with manure effectively mitigates CH_4 emissions associated with in-field straw incorporation along with CH_4 and N_2O emissions from manure management. Rice yield remained stable with 40-60% less chemical fertilizer when using rice straw manure (RSM). It also sustained soil silicon levels and boosted microbial activity and protein content compared to non-RSM soil (Man *et al.*, 2007). Petersen *et al.,* (2013) suggest that using aerated manure with straw can decrease CH_4 emissions up to 90% compared to anaerobic storage. Improper manure or compost application can lead to nearly total loss of manure N, impacting GHG emissions and fertilizer N supply. This often occurs when manure is applied to high pH, low CEC soils without incorporation. In such cases, composting manure with rice straw can significantly reduce emissions **(***Gummert et al., 2020).*

Rice straw, with its high C:N ratio, is an effective manure compost bulking agent that reduces nitrogen loss to as little as 13% of the initial feedstock nitrogen by enhancing immobilization and substrate adsorption (Chadwick *et al.,* 2011). Furthermore, Spaccini and Piccolo (2017) suggest that composting enhances the stabilized fraction of SOC and sequesters more carbon than in-field aerobic residue decomposition. The added step of producing mushrooms from straw compost may potentially lower N_2O emissions by promoting nitrogen immobilization through mushroom nutrient uptake (Gummert *et al.,* 2020). However, studies on composting show that adding biochar can cut total nitrogen losses by about 52% (Steiner *et al.,* 2010).

d) Biochar production and utilization

Biochar can be prepared from rice straw under controlled pyrolysis (Foong *et al.,* 2022). Biochar production stands out as the optimal approach for agricultural residue management, given the lowest GWP impact and the highest net cash flow (Prateep Na Talang *et al.,* 2024). According to Sun *et al.,* (2019), the application of rice straw-based biochar was more effective in curbing overall NH_3 volatilization compared to the direct incorporation of rice straw. Crop residue decomposition, whether through incorporation or composting, may result in over 80% loss of the initial carbon as CO_2, with rice residue reaching 32.8% oxidation (Sarma *et al.,* 2013). Biochar, by contrast, stabilizes straw carbon more effectively, retaining 40%-50% as long-term soil organic carbon, offering greater climate benefits (Bhattacharyya *et al.,* 2021; Lehmann *et al.,* 2006; Yin *et al.,* 2014). Jia *et al.,* (2025) recommends 30 t ha^{-1} biochar to optimize crop production, enhance carbon balance, and mitigate climate change impacts, highlighting biochar's potential as a sustainable soil amendment in arid ecosystems. Comprehensive meta-analyses revealed high GHGs mitigation potential of biochar application (Allen *et al.,* 2020) alongside up to 70% decrease in the overall carbon footprint associated with rice production (Mohammadi *et al.,* 2016). Liu *et al.,* (2019b) observed a 41% reduction in GHG intensity (yield-scaled emissions) in upland soils and a 17% reduction in paddy soils with use of biochar in different cropping systems. Furthermore, co-application of low biochar (≤9 tons/ha) and medium N (>140 and ≤240 kg N/ha) produced low GHGs emissions, high grain yield, and the lowest GHGI (Iboko *et al.,* 2023; Dong *et al.,* 2024). According to Shen *et al.,* (2024), incorporating biochar into tropical paddy soils can increase rice productivity and decrease N_2O emissions by modifying the genes linked to nitrogen metabolism.

Microbiota management

Soil microbial dynamics influence emissions of CO_2, N_2O and CH_4 from rice soils. In soil, plant root/rhizospheric respiration and microbial respiration significantly contribute to elevated CO_2 concentrations in soil air compared to atmospheric levels. Research highlights that probiotic modulation can lead to significant GHG emission reductions, with a particular study noting a 47.58% decrease in CO_2, 21.53% in CH_4, and 88.50% in N_2O emissions, while increasing rice yield by 27.75% (Pao *et al.*, 2025). Additionally, N-fixing and CH_4-oxidizing bacteria contribute to GHG mitigation by utilizing CH_4 as an energy source and reducing N_2O emissions, fostering sustainable agricultural practices (Minamisawa, 2022). Cable bacteria boost sulphate *via* electrogenic sulphide oxidation, suppressing methanogens and cutting rice soil CH_4 emissions by 93% after one-time inoculation of rice-vegetated soil (Scholz *et al.*, 2020). Inoculating rice seeds with Betaproteobacterium *Azoarcus* sp. KH32C bacteria reduced soil CH_4-producing microbes, cutting CH_4 emissions by 17.2% (no fertilizer) and 23.5% (with nitrogen fertilizer), while maintaining rice grain yield (Sakoda *et al.*, 2022). Furthermore, the integration of microbial bio-stimulants has also proven effective in enhancing grain yields and decreasing CH_4 emissions, which is crucial given that rice accounts for approximately 11% of global anthropogenic CH_4 emissions (Kumar *et al.*, 2024).

The use of man-made (*i.e.*, silicone tube-based) aerenchymatous tissues (MAT) has been demonstrated to enhance soil oxygenation, resulting significant abatement in CH_4 emissions by about 50% in various both in mesocosms and paddy field trials (Yuan *et al.*, 2023). Moreover, they showed that the performance of MAT can be further improved by simply increasing the air pressure in MAT (e.g., -74.2% CH_4 emission at 200 kPa air pressure). Studies demonstrate that Plant Microbial Fuel Cells (PMFCs) can lower CH_4 emissions by up to 57% compared to conventional rice cultivation, especially when integrated with biochar and other enhancements (Al Hussain *et al.*, 2024; Kumar *et al.*, 2023b). The competition for organic substrates between electrogens and methanogens in PMFCs further enhances this reduction (Arends *et al.*, 2014; Deng *et al.*, 2016), with notable studies reporting reductions ranging from 38% to 84% through advanced fertilization techniques (Al Hussain *et al.*, 2024).

Challenges in GHG mitigation from rice fields

The expected rise in both the global population and rice consumption has sparked major concerns about limiting GHG emissions to mitigate future global climate change. The challenge lies in producing more food using less land and fewer resources. Significant advancements in agricultural technology will be required, including the development of high yielding, stress tolerant, low emission rice varieties. Water and fertilizers are the major drivers of GHG emissions from rice fields, primarily CH_4 and N_2O. Research indicates that integrating AWD practices can lower CH_4 emissions, but widespread adoption remains a challenge due to varying farmer incentives and local conditions. Additionally, the variability in soil types and climatic conditions across different regions complicates the implementation of uniform mitigation strategies. Furthermore, a trade-off between CH_4 and N_2O emissions is established; while AWD effectively curtails CH_4, it raises concerns about increased N_2O emissions, necessitating careful management. The DSR, SRI, and aerobic rice production systems effectively mitigates GHG emissions. However, despite its potential benefits, the adoption of such methods has been limited due to several constraints, including lack of awareness among farmers, significant changes in crop management practices compared to traditional practices such as nutrient management, weed management, etc.

While various mitigation strategies have shown promise in reducing GHG emissions from rice fields, several challenges remain, including balancing emissions reduction with yield maintenance, addressing the trade-off between CH_4 and N_2O emissions, adapting mitigation strategies to diverse agroecological conditions, incentivizing farmer adoption of emission-reducing practices, and improving understanding of soil-plant-microbe interactions in GHG production and emission.

However, balancing GHG reduction with food security remains complex, as some mitigation efforts may inadvertently impact crop yields and food availability (Creason *et al.*, 2016). Thus, integrated approaches that combine effective water management, appropriate fertilization, and cultivar selection are essential for sustainable rice production and effective GHG reduction (Sander, 2017). Future research should focus on developing rice varieties with lower GHGE potential, improving models to predict GHG emissions under various management scenarios, exploring the potential of microbial interventions to reduce GHG production, investigating the long-term impacts of mitigation strategies on soil health and productivity, and assessing the economic feasibility of various mitigation options. Furthermore, rice farmers are unlikely to adopt a practice unless it offers higher net returns. Moreover, socio-economic factors, such as access to technology and financial resources, play a crucial role in the adoption of sustainable practices, highlighting the importance of targeted policies and support systems to facilitate change. Addressing these challenges require coordinated effort among researchers, policymakers, and farmers to develop and implement effective mitigation strategies.

