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SUSTAINABLE RICE FARMING FOR A LOW EMISSION FUTURE: A REVIEW

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ABSTRACT

Rice is a prime crop cultivated primarily in Asian countries and is the backbone of world food security. The majority of regions follow flooded cultivation due to its added advantage of higher yield and minimal incidences of weeds. Flooded rice is attributed to the source of greenhouse gases (GHGs), like methane and nitrous oxide, due to variations in soil moisture, resulting in a higher inventory of carbon footprints from the agricultural sector. Sustainable rice farming is the need of the hour, and cultivation practices should be aligned to reduce the inventory of greenhouse gases, coupled with higher water use efficiency. Various management practices, like selection of varieties, tillage, liming, application of biochar and fertilizers, method of planting, irrigation management, application of herbicides and growth hormones, and use of industrial wastes, can be promising strategies to lower GHG emissions intensity in rice production. A detailed understanding of the impacts accrued on the adoption of these management practices in rice cultivation helps to attain the sustainable rice production goal coupled with low emissions. Coordinated integration of these diverse management options and methods will influence improved production practices that are to be followed in the changing scenario of climate to ensure resilience and sustainability, emphasizing soil health and efficient water use.

***Key words*:** Rice, Greenhouse gases, Climate change, Crop management

Introduction

Rice (*Oryza sativa* L.) is a food crop and is consumed by the majority of the world's population. The global rice system is dominated by Asian countries, with about 86% of the cultivated area and 89% of rice production (USDA, 2023). Flooded rice cultivation is followed in the majority of rice-growing regions with a growing cycle of 80-180, days depending on the variety. Rice contributes to greenhouse gas emissions from the agricultural sector to the tune of about 10% (Bhattacharyya *et al.*, 2012). Flooded rice systems are the source of methane, a major greenhouse gas. Anaerobic decomposition of organic residues on water stagnation in rice fields leads to the production of methane and further transport to the atmosphere through plants, ebullition, and diffusion process (Seiler *et al*., 1984; Khosa *et al*., 2010). Similarly, the application of nitrogen-containing fertilizers results in the emission of nitrous oxide from the rice system (Pathak *et al*.; 2002, Beeckman *et al*., 2018). The cultivated area under flooded rice will increase the atmospheric methane concentration, and the emission of N_2O from the rice soils, which eventually adds to the greenhouse gas footprints from the flooded rice ecosystem. The rise in concentration of greenhouse gases is the main suspect to climate change and associated altered atmospheric temperature and rainfall distribution (Ramanathan and Feng, 2009; Sapkota *et al*., 2015). Furthermore, higher water requirement in conventional flooding leads to depletion of freshwater reserves. Therefore, the focus should be on developing cost-effective cultivation practices that reduce greenhouse gas emissions, besides increasing water and nutrient use efficiency. A

combination of various practices, such as nutrient and irrigation management, application of soil conditioners, cultural operations, *etc*., can effectively be employed to optimize both productivity and environmental sustainability in rice cultivation.

Mitigation practices to reduce greenhouse gas emissions

Emission of GHGs from the rice system depends mainly on management practices followed during crop growth; however, managing these could considerably lower the intensity of emissions. Greenhouse gases, namely CH_4 and N_2O emissions from the system, can be reduced through different practices such as management of irrigation, and organic residues, selecting suitable cultivars, tillage practices, use of an appropriate quantity of N fertilizers and split application, *etc*. Some of the mitigating strategies are mentioned below.

Tillage:

Use of tillage implements for land preparation greatly influences the aeration status of soil due to the porous structure of soil, which further accelerates CH_4 oxidation under rice ecosystems due to improved activity of methanotrophic bacteria (Khan, 1996; Hutsch, 1998; Ussiri *et al*., 2009). Soils under no tillage/zero tillage make soil moist rich with higher organic matter concentration near the soil surface. This in turn favours reduced conditions and thereby increased persistence of anaerobic methanogens, which results in more CH_4 production and emission (Guzha, 2004). It has also been reported that the micro-sized pores created under the no-tillage system result in an anaerobic environment, leading to greater denitrification and nitrogen loss. Similarly, high organic content in soil under reduced conditions accelerates the activity of bacteria and results in the availability of protease enzyme in soil, consequently increased mineralization of N in soil, which catalyzes biological processes of nitrification and denitrification, and associated N_2O production (Venterea *et al*., 2005; Ball *et al*., 2008). According to Zhang *et al*., (2015), adopting no-tillage system in the rice-wheat cropping system significantly increased greenhouse gas emissions in both cropping seasons compared to conventional and reduced tillage methods. The lower GHG emission observed in reduced and conventional tillage was due to better aeration of soil by porous soil structure and consequent oxidation of methane.