Conclusion

Rice production system and its cultivation significantly contribute towards GHG (CH_4 and N_2O) releases and lead to global warming. Reducing GHG emissions from paddy fields is very important to stabilize atmospheric concentration of the GHGs, which can contribute significantly to mitigate global warming. Achieving the Paris Agreement's goal of restricting global warming to below 2°C calls for special focus on the rice sector. Increasing population and escalating rice demand in the future raise serious concerns to curtail GHG emissions from rice cultivation without compromising the yield. By understanding the production mechanisms of CH_4 and N_2O from paddy fields, proper management practices with prime focus on water and fertilizer may play a significant role in mitigating the anthropogenic GHGE from agricultural soil. Crop management practices such as AWD, DSR, SRI, aerobic rice, conservation tillage, addition of compost, integrated biological-chemical nutrient management, efficient crop residue management along with climate resilient varietal selection can mitigate GHG emissions without any yield penalty.

References

Abdo AI, Tian M, Shi Z, Sun D, Abdel-Fattah MK, Zhang J, Wei H and Abdeen MA. 2024. Carbon footprint of global rice production and consumption. *Journal of Cleaner Production*, 474: 143560.

Adhikary PP, Mohanty S, Rautaray SK, Manikandan N and Mishra A. 2023. Alternate wetting and drying water management can reduce phosphorus availability under lowland rice cultivation irrespective of nitrogen level. *Environmental Monitoring and Assessment*, 195(12): 1420.

Ahmad S, Li C, Dai G, Zhan M, Wang J, Pan S and Cao C. 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. *Soil and Tillage Research*, 106(1): 54-61.

Ahmed Z, Gui D, Qi Z, Liu J, Ali A, Murtaza G, Shabbir RN, Tariq M, Shareef M, Zafar S and Khan MS. 2023. Greenhouse gas emissions and mitigation strategies in rice production systems. In: *Global Agricultural Production: Resilience to Climate Change*. Springer zInternational Publishing, Cham, Switzerland. pp. 237-265.

Akiyama H, Yagi K and Yan X. 2005. Direct N2O emissions from rice paddy fields: summary of available data. *Global Biogeochemical Cycles*, 19(1): GB1005

Al Hussain MM, Al Harun MA, Bahar MM, Bhonni NA, Azad MJ and Islam SM. 2024. Enhancing bioelectricity generation and mitigating methane emissions in paddy fields: A novel approach using activated biochar in plant microbial fuel cells. *Energy Conversion and Management*, 307: 118327.

Ali MA, Farouque MG, Haque M and ul Kabir A. 2012. Influence of soil amendments on mitigating methane emissions and sustaining rice productivity in paddy soil ecosystems of Bangladesh. *Journal of Environmental Science and Natural Resources*, 5(1): 179-185.

Allen J, Pascual KS, Romasanta RR, Van Trinh M, Van Thach T, Van Hung N, Sander BO and Chivenge P. 2020. Rice straw management effects on greenhouse gas emissions and mitigation options. In: Gummert M, Hung NV, Chivenge P and Douthwaite B (eds.) *Sustainable Rice Straw Management*. Springer Nature. Cham, Switzerland. pp. 145-159.

Anushka AS, Nunavath U, Kumar GS, Kanade AK, Pradeepkumar S and Sritharan N. 2024. Effect of nano urea on greenhouse gas emissions in transplanted rice (*Oryza sativa* L.) ecosystems. *Plant Science Today*, 11(sp4): 01-07.

Arenas-Calle L, Sherpa S, Rossiter D, Nayak H, Urfels A, Kritee K, Poonia S, Singh DK, Choudhary A, Dubey R and Kumar V. 2024. Hydrologic variability governs GHG emissions in rice-based cropping systems of Eastern India. *Agricultural Water Management*, 301: 108931.

Arends JB, Speeckaert J, Blondeel E, De Vrieze J, Boeckx P, Verstraete W, Rabaey K and Boon N. 2014. Greenhouse gas emissions from rice microcosms amended with a plant microbial fuel cell. *Applied Microbiology and Biotechnology*, 98(7): 3205-3217.

Asch F, Johnson K, Vo TB, Sander BO, Duong VN and Wassmann R. 2023. Varietal effects on methane intensity of paddy fields under different irrigation management. *Journal of Agronomy and Crop Science*, 209(6): 876-886.

Aulakh MS, Bodenbender J, Wassmann R and Rennenberg H. 2000. Methane transport capacity of rice plants. II. Variations among different rice cultivars and relationship with morphological characteristics. *Nutrient Cycling in Agroecosystems*, 58(1): 367-375.

Aulakh MS, Wassmann R, Bueno C and Rennenberg H. 2001. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. *Plant and Soil*, 230(1): 77-86.

Balcombe P, Speirs JF, Brandon NP and Hawkes AD. 2018. Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes and Impacts*, 20(10): 1323-1339.

Banger K, Tian H and Lu C. 2012. Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields?. *Global Change Biology*, 18(10): 3259-3267.

Basheer S, Wang X, Farooque AA, Nawaz RA, Pang T and Neokye EO. 2024. A review of greenhouse gas emissions from agricultural soil. *Sustainability*, 16(11): 4789.

Belenguer-Manzanedo M, Alcaraz C, Camacho A, Ibáñez C, Català-Forner M and Martínez-Eixarch M. 2022. Effect of post-harvest practices on greenhouse gas emissions in rice paddies: flooding regime and straw management. *Plant and Soil*, 474(1): 77-98.

Bharali A, Baruah KK and Gogoi N. 2017. Potential option for mitigating methane emission from tropical paddy rice through selection of suitable rice varieties. *Crop and Pasture Science*, 68(5): 421-433.

Bhatia A, Pathak H, Jain N, Singh PK and Singh AK. 2005. Global warming potential of manure amended soils under rice–wheat system in the Indo-Gangetic plains. *Atmospheric Environment*, 39(37): 6976-6984.

Bhattacharyya P and Barman D. 2018. Crop residue management and greenhouse gases emissions in tropical rice lands. In: Munoz MA and Zornoza R (eds.) Soil Management and Climate Change: Effects on Organic Carbon, Nitrogen Dynamics, and Greenhouse Gas Emissions, Academic Press. pp. 323-335.

Bhattacharyya P, Bisen J, Bhaduri D, Priyadarsini S, Munda S, Chakraborti M, Adak T, Panneerselvam P, Mukherjee AK, Swain SL and Dash PK. 2021. Turn the wheel from waste to wealth: economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. *Science of the Total Environment*, 775: 145896.

Bhattacharyya P, Nayak AK, Raja R and Rao K.S. (Eds.) 2012. *Climate Change: Greenhouse Gas Emission. In Rice Farming and Mitigation Options.* Central Rice Research Institute, Cuttack, Odisha, India. p.165.

Bhattacharyya P, Roy KS, Neogi S, Dash PK, Nayak AK, Mohanty S, Baig MJ, Sarkar RK and Rao KS. 2013. Impact of elevated CO_2 and temperature on soil C and N dynamics in relation to CH_4 and N_2O emissions from tropical flooded rice (*Oryza sativa* L.). *Science of the Total Environment*, 461: 601-611.

Bodelier PL. 2015. Bypassing the methane cycle. *Nature*, 523(7562): 534-535.

Borah L and Baruah KK. 2016. Effects of foliar application of plant growth hormone on methane emission from tropical rice paddy. *Agriculture, Ecosystems and Environment*, 233: 75-84.

Bordoloi N, Baruah KK, Bhattacharyya P and Gupta PK. 2019. Impact of nitrogen fertilization and tillage practices on nitrous oxide emission from a summer rice ecosystem. *Archives of Agronomy and Soil Science,* 65(11): 1493-1506.

Chadwick D, Sommer S, Thorman R, Fangueiro D, Cardenas L, Amon B and Misselbrook T. 2011. Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology,* 166: 514-531.

Charumathi M, Girija Rani M, Suneetha Y, Satish Y, Ramana Rao PV, Ravi Kumar BNVSR, Mahesh S, Dayal Prasad Babu J and Srinivas T. 2024. Development of high yielding deep water rice variety MTU 1184 suitable for semi-deep flooded ecosystem of South Eastern region of India. *Journal of Rice Research*, 17(1): 72–80.

Chen J, Gong Y, Wang S, Guan B, Balkovic J and Kraxner F. 2019. To burn or retain crop residues on croplands? An integrated analysis of crop residue management in China. *Science of the Total Environment*, 662: 141-150.

Chen Y, Guo W, Ngo HH, Wei W, Ding A, Ni B, Hoang NB and Zhang H. 2024. Ways to mitigate greenhouse gas production from rice cultivation. *Journal of Environmental Management*, 368: 122139.

Chirinda N, Arenas L, Katto M, Loaiza S, Correa F, Isthitani M, Loboguerrero AM, Martínez-Barón D, Graterol E, Jaramillo S and Torres CF. 2018. Sustainable and low greenhouse gas emitting rice production in Latin America and the Caribbean: A review on the transition from ideality to reality. *Sustainability*, 10(3): 671.

Chowdhury TR and Dick RP. 2013. Ecology of aerobic methanotrophs in controlling methane fluxes from wetlands. *Applied Soil Ecology*, 65: 8-22.

Christensen TR. 2024. Wetland emissions on the rise. *Nature Climate Change*, 14(3): 210-211.

Conrad R. 2007. Microbial ecology of methanogens and methanotrophs. *Advances in Agronomy*, 96: 1-63.

Copernicus Climate Change Service. 2024. [Online] Available: https://climate.copernicus.eu/copernicus - 2024 -world -experienced -warmest-january-record [07 July 2024].

Creason J, Beach R, Hussein Z, Ragnauth S, Ohrel S and Li C. 2016. Crop yields, food security, and GHG emissions: An analysis of global mitigation options for rice cultivation. Presented at the 19th Annual Conference on Global Economic Analysis, Washington DC, USA.

Dahlgreen J and Parr A. 2023. The impact on greenhouse gas emissions of rice crop management under the system of rice intensification: a review. *Preprints.org*., [online] Available at: https://doi.org/10.20944/preprints202310.1922.v1 [Accessed 6 February. 2024].

Dahlgreen J and Parr A. 2024. Exploring the impact of alternate wetting and drying and the system of rice intensification on greenhouse gas emissions: a review of rice cultivation practices. *Agronomy*, 14(2): 378.

Danso F, Bankole OO, Zhang N, Dong W, Zhang K, Lu C, Shang Z, Li G, Deng A, Song Z and Zheng C. 2023. Plough tillage maintains high rice yield and lowers greenhouse gas emissions under straw incorporation in three rice-based cropping systems. *Agronomy*, 13(3): 880.

Das S and Kim PJ. 2024. Rice breeding for low methane and high yields. *Plant Communications*, 5(5): 100924.

Das S, Chou ML, Jean JS, Liu CC and Yang HJ. 2016. Water management impacts on arsenic behavior and rhizosphere bacterial communities and activities in a rice agro-ecosystem. *Science of the Total Environment*, 542: 642-652.

Dash PK, Bhattacharyya P, Padhy SR, Nauak AK, Poonam A and Mohanty S. 2023. Life cycle greenhouse gases emission from five contrasting rice production systems in the tropics. *Pedosphere*, 33(6): 960–971.

Datta A, Santra SC and Adhya TK. 2013. Effect of inorganic fertilizers (N, P, K) on methane emission from tropical rice field of India. *Atmospheric Environment*, 66: 123-130.

Deng H, Cai LC, Jiang YB and Zhong WH. 2016. Application of microbial fuel cells in reducing methane emission from rice paddy. *Huanjing kexue*, 37(1): 359-365.

Derpsch R, Friedrich T, Kassam A and Li H. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering*, 3(1): 1-25.

Dhillon BS and Sohu VS. 2024. Climate change shocks and crop production: The foodgrain bowl of India as an example. *Indian Journal of Agronomy*, 69(1): 1-10.

Dong W, Danso F, Tang A, Zhang J, Liu Y, Meng Y, Zhang X, Wang L and Yang Z. 2024. Biochar: An Option to Maintain Rice Yield and Mitigate Greenhouse Gas Emissions from Rice Fields in Northeast China. *Agronomy*, 14(12): 3050.

EEA [European Environment Agency]. 2025. https://www.eea.europa.eu/en/analysis/indicators/atmospheric-greenhouse-gas-concentrations.

Etminan M, Myhre G, Highwood EJ and Shine KP. 2016. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, 43(24): 12-614.

Fahad S, Adnan M, Hassan S, Saud S, Hussain S, Wu C, Wang D, Hakeem KR, Alharby HF, Turan V and Khan MA. 2019. Rice responses and tolerance to high temperature. In: *Advances in Rice Research for Abiotic Stress Tolerance,* Woodhead Publishing, pp. 201-224.

Fahad S, Adnan M, Saud S and Nie L. (eds.). 2022. Climate Change and Ecosystems: Challenges to Sustainable Development. CRC Press, Boca Raton, 278p.

Fazli P, Man HC, Shah UK and Idris A. 2013. Characteristics of methanogens and methanotrophs in rice fields: a review. *Asia-Pacific Journal of Molecular Biology and Biotechnology*, 21(1): 3-17.

Feng J, Li F, Zhou X, Xu C, Ji L, Chen Z and Fang F. 2018. Impact of agronomy practices on the effects of reduced tillage systems on CH_4 and N_2O emissions from agricultural fields: a global meta-analysis. *PLos One*, 13(5): e0196703.

Feng L, Palmer PI, Parker RJ, Lunt MF and Bösch H. 2023. Methane emissions are predominantly responsible for record-breaking atmospheric methane growth rates in 2020 and 2021. *Atmospheric Chemistry and Physics*, 23(8): 4863-4880.

Foong SY, Chan YH, Chin BL, Lock SS, Yee CY, Yiin CL, Peng W and Lam SS. 2022. Production of biochar from rice straw and its application for wastewater remediation− An overview. *Bioresource Technology*, 360: 127588.

Gaihre YK, Singh U, Bible WD, Fugice Jr J and Sanabria J. 2020. Mitigating N_2O and NO emissions from direct-seeded rice with nitrification inhibitor and urea deep placement. *Rice Science*, 27(5): 434-444.

Galgo SJ, Canatoy RC, Lim JY, Park HC and Kim PJ. 2024. A potential of iron slag-based soil amendment as a suppressor of greenhouse gas (CH_4 and N_2O) emissions in rice paddy. *Frontiers in Environmental Science*, 12: 1290969.

Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB and Cosby BJ. 2003. The nitrogen cascade. *Bioscience*, 53(4): 341-356.

Gbedourorou SK, Tovihoudji PG, Vanclooster M and Akponikpe IP. 2024. Mitigation of nitrogen loss in rice fields through soil desaturation prior to re-irrigation and the application of controlled-release nitrogen fertilizer: a meta-analysis (No. EGU24-15361). Copernicus Meetings.

George D. 2018. Aerobic rice: Rice for future. *International Journal of Chemical Studies*, 6(6): 481-485.

Gogoi B and Baruah KK. 2014. Seasonal and temporal changes in nitrous oxide emission with fertilizer application in rice ecosystem of North Bank Plain Agroclimatic Zone of North East India. *International Journal of Environmental. Monitoring and Analysis*, 2(5): 289-296.

GOI [Government of India]. Ministry of Agriculture & Farmers Welfare. 2025. 'Union Agriculture Minister Shri Shivraj Singh Chouhan Announces Two Genome-Edited Rice Varieties Developed in India', Press Information Bureau, Government of India, 4 May. Available at: https://pib.gov.in/PressReleasePage.aspx?PRID=2126802 (Accessed: 28 July 2025).

Gummert M, Hung NV, Chivenge P and Douthwaite B (eds.). 2020. Sustainable rice straw management. Springer Nature, Cham, Switzerland. 192p.

Gupta K, Kumar R, Baruah KK, Hazarika S, Karmakar S and Bordoloi N. 2021. Greenhouse gas emission from rice fields: a review from Indian context. *Environmental Science and Pollution Research*, 28(24): 30551-30572.

Hoang VP, Ha XL and Le TT. 2021. The advantages of the system of rice intensification (SRI) in environmental protection and climate change mitigation in rice production–a review. *TNU Journal of Science and Technology*, 226(09): 11-21.

Holmes CD. 2018. Methane feedback on atmospheric chemistry: Methods, models, and mechanisms. *Journal of Advances in Modeling Earth Systems*, 10(4): 1087-1099.

Hossain MB, Rahman MM, Biswas JC, Miah MM, Akhter S, Maniruzzaman M, Choudhury AK, Ahmed F, Shiragi MH and Kalra N. 2017. Carbon mineralization and carbon dioxide emission from organic matter added soil under different temperature regimes. *International Journal of Recycling of Organic Waste in Agriculture*, 6(4): 311-319.

Hosseiniyan Khatibi SM, Adviento-Borbe MA, Dimaano NG, Radanielson AM and Ali J. 2025. Advanced technologies for reducing greenhouse gas emissions from rice fields: Is hybrid rice the game changer?. *Plant Communications*, 6(2): 101224.

Hu J, Bettembourg M, Moreno S, Zhang A, Schnürer A, Sun C, Sundström J and Jin Y. 2023. Characterisation of a low methane emission rice cultivar suitable for cultivation in high latitude light and temperature conditions. *Environmental Science and Pollution Research*, 30(40): 92950-92962.