Selection of varieties:

Rice varieties differ in their potential to favour methane emission, and it depends on duration, biomass production, size of aerenchyma tissue, the amount of rhizodeposits or carbon excretion, *etc*. under similar management practices (Lu *et al*., 1999; Wassmann *et al*., 2000; Aulakh *et al*., 2001). Bharali *et al*. (2017) has studied the physiological characteristics in rice plants influencing CH_4 emission in six rice varieties. The major factors influencing CH_4 emission were photosynthetic rate and xylem vessel size, and varieties with smaller xylem vessels emitted low CH_4. In a study conducted by Gogoi *et al*., (2008), traditional rice varieties with profuse biomass production resulted in higher GHG production compared to high-yielding varieties with less biomass production, with similar crop duration. They have noted a positive correlation of leaf number, tiller number, and leaf area index with methane flux values during crop growth. Similarly, early maturing varieties produced low CH_4 emission compared with the late maturing varieties, as the extent of anaerobic atmosphere in soil due to crop water submergence in the field varies with the duration of the varieties (Setyanto *et al*., 2000; Habib *et al*., 2023). It has also been reported that rice varieties with larger roots make more oxygen available at the rhizosphere region and have higher oxidation of CH_4, which results in lower CH_4 emission compared to varieties with meager root formation (Zheng *et al*., 2018; Ding *et al*., 2022). These traits can be considered while developing new low-methane-emitting varieties by the breeders.

Liming:

Liming practice is adopted to neutralize soil acidity and to ensure better nutrient absorption from the soil. Lime application enhances the soil microbial activity, which favours increased soil organic matter decomposition and higher plant growth due to higher nutrient uptake (Xu *et al*., 2015; Cao *et al*., 2016). Emission of methane and nitrous oxide from soil was found to be reduced on liming, as the higher rate of organic matter decomposition by enhanced activity of soil microbes, resulting in less carbon substrate for methanogens to produce methane, will be available under neutral soil pH (Shaaban *et al*., 2015; Khaliq *et al*., 2019; Wang and Kuzyakoz, 2024).

The activity of enzymes in soil is greatly influenced by soil pH, like CH_4-monooxygenase, which oxidizes CH_4. Its concentration in soil increases upon liming (Conrad, 1996). Similarly, N_2O-reductase enzyme (NOR) is the main factor responsible for reducing N_2O to N_2 and is highly sensitive to low soil pH. A small rise in soil pH due to liming material enhances the activity of NOR enzyme, and eventually results in reduced N_2O emissions (Liu *et al*., 2010). It has also been reported that the activity of methanotrophs is higher at increased soil pH, which further oxidizes the CH_4 produced under anoxic conditions in soil (Khaliq *et al*., 2019). According to Jiang

et al., (2018), application of lime significantly increased the aboveground rice biomass while simultaneously decreasing the emission potential of methane (CH_4) and nitrous oxide (N_2O).

Moreover, the application of lime improved the soil respiration of the fallow season, hence a lower abundance of methanogens at the succeeding rice crop season. This reduction was ascribed to better decomposition of organic residues during the fallow season, which in turn lowered the carbon availability for methanogens.

Biochar application

Biochar is made from burning organic materials (feedstock) under limited oxygen conditions, which is a solid carbon-rich, fine-grained porous material (Xu *et al*., 2011). Crop residues are mainly used as feedstock to yield biochar (Li *et al*., 2020) and are barely resistant to microbial breakdown as they contain aromatic compounds in their structure and, which benefits soil carbon sequestration (Brown *et al*., 2020). Application of biochar has resulted in both benefits and negative impacts on GHG emissions (Amalina *et al*., 2022).