Huang J, Nie T, Li T, Chen P, Zhang Z, Zhu S, Sun Z and E L. 2022. Effects of straw incorporation years and water-saving irrigation on greenhouse gas emissions from paddy fields in cold region of northeast China. *Agriculture*, 12(11): 1878.

Huang X, Zou Y, Qiao C, Liu Q, Liu J, Kang R, Ren L and Wu W. 2023. Effects of biological nitrification inhibitor on nitrous oxide and nosZ, nirK, nirS denitrifying bacteria in Paddy soils. *Sustainability*, 15(6): 5348.

Huda A, Gaihre YK, Islam MR, Singh U, Islam MR, Sanabria J, Satter MA, Afroz H, Halder A and Jahiruddin M. 2016. Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. *Nutrient Cycling in Agroecosystems*, 104(1): 53-66.

Hussain S, Huang J, Huang J, Ahmad S, Nanda S, Anwar S, Shakoor A, Zhu C, Zhu L, Cao X and Jin Q. 2020. Rice production under climate change: adaptations and mitigating strategies. In: *Environment, Climate, Plant and Vegetation Growth*: Springer International Publishing. pp. 659-686.

Hussain S, Peng S, Fahad S, Khaliq A, Huang J, Cui K and Nie L. 2015. Rice management interventions to mitigate greenhouse gas emissions: a review. *Environmental Science and Pollution Research*, 22(5): 3342-3360.

Hussain T, Hussain N, Tahir M, Raina A, Ikram S, Maqbool S, Fraz Ali M and Duangpan S. 2022. Impacts of drought stress on water use efficiency and grain productivity of rice and utilization of genotypic variability to combat climate change. *Agronomy*, 12(10): 2518.

Iboko MP, Dossou-Yovo ER, Obalum SE, Oraegbunam CJ, Diedhiou S, Brümmer C and Témé N. 2023. Paddy rice yield and greenhouse gas emissions: Any trade-off due to co-application of biochar and nitrogen fertilizer? A systematic review. *Heliyon*, 9(11): e22132.

IFA [International Fertilizer Association]. 2022. Fertilizer use by crop and country for the 2017-2018 period. International Fertilizer Association (IFA), Paris, France; [Available at https://www.ifastat.org/consumption/fertilizeruse-by-crop].

IPCC [Intergovernmental Panel on Climate Change]. 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Core Writing Team, Lee, H. and Romero, J. (eds.)]. IPCC, Geneva, Switzerland.184p.

Iqbal MF, Zhang Y, Kong P, Wang Y, Cao K, Zhao L, Xiao X and Fan X. 2023. High-yielding nitrate transporter cultivars also mitigate methane and nitrous oxide emissions in paddy. *Frontiers in Plant Science*, 14: 1133643.

IRRI [International Rice Research Institute]. 2024. GHG mitigation in rice - Vietnam. GHG Mitigation in Rice. Retrieved from https://ghgmitigation.irri.org/focus-countries/vietnam.

IRRI [International Rice Research Institute]. 2025. Hybrid rice innovations: A path forward for climate-smart agriculture. https://www.irri.org/news-and-events/news/hybrid-rice-innovations-path-forward-climate-smart-agriculture

IRRI. [International Rice Research Institute]. 2018. Rice Straw Management. https://www.irri.org/rice-straw-management

Islam SFU, Sander BO, Quilty JR, De Neergaard A, Van Groenigen JW and Jensen LS. 2020a. Mitigation of greenhouse gas emissions and reduced irrigation water use in rice production through water-saving irrigation scheduling, reduced tillage and fertiliser application strategies. *Science of the Total Environment*, 739: 140215.

Islam SMM, Gaihre YK, Biswas JC, Jahan MS, Singh U, Adhikary SK, Satter MA and Saleque MA. 2018. Different nitrogen rates and methods of application for dry season rice cultivation with alternate wetting and drying irrigation: Fate of nitrogen and grain yield. *Agricultural Water Management*, 196: 144–153.

Islam SMM, Gaihre YK, Islam MR, Ahmed MN, Akter M, Singh U and Sander BO. 2022a. Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. *Journal of Environmental Management*, 307: 114520.

Islam SMM, Gaihre YK, Islam MR, Akter M, Al Mahmud A, Singh U and Sander BO. 2020b. Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh. *Science of the Total Environment*, 734: 139382.

Islam SMM, Gaihre YK, Islam MR, Khatun A and Islam A. 2022b. Integrated plant nutrient systems improve rice yields without affecting greenhouse gas emissions from lowland rice cultivation. *Sustainability*, 14(18): 11338.

Jackson RB, Saunois M, Bousquet P, Canadell JG, Poulter B, Stavert AR, Bergamaschi P, Niwa Y, Segers A and Tsuruta A. 2020. Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environmental Research Letters*, 15(7): 071002.

Ji Y, Zhou Y, Li Z, Feng K, Sun X, Xu Y, Wu W and Zou H. 2024. Carbon footprint research and mitigation strategies for rice-cropping systems in China: a review. *Frontiers in Sustainable Food Systems*, 8: 1375092.

Jia Y, Sun Y, Zhang D, Yang W, Pang J, Siddique KH and Qu Z. 2025. Mitigation of Greenhouse Gas Emissions Using Straw Biochar in Arid Regions of Northwest China: Evidence from Field Experiments. *Agronomy*, 15(5): 1007.

Jia ZJ, Cai ZC, Xu H and Tsuruta H. 2002. Effects of rice cultivars on methane fluxes in a paddy soil. *Nutrient Cycling in Agroecosystems*, 64(1): 87-94.

Jiang Y and Zhang WJ. 2013. Super rice cropping will enhance rice yield and reduce CH_4 emission: a case study in Nanjing, China. *Rice Science*, 20(6): 427-433.

Jiang Y, Carrijo D, Huang S, Chen JI, Balaine N, Zhang W, van Groenigen KJ and Linquist B. 2019. Water management to mitigate the global warming potential of rice systems: A global meta-analysis. *Field Crops Research*, 234: 47-54.

Jiménez JDLC and Pedersen O. 2023. Mitigation of greenhouse gas emissions from rice via manipulation of key root traits. *Rice*, 16(1): 24.

Jinsy VS. 2014. Productivity analysis of aerobic rice (*Oryza sativa* L.) and its impact on greenhouse gas emission. Ph D. Thesis. Kerala Agricultural University, Thrissur, 183p.

Kang YG, Lee JY, Cho G, Yun Y and Oh TK. 2024. Synergy effect of silicate fertilizer and iron slag: A sustainable approach for mitigating methane emission in rice farming. *Science of the Total Environment*, 935: 173392.

Khosa MK, Sidhu BS and Benbi DK. 2010. Effect of organic materials and rice cultivars on methane emission from rice field. *Journal of Environmental Biology*, 31(3): 281-285.

Kritee K, Nair D, Zavala-Araiza D, Proville J, Rudek J, Adhya TK, Loecke T, Esteves T, Balireddygari S, Dava O and Ram K. 2018. High nitrous oxide fluxes from rice indicate the need to manage water for both long-and short-term climate impacts. *Proceedings of the National Academy of Sciences*, 115(39): 9720-9725.

Kuchi S, Manasa V, Gobinath R, Rao DVKN, Kumar MR, Brajendra P. 2024. Assessment of genotypic variability for nitrogen use efficiency (NUE) and improving NUE through urease inhibitors in irrigated rice. *Journal of Rice Research*, 17(1): 81-89.

Kumar A, Nayak AK, Sharma S, Senapati A, Mitra D, Mohanty B, Prabhukarthikeyan SR, Sabarinathan KG, Mani I, Garhwal RS and Thankappan S. 2023a. Rice straw recycling: A sustainable approach for ensuring environmental quality and economic security. *Pedosphere*, 33(1): 34-48.

Kumar K, Manju P and Gajalakshmi S. 2023b. Harnessing plant microbial fuel cells for resource recovery and methane emission reduction in paddy cultivation. *Energy Conversion and Management*, 294: 117545.

Kumar SR, David EM, Pavithra GJ, Sajith GK, Lesharadevi K, Akshaya S, Bassavaraddi C, Navyashree G, Arpitha PS, Sreedevi P, Zainuddin K, Saiyyeda F, Ravindra BB, Udagatti PM, Ganesan R, Palabhanvi B, CS, Kumar VMLD, Theivasigamani P and Subbian E. 2024. Methane-derived microbial biostimulant reduces greenhouse gas emissions and improves rice yield. *Frontiers in Plant Science*, 15: 1432460.

Kumar V. 2024. The Physics Behind Climate Change: Understanding Greenhouse Gases. *International Journal of Innovations in Science, Engineering and Management*, 3(4): 21-25.

Kuypers MM, Marchant HK and Kartal B. 2018. The microbial nitrogen-cycling network. *Nature Reviews Microbiology*, 16(5): 263-276.

Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology*, 24(8): 3285-3301.

Lamb WF, Wiedmann T, Pongratz J, Andrew R, Crippa M, Olivier JG, Wiedenhofer D, Mattioli G, Al Khourdajie A, House J and Pachauri S. 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*, 16(7): 073005.

Lampayan RM, Rejesus RM, Singleton GR and Bouman BA. 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, 170: 95-108.

Lee JH, Lee JY, Kang YG, Kim JH and Oh TK. 2023a. Evaluating methane emissions from rice paddies: A study on the cultivar and transplanting date. *Science of the Total Environment*, 902: 166-174.

Lee JM, Jeong HC, Lee HS, Park HR, Kim GS and Lee SI. 2023b. Effects of water management practices on methane emissions and rice yields in East Asian paddy fields: A regional-scale meta-analysis. *Korean Journal of Soil Science and Fertilizer*, 56(4): 313-324.

Lehmann J, Gaunt J and Rondon M. 2006. Bio-char sequestration in terrestrial ecosystems–a review. *Mitigation and Adaptation Strategies for Global Change*, 11(2): 403-427.

Leon A, Kohyama K, Yagi K, Takata Y and Obara H. 2017. The effects of current water management practices on methane emissions in Japanese rice cultivation. *Mitigation and Adaptation Strategies for Global Change*, 22(1): 85-98.

Linquist B, Van Groenigen KJ, Adviento-Borbe MA, Pittelkow C and Van Kessel C. 2012b. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology,* 18(1): 194-209.

Linquist BA, Adviento-Borbe MA, Pittelkow CM, van Kessel C and van Groenigen KJ. 2012a. Fertilizer management practices and greenhouse gas emissions from rice systems: a quantitative review and analysis. *Field Crops Research,* 135: 10-21.

Linquist BA, Marcos M, Adviento-Borbe MA, Anders M, Harrell D, Linscombe S, Reba ML, Runkle BR, Tarpley L and Thomson A. 2018. Greenhouse gas emissions and management practices that affect emissions in US rice systems. *Journal of Environmental Quality*, 47(3): 395-409.

Liu C, Lu M, Cui J, Li B and Fang C. 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. *Global Change Biology,* 20(5): 1366-1381.

Liu X, Mao P, Li L and Ma J. 2019b. Impact of biochar application on yield-scaled greenhouse gas intensity: a meta-analysis. *Science of the Total Environment*, 656: 969-976.

Liu X, Zhou T, Liu Y, Zhang X, Li L and Pan G. 2019a. Effect of mid-season drainage on CH_4 and N_2O emission and grain yield in rice ecosystem: A meta-analysis. *Agricultural Water Management*, 213: 1028-1035.

Liu Y, Wan KY, Tao Y, Li ZG, Zhang GS, Li SL and Chen F. 2013. Carbon dioxide flux from rice paddy soils in central China: effects of intermittent flooding and draining cycles. *PLos One*, 8(2): e56562.

Lu F, Wang X, Han B, Ouyang Z, Duan X and Zheng H. 2010. Net mitigation potential of straw return to Chinese cropland: estimation with a full greenhouse gas budget model. *Ecological Applications*, 20(3): 634-647.

Lu Y, Hua Y, Lv N, Zu W, Kronzucker HJ, Dong G and Shi W. 2022. Syringic acid from rice roots inhibits soil nitrification and N_2O emission under red and paddy soils but not a calcareous soil. *Frontiers in Plant Science*, 13: 1099689.

Maiti D, Das DK, Karak T and Banerjee M. 2004. Management of nitrogen through the use of leaf color chart (LCC) and soil plant analysis development (SPAD) or chlorophyll meter in rice under irrigated ecosystem. *The Scientific World Journal*, 4(1): 838-846.

Mallareddy M, Thirumalaikumar R, Balasubramanian P, Naseeruddin R, Nithya N, Mariadoss A, Eazhilkrishna N, Choudhary AK, Deiveegan M, Subramanian E and Padmaja B. 2023. Maximizing water use efficiency in rice farming: A comprehensive review of innovative irrigation management technologies. *Water*. 15(10): 1802.

Malyan SK, Bhatia A, Kumar A, Gupta DK, Singh R, Kumar SS, Tomer R, Kumar O and Jain N. 2016a. Methane production, oxidation and mitigation:

a mechanistic understanding and comprehensive evaluation of influencing factors. *Science of the Total Environment*, 572: 874-896.

Malyan SK, Bhatia A, Kumar O and Tomer R. 2016b. Impact of nitrogen fertilizers on methane emissions from flooded rice. *Current World Environment*, 11(3): 846-850.

Man LH, Khang VT and Watanabe T. 2007. Improvement of soil fertility by rice straw manure. In: Development of Technologies and Sustainable Farming Systems in the Mekong Delta of Vietnam, JIRCAS Working Report, Japan International Research Center for Agricultural Sciences -Tsukuba, Japan, 55: pp.76-77.

Maraseni TN, Deo RC, Qu J, Gentle P and Neupane PR. 2018. An international comparison of rice consumption behaviours and greenhouse gas emissions from rice production. *Journal of Cleaner Production*, 172: 2288-2300.

Mboyerwa PA, Kibret K, Mtakwa P and Aschalew A. 2022. Greenhouse gas emissions in irrigated paddy rice as influenced by crop management practices and nitrogen fertilization rates in eastern Tanzania. *Frontiers in Sustainable Food Systems*, 6: 868479.

Menegat S, Ledo A and Tirado R. 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilizers in agriculture. *Scientific Reports*, 12(1): 14490.

Minamisawa K. 2023. Mitigation of greenhouse gas emission by nitrogen-fixing bacteria. *Bioscience, Biotechnology, and Biochemistry*, 87(1): 7-12.

Mishra S, Chaubey AK and Pathak J. 2023. Direct seeded rice: Prospects, constraints and future research work. *Indian Farming,* 73(9): 11–14.

Moe MM, Bunyasiri I and Sirisupluxna P. 2024. Quantifying and comparing greenhouse gas emissions in monsoon rice production: A comprehensive analysis of transplanting and broadcasting sowing methods in Myanmar. *The Open Agriculture Journal,* 18(1): e18743315290024.

Mohammadi A, Cowie A, Mai TL, de la Rosa RA, Kristiansen P, Brandao M and Joseph S. 2016. Biochar use for climate-change mitigation in rice cropping systems. *Journal of Cleaner Production*, 116: 61-70.

Mohanraj J, Lakshmanan A and Subramanian K. 2017. Nano-zeolite amendment to minimize greenhouse gas emission in rice soil. *Journal of Environment and Nanotechnology*, 6(3): 73-76.

Mohanty S, Swain CK, Sethi SK, Dalai PC, Bhattachrayya P, Kumar A, Tripathi R, Shahid M, Panda BB, Kumar U and Lal B. 2017. Crop establishment and nitrogen management affect greenhouse gas emission and biological activity in tropical rice production. *Ecological Engineering*, 104: 80-98.

Muliarta IN, Sukmadewi DKT, Selangga DGW, Kariasa IG, Prawerti DAD, Parwata IKA and Landra IW. 2022. Implementation of LEISA Concept through composting rice straw waste in Subak Telun Ayah, Tegallalang. *Abdimas: Jurnal Pengabdian Masyarakat Universitas Merdeka Malang*, 7(4): 663-675.

Nazaries L, Murrell JC, Millard P, Baggs L and Singh BK. 2013. Methane, microbes and models: fundamental understanding of the soil methane cycle for future predictions. *Environmental Microbiology*, 15(9): 2395-2417

Ngo TT, Ho VK, Tran SN, Duong VC, Nguyen VC and Nguyen VH. (2018). Quantification of direct and indirect greenhouse gas emissions from rice field cultivation with different rice straw management practices–A study in the autumn-winter season in An Giang Province, Vietnam. *Journal of Vietnamese Environment*, 10(1): 49-55.

Nguyen VH, Topno S, Balingbing C, Nguyen VC, Röder M, Quilty J, Jamieson C, Thornley P and Gummert M. 2016. Generating a positive energy balance from using rice straw for anaerobic digestion. *Energy Reports*, 2: 117–122.

Nyamadzawo G, Wuta M, Chirinda N, Mujuru L and Smith JL. 2013. Greenhouse gas emissions from intermittently flooded (Dambo) rice under different tillage practices in chiota smallholder farming area of Zimbabwe. *Atmospheric and Climate Sciences*, 3(4):13-20

Oanh NTK. 2021. Rice straw open burning: emissions, effects and multiple benefits of non-burning alternatives. Vietnam *Journal of Science, Technology and Engineering*, 63(4): 79-85.