Application of biochar to rice field improves the physico-chemical and biological properties of soil due to addition of a huge carbon substrate to it, but the activity of methanogenic bacteria will be increased on availability of carbon substrate in plenty, which further enhance the methane formation and release to the atmosphere (Chen *et al*., 2016; Qi *et al*., 2020; Singh *et al*., 2022). It has also been observed the inhibitory effect of biochar on methanotrophs in soil and reduction in the oxidation of methane formed in soils. However, biochar application along with N fertilizer has resulted in higher grain yield coupled with reduced nitrous oxide emission from the rice ecosystem. It may be due to the inhibitory effect of chemicals like dioxins and polycyclic aromatic hydrocarbons present in biochar over denitrifying bacteria, and consequent drop in the process of denitrification in soil (Zhang *et al*., 2010; Hale *et al*., 2012).

Nutrient management

The emission response of flooded rice to the application of different fertilizer nutrients varies, as they effect plant growth directly or indirectly (Adhya *et al*., 1998). Potassium application plays a key role in plant growth and development as it imparts drought resistance, protection from pests and diseases, and improves the quality of grains/fruits. Also, flourishing growth of aerenchyma tissues on K sufficiency, transfer of oxygen to roots, and its oxidizing power stands at peak; thereby, a higher volume of oxygen can be transported to the rice rhizosphere soil (Zain and Ismail, 2016). Higher oxidizing power of rice roots limits the activity of anaerobic methanogens and associated CH_4 formation and its release to the atmosphere (Babu *et al*., 2006).

Sulphur (S) has a major role in the growth, component in chlorophyll and protein synthesis, grain formation, *etc*. (Singh *et al*., 2012). Deficiency of S is less common in irrigated rice as the majority of it is grown in lowland soils (Yamaguchi, 1999). Application of sulphur to a submerged ecosystem will enhance the population of sulphate-reducing bacteria (SRBs) in soil due to the availability of soluble sulphate in soil. Sulphate reducing bacteria are strictly anaerobic in nature, and hence, both methanogenic bacteria and sulphate-reducing bacteria will compete for the same carbon substrate under anaerobic soil, which creates mutual competition among them and further reduces the population of methanogens due to the limited availability of carbon source. Consequently, the emission of methane under a submerged ecosystem will be reduced (Sun *et al*., 2018). According to Rath *et al*., (2002), the application of sulphur to rice at various levels has resulted in increased population of SRBs and reduced methanogens' activity under the rice system, with reduced emission of methane. Similarly, application of soil amendments or materials containing iron proliferate the iron-reducing bacteria in soil, and they compete for the same electron source with methanogens, resulting in reduced methane emission (Gwon *et al*., 2018).

Silica fertilization has also been found to reduce methane emissions as the availability of silica in soil helps to develop aerenchyma tissues, as potassium application does, which further transports more oxygen to the root region and consequent oxidation of methane (Ali *et al*., 2012; Bhattacharyya *et al*., 2019).

Site specific nutrient management

Site-specific nutrient management (SSNM) is aimed at supplying the optimum nutrient inputs, taking into account its availability from indigenous soil sources and demand from the plant. This approach is specific to the field, crops grown, and nutrient management across time and space. Implementing this to achieve enhanced use efficiency of applied nutrients could be accomplished by the use of available practices and technologies like the leaf colour chart, chlorophyll meter, and green seeker (Witt *et al*., 2005; Shapiro *et al*., 2006; Singh *et al*., 2015). Moreover, options like decision support systems, such as Rice Crop Manager and Nutrient Expert, can also provide guidance.

According to a study by Sapkota *et al*., (2021), nutrient management efficiency in rice and wheat was evaluated using the Nutrient Expert (NE) tool, which is a

decision support system to recommend nutrient management specific to farmers' fields even without a soil test report. Here, a field study comprised of about 1600 comparison trials of farmer fertilization practice was evaluated. The findings revealed that fertilizer management based on the NE tool could reduce the global warming potential in rice to the tune of 2.5% and about 20% in wheat compared to the farmers' fertilization practice. Moreover, it could also improve