Ogawa S, Yamamoto K, Uno K, Thuan NC, Togami T and Shindo S. 2022. Optimal water level management for mitigating GHG emissions through water-conserving irrigation in an giang province, Vietnam. *Sensors*, 22(21): 8418.

Omonode RA, Vyn TJ, Smith DR, Hegymegi P and Gál A. 2007. Soil carbon dioxide and methane fluxes from long–term tillage systems in continuous corn and corn–soybean rotations. *Soil and Tillage Research,* 95: 182-195.

Oo AZ, Sudo S, Inubushi K, Chellappan U, Yamamoto A, Ono K, Mano M, Hayashida S, Koothan V, Osawa T and Terao Y. 2018. Mitigation potential and yield-scaled global warming potential of early-season drainage from a rice paddy in Tamil Nadu, India. *Agronomy*, 8(10): 202.

Oo AZ, Win KT, Motobayashi T and Bellingrath-Kimura SD. 2016. Effect of cattle manure amendment and rice cultivars on methane emission from paddy rice soil under continuously flooded conditions. *Journal of Environmental Biology*, 37(5): 1029.

Oorts K, Merckx R, Gréhan E, Labreuche J and Nicolardot B. 2007. Determinants of annual fluxes of CO_2 and N_2O in long–term no tillage and conventional tillage systems in northern France. *Soil and Tillage Research*, 95(2): 133-148.

Panchasara H, Samrat NH and Islam N. 2021. Greenhouse gas emissions trends and mitigation measures in Australian agriculture sector-A review. *Agriculture*. 11(2): 85.

Pandey D, Agrawal M and Bohra JS. 2012. Greenhouse gas emissions from rice crop with different tillage permutations in rice–wheat system. *Agriculture, Ecosystems & Environment*, 159: 133-144.

Pao SH, Wu H, Hsieh HL, Chen CP and Lin HJ. 2025. Effects of modulating probiotics on greenhouse gas emissions and yield in rice paddies. *Plant, Soil and Environment*, 71(1): 21-35.

Parihar DS, Narang MK, Dogra B, Prakash A and Mahadik A. 2023. Rice residue burning in northern India: an assessment of environmental concerns and potential solutions–a review. *Environmental Research Communications*, 5(6): 062001.

Pathak H, Bhatia A and Jain N. 2014. *Greenhouse Gas Emission from Indian Agriculture: Trends, Mitigation and Policy Needs*. Indian Agricultural Research Institute, New Delhi - 110012, pp15-17.

Patterson J. 2012. Exploitation of unconventional fossil fuels: Enhanced greenhouse gas emissions. In: Liu G. (ed.) Greenhouse Gases-Emission, Measurement and Management, InTech, Janeza Tridine 9, 51000 Rijeka. Croatia, pp. 147-170.

Peng S, Huang J, Sheehy JE, Laza RC, Visperas RM, Zhong X, Centeno GS, Khush GS and Cassman KG. 2004. Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences,* 101(27): 9971-9975.

Penning H and Conrad R. 2007. Quantification of carbon flow from stable isotope fractionation in rice field soils with different organic matter content. *Organic Geochemistry*, 38(12): 2058-2069

Perry H, Carrijo DR, Duncan AH, Fendorf S and Linquist BA. 2024. Mid-season drain severity impacts on rice yields, greenhouse gas emissions and heavy metal uptake in grain: evidence from on farm studies. *Field Crops Research,* 307: 109248.

Petersen SO, Blanchard M, Chadwick D, Del Prado A, Edouard N, Mosquera and Sommer SG. 2013. Manure management for greenhouse gas mitigation. *Animal*. 7(s2): 266-282.

Phungern S, Azizan SN, Yusof NB and Noborio K. 2023. Effects of water management and rice varieties on greenhouse gas emissions in central Japan. *Soil Systems*, 7(4): 89.

Pittelkow CM, Adviento-Borbe MA, Hill JE, Six J, van Kessel C and Linquist BA. 2013. Yield–scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agriculture, Ecosystems and Environment*, 177: 10-20

Pramono A, Adriany TA and Susilawati HL. 2020. Mitigation scenario for reducing greenhouse gas emission from rice field by water management and rice cultivars. *Journal of Tropical Soils*, 25(2): 53-60.

Prangbang P, Yagi K, Aunario JK, Sander BO, Wassmann R, Jäkel T, Buddaboon C, Chidthaisong A and Towprayoon S. 2020. Climate-based suitability assessment for methane mitigation by water saving technology in paddy fields of the central plain of Thailand. *Frontiers in Sustainable Food Systems*, 4: 575823.

Prateep Na Talang R, Na Sorn W, Polruang S and Sirivithayapakorn S. 2024. Alternative crop residue management practices to mitigate the environmental and economic impacts of open burning of agricultural residues. *Scientific Reports*, 14(1): 14372. https://doi.org/10.1038/s41598-024-65389-3.

Qian H, Zhu X, Huang S, Linquist B, Kuzyakov Y, Wassmann R, Minamikawa K, Martinez-Eixarch M, Yan X, Zhou F and Sander BO. 2023. Greenhouse gas emissions and mitigation in rice agriculture. *Nature Reviews Earth & Environment*, 4(10): 716-732.

Qin X, Li YE, Wan Y, Liao Y, Fan M, Gao Q, Liu S and Ma X. 2014. Effect of tillage and rice residue return on CH_4 and N_2O emission from double rice field. *Transactions of the Chinese Society of Agricultural Engineering*, 30(11): 216-224.

Qin Y, Liu S, Guo Y, Liu Q and Zou J. 2010. Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. *Biology and Fertility of Soils*, 46(8): 825-834.

Rahman MM, Biswas JC, Maniruzzaman M, Choudhury AK and Ahmed F. 2017. Effect of tillage practices and rice straw management on soil environment and carbon dioxide emission. *The Agriculturists*, *15*(1): 127-142.

Rahman MM. 2013. Carbon dioxide emission from soil. *Agricultural Research*, 2(2): 132-139. https://doi.org/10.1007/s40003-013-0061-y.

Rajasekar P and Selvi JAV. 2022. Sensing and analysis of greenhouse gas emissions from rice fields to the near field atmosphere. *Sensors*, 22(11): 4141. https://doi.org/10.3390/s22114141

Rajbonshi MP, Mitra S and Bhattacharyya P. 2024. Agro-technologies for greenhouse gases mitigation in flooded rice fields for promoting climate smart agriculture. *Environmental Pollution*, 350: 123973. https://doi.org/10.1016/j.envpol.2024.123973.

Rajendran S, Park H, Kim J, Park SJ, Shin D, Lee JH, Song YH, Paek NC and Kim CM. 2024. Methane emission from rice fields: Necessity for molecular approach for mitigation. *Rice Science*, 31(2): 159-178.

Ramesh T and Rathika S. 2020. Evaluation of rice cultivation systems for greenhouse gases emission and productivity. *International Journal of Ecology and Environmental Sciences*, 2: 49-54. https://www.researchgate.net/publication/342347798.

Ravishankara AR, Daniel JS and Portmann RW. 2009. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. *Science*. 326(5949): 123-125.

Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F and Crutzen PJ. 2012. Global agriculture and nitrous oxide emissions. *Nature Climate Change*, 2(6): 410–416.

Rychel V, Meurer KH, Börjesson G, Strömgren M, Getahun GT, Kirchmann H and Kätterer T. 2020. Deep N fertilizer placement mitigated N_2O emissions in a Swedish field trial with cereals. *Nutrient Cycling in Agroecosystems,* 118(1): 133–148.

Sakoda M., Tokida, T., Sakai, Y., Senoo, K. and Nishizawa, T., 2022. Mitigation of paddy field soil methane emissions by betaproteobacterium *Azoarcus* inoculation of rice seeds. *Microbes and Environments*, 37(4): ME22052. doi: 10.1264/jsme2.ME22052.

Sanadya A, Yadu A, Raj J, Chandrakar H and Singh R. 2023. Effect of Temperature on Growth, Quality, Yield Attributing Characters and Yield of Rice–A Review. *International Journal of Environment and Climate Change*, 13(8): 804-814.

Sanchis E, Ferrer M, Torres AG, Cambra-López M and Calvet S. 2012. Effect of water and straw management practices on methane emissions from rice fields: a review through a meta-analysis. *Environmental Engineering Science*, 29(12): 1053-1062.

Sander BO, Samson M, Sanchez PB, Valencia KP, Demafelix EA and Buresh RJ. 2018. Contribution of fallow periods between rice crops to seasonal GHG emissions: effect of water and tillage management. *Soil Science and Plant Nutrition*, 64(2): 200-209.

Sander BO, Schneider P, Romasanta R, Samoy-Pascual K, Sibayan EB, Asis CA and Wassmann R. 2020. Potential of alternate wetting and drying irrigation practices for the mitigation of GHG emissions from rice fields: two cases in Central Luzon (Philippines). *Agriculture*, 10(8): 350. https://doi.org/10.3390/agriculture10080350.

Sander BO. 2017. From Research to Implementation: IRRI's Activities on GHG Mitigation in Rice Cultivation, 1-16 pages.

Sandford C, Dunn R, Titchner H, Kendon M, Rayner N, Morice C, Palmer M, McCarthy M and Kaye N. 2024. Global and regional climate in 2023. *Weather*, 79(12): 400-412. DOI: 10.1002/wea.7636.

Saraiva R, Ferreira Q, Rodrigues GC and Oliveira M. 2023. Nanofertilizer use for adaptation and mitigation of the agriculture/climate change dichotomy effects. *Climate*, 11(6): 129. ; https://doi.org/10.3390/cli11060129.

Sarma UJ, Chakravarty M and Bhattacharyya HC. 2013. Emission and sequestration of carbon in soil with crop residue incorporation. *Journal of the Indian Society of Soil Science*, 61(2): 117-121.

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

Saxena R and Naresh Kumar S. 2022: Simulating the impact of climate change on rice yield and adaptation strategies in major rice growing regions of India. *Journal of Agrometeorology*, 16(1): 18-25. https://doi.org/10.54386/jam.v16i1.1481.

Schimel J. 2000. Rice, microbes and methane. *Nature*, 403(6768): 375-377. ttps:// doi.org/10.1038/35000325.

Scholz VV, Meckenstock RU, Nielsen LP and Risgaard-Petersen N. 2020. Cable bacteria reduce methane emissions from rice-vegetated soils. *Nature Communications*, 11(1): 1878. https://doi.org/10.1038/s41467-020-15812-w.

Shahbandeh M. 2025. *World Rice Acreage. 2023*. https://www.statista.com/statistics/ 271969/world-rice-acreage-since-2008/.

Shakoor A, Xu Y, Wang Q, Chen N, He F, Zuo H, Yin H, Yan X, Ma Y and Yang S. 2018. Effects of fertilizer application schemes and soil environmental factors on nitrous oxide emission fluxes in a rice-wheat cropping system, east China. *PLos One*, 13(8): e0202016. https://doi.org/10.1371/journal.pone.0202016.

Sharma A and Bhattu BS. 2015. Baler technology for the paddy residue management–Need of the hour. *International Journal of Computer Applications*, 975(1): 22-23.

Shen Q, Wang H, Lazcano C, Voroney P, Elrys A, Gou G, Li H, Zhu Q, Chen Y, Wu Y and Meng L. 2024. Biochar amendments to tropical paddy soil increase rice yields and decrease N_2O emissions by modifying the genes involved in nitrogen cycling. *Soil and Tillage Research,* 235: 105917. https://doi.org/10.1016/j.still.2023.105917.

Shyamsundar P, Springer NP, Tallis H, Polasky S, Jat ML, Sidhu HS, Krishnapriya PP, Skiba N, Ginn W, Ahuja V and Cummins J. 2019. Fields on fire: Alternatives to crop residue burning in India. *Science*, 365(6453): 536-538. DOI: 10.1126/science.aaw4085.

Singh SK, Monu Kumar HJ, Maurya S, Kumar A, Yadav S and Sah D. 2024. Direct-seeded rice: potential benefits, constraints and prospective. *Journal of Scientific Research and Reports*, 30(7): 272-280.

Slameto, Fahrudin DE and Saputra MW. 2024. Effect of fertilizer composition and different varieties on yield, methane and nitrous oxide emission from rice field in East Java Indonesia. *Frontiers in Agronomy*, 6: 1345283. doi: 10.3389/fagro.2024.1345283

Slayden JM, Brye KR, Della Lunga D, Henry CG, Wood LS and Lessner DJ. 2022. Site position and tillage treatment effects on nitrous oxide emissions from furrow-irrigated rice on a silt-loam Alfisol in the Mid-south, USA. *Geoderma Regional*, 28: e00491. https://doi.org/10.1016/j.geodrs.2022.e00491

Song HJ, Lee JH, Jeong HC, Choi EJ, Oh TK, Hong CO and Kim PJ. 2019. Effect of straw incorporation on methane emission in rice paddy: conversion factor and smart straw management. *Applied Biological Chemistry*, 62(1): 70. https://doi.org/10.1186/s13765-019-0476-7

Sonwani, S. and Saxena, P. 2022. Greenhouse gases: sources, sinks, and mitigation. *Springer Nature*, Singapore, 257p.

Spaccini R and Piccolo A. 2017. Soil organic carbon stabilization in compost amended soils. Global Symposium on Soil Organic Carbon. 21st–23rd March 2017. Rome, Italy.

Srivastava P, Das A, Gupta K, Muthukumaran M, Kurdekar AK, Sharma U and Zaman MI. 2023. Impact of nano and non-nano fertilizers on rice quality and productivity: a review. *International Journal of Environment and Climate Change*, 13(8): 973-987.

Steiner C, Das KC, Melear N and Lakly D. 2010. Reducing nitrogen loss during poultry litter composting using biochar. *Journal of Environmental Quality,* 39(4): 1236-1242.

Su J, Hu C, Yan X, Jin Y, Chen Z, Guan Q, Wang Y, Zhong D, Jansson C, Wang F and Schnürer A. 2015. Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. *Nature*, 523(7562): 602-606.

Sultan M, Imran M, Ahmad F and Grichar WJ. (eds.). 2024. Irrigation systems and applications. *Agricultural Sciences*. Intech Open. Available at: http://dx.doi.org/10.5772/intechopen.107802.

Sun X, Zhong T, Zhang L, Zhang K and Wu W. 2019. Reducing ammonia volatilization from paddy field with rice straw derived biochar. *Science of the Total Environment*, 660: 512-518.

Tian H, Xu R, Canadell JG, Thompson RL, Winiwarter W, Suntharalingam P, Davidson EA, Ciais P, Jackson RB, Janssens-Maenhout G and Prather MJ. 2020. A comprehensive quantification of global nitrous oxide sources and sinks. *Nature*, 586(7828): 248-256.

Timilsina A, Bizimana F, Pandey B, Yadav RK, Dong W and Hu C. 2020. Nitrous oxide emissions from paddies: understanding the role of rice plants. *Plants*, 9(2): 180. https://doi.org/10.3390/plants9020180.

Tin MT, Chidthaisong A, Pumijumnong N, Arunrat N and Yuttitham M. 2022. Methane and Nitrous Oxide Emissions from Lowland Rice as Affected by Farmers' Adopted Fertilizer Applications under Two Crop Establishment Methods in Myanmar. *Environment and Natural Resources Journal*, 20(6): 621-633. 10.32526/ennrj/20/202200095.

Trang VH, Nelson KM, Rose S, Khatri-Chhetri A, Wollenberg EK and Sander BO. 2022. Rice cultivation ambition in the new and updated Nationally Determined Contributions: 2020-2021: Analysis of agricultural sub-sectors in countries' climate change strategies. CCAFS Info Note, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, Netherlands, 9p.

Umali-Deininger D. 2022. Greening the rice we eat. *East Asia and Pacific on the rise.* [Online] Available: https://blogs.worldbank.org/en/eastasiapacific/greening-rice-we-eat [07 July. 2024].

Umarani E, Hemalatha V, Saritha A and Ramanjaneyulu AV. 2020. Impact of high temperature stress in rice. *International Journal of Economic Plants*, 7(3): 108-110.

UNFCC [United Nations Framework Convention on Climate Change]. 2015. Paris Agreement. [Online] Available: https://unfccc.int/process-and-meetings/the-paris agreement?gad_source=1&gclid=Cj0KCQjwiOy1BhDCARIsADGvQnBntTHqiclzFcNdkBYJLbt-zN6LeUVVI8oDpNxiX5TmDiqluAeaA-EaAqt1EALw_wcB [07 July. 2024]

Uphoff N. 2024. The principles that constitute System of Rice Intensification (SRI) and the practices for applying them at field level. *Journal of Rice Research*, 17(1): 1-19.

USDA [United States Department of Agriculture]. 2023. Rice sector at a glance. Economic research service. [Online] Available: https://www.ers.usda.gov/topics/crops/rice/rice-sector-at-a-glance [10 July. 2024].

Ussiri D and Lal R. 2012. Soil emission of nitrous oxide and its mitigation. *Springer* Science and Business Media, 369-378.

Van Hung N, Maguyon-Detras MC, Migo MV, Quilloy R, Balingbing C, Chivenge P and Gummert M. 2020. Rice straw overview: availability, properties, and management practices. In: Gummert M, Hung NV, Chivenge P and Douthwaite B. (eds.) *Sustainable rice straw management, Springer Nature* Switzerland AG, Switzerland. pp.1-13.

Van Spanning RJ, Delgado MJ and Richardson DJ. 2005. The nitrogen cycle: denitrification and its relationship to N2 fixation. In: Nitrogen fixation in agriculture, forestry, ecology, and the environment (pp. 277-342). Dordrecht: *Springer* Netherlands.

Vijayaprabhakar A, Durairaj SN, Hemalatha M and Joseph M. 2021. Study on residue management options in combine harvested rice field in relation to yield and economic benefits of succeeding rice crop. *Agricultural Science Digest-A Research Journal*, 41(1): 85-88.

Wang B and Adachi K. 2000. Differences among rice cultivars in root exudation, methane oxidation, and populations of methanogenic and methanotrophic bacteria in relation to methane emission. *Nutrient Cycling in Agroecosystems,* 58(1): 349-356.

Wang C, Lai DY, Sardans J, Wang W, Zeng C and Peñuelas J. 2017. Factors related with CH_4 and N_2O emissions from a paddy field: clues for management implications. *PLos One*. 12(1): 0169254. https://doi.org/10.1371/journal.pone.0169254.

Wang J, Ciais P, Smith P, Yan X, Kuzyakov Y, Liu S, Li T and Zou J. 2023. The role of rice cultivation in changes in atmospheric methane concentration and the Global Methane Pledge. *Global Change Biology,* 29(10): 2776–2789.

Wang J, Wang J, Zhao H and Zheng Y. 2024. Observation and Simulation of CO2 Fluxes in Rice Paddy Ecosystems Based on the Eddy Covariance Technique. *Atmosphere*, 15(5): 517. https://doi.org/10.3390/atmos15050517.

Wassmann R, Lantin RS, Neue HU, Buendia LV, Corton TM and Lu Y. 2000. Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems*, 58(1): 23-36.

Win EP, Win KK, Bellingrath-Kimura SD and Oo AZ. 2021. Influence of rice varieties, organic manure and water management on greenhouse gas emissions from paddy rice soils. *PLos One*. 17(1): e0263554. https://doi.org/10.1371/journal.pone.0263554 .

WMO [World Meteorological Organization]. 2023. *State of the Global Climate Report 2023*. WMO-No. 1347, Genewa, Switzerland, 53p.

Wu Q, He Y, Qi Z and Jiang Q. 2022. Drainage in paddy systems maintains rice yield and reduces total greenhouse gas emissions on the global scale. *Journal of Cleaner Production*, 370: 133515. https://doi.org/10.1016/j.jclepro.2022.133515.

Xie JF and Li Y.E. 2002. A review of studies on mechanism of greenhouse gas (GHG) emission and its affecting factors in arable soils. *Chinese Journal of Agrometerology,* 23: 47-52. https://doi.org/10.3390/su16114789.

Xing G, Zhao X, Xiong Z, Yan X, Xu H, Xie Y and Shi S. 2009. Nitrous oxide emission from paddy fields in China. *Acta Ecologica Sinica,* 29(1): 45-50.

Xing GX, Cao YC, Shi SL, Sun GQ, Du LJ and Zhu JG. 2002. Denitrification in underground saturated soil in a rice paddy region. *Soil Biology and Biochemistry*, 34(11): 1593-1598.

Xu Y, Zhan M, Cao C, Tian S, Ge J, Li S, Wang M and Yuan G. 2016. Improved water management to reduce greenhouse gas emissions in no-till rapeseed–rice rotations in Central China. *Agriculture, Ecosystems and Environment*, 221: 87-98. https://doi.org/10.1016/j.agee.2016.01.021.

Yadav GS, Babu S, Das A, Mohapatra KP, Singh R, Avasthe RK and Roy S. 2020. No-till and mulching enhance energy use efficiency and reduce carbon footprint of a direct-seeded upland rice production system. *Journal of Cleaner Production*, 271: 122700. https://doi.org/10.1016/j.jclepro.2020.122700.

Yadav SP, Ghimire NP, Paudel P, Mehata DK and Bhujel S. 2024. Advancing effective methods for mitigating greenhouse gas emissions from rice (*Oryza sativa* L.) fields. *Journal of Sustainable Agriculture and Environment*, 3(4): e70012. https://doi.org/10.1002/sae2.70012.

Yadvinder-Singh YS, Bijay-Singh BS and Timsina J. 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. *Advances in Agronomy*, 85: 269–407. DOI: 10.1016/S0065-2113(04)85006-5.

Yang T, Wang M, Wang X, Xu C, Fang F and Li F. 2022. Product type, rice variety, and agronomic measures determined the efficacy of enhanced-efficiency nitrogen fertilizer on the CH_4 emission and rice yields in paddy fields: A meta-analysis. *Agronomy*, 12(10): 2240. https://doi.org/10.3390/agronomy12102240.

Yin Y-F, He X-H, Gao R, Ma H-L and Yang Y-S. 2014. Effects of rice straw and its Biochar addition on soil labile carbon and soil organic carbon. *Journal of Integrative Agriculture*, 13(3): 491-498.

Yuan Q, Pump J and Conrad R. 2012. Partitioning of CH_4 and CO_2 production originating from rice straw, soil and root organic carbon in rice microcosms. *PLos One*, 7(11): e49073. https://doi.org/10.1371/journal.pone.0049073.

Yuan S, Linquist BA, Wilson LT, Cassman KG, Stuart AM, Pede V, Miro B, Saito K, Agustiani N, Aristya VE and Krisnadi LY. 2021. Sustainable intensification for a larger global rice bowl. *Nature Communications*, 12(1): 7163. https://doi.org/10.1038/s41467-021-27424-z.

Yuan ZF, Zhou Y, Chen Z, Tang X, Wang Y, Kappler A and Xu J. 2023. Reduce methane emission from rice paddies by man-made aerenchymatous tissues. *Carbon Research*, 2(1): 17. https://doi.org/10.1007/s44246-023-00049-1.

Zafar S. 2018. Rice straw as bioenergy resource. *Bio Energy Consult. Retrieved from the World Wide Web: https://www.bioenergyconsult.com/rice-straw-as-bioenergy-resource*.

Zaidi ST. 2021. Rice Crop Residue burning and alternative measures by India: A Review. *Journal of Scientific Research*, 65(1): 132-137.

Zhang W, Du B, Duan X, Liang Z, Tang Y, Li J and Yao X. 2024. Effects of different rice varieties and water management practices on greenhouse gas (CH_4 and N_2O) emissions in the ratoon rice system in the upper yangtze river region, China. *Agriculture*, 14(12): 2251. https://doi.org/10.3390/agriculture14122251.

Zhang W, Yu Y, Huang Y, Li T and Wang P. 2011. Modeling methane emissions from irrigated rice cultivation in China from 1960 to 2050. *Global Change Biology*, 17(12): 3511-3523.

Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P and Durand JL. 2017. Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, 114(35): 9326-9331.

Zhao C, Qiu R, Zhang T, Luo Y and Agathokleous E. 2024. Effects of alternate wetting and drying irrigation on methane and nitrous oxide emissions from rice fields: A meta-analysis. *Global Change Biology*, 30(12): e17581. doi: 10.1111/gcb.17581. PMID: 39625221.

Zhao X, Pu C, Ma ST, Liu SL, Xue JF, Wang X, Wang YQ, Li SS, Lal R, Chen F and Zhang HL. 2019. Management-induced greenhouse gases emission mitigation in global rice production. *Science of the Total Environment*, 649: 1299-1306.

Zheng H, Huang H, Yao L, Liu J, He H and Tang J. 2014. Impacts of rice varieties and management on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. *Biogeosciences*, 11(13): 3685-3693.

Zhong Y, Wang X, Yang J, Zhao X and Ye X. 2016. Exploring a suitable nitrogen fertilizer rate to reduce greenhouse gas emissions and ensure rice yields in paddy fields. *Science of the Total Environment*, 565: 420-426.

Zhu X, Li J, Liang X, Chen Y, Chen X, Ji J, Xia W, Lan X, Peng C and Chen J. 2022. Long-term P fertilizer application reduced methane emissions from paddies in a double-rice system. *Agronomy*, 12(9): 2166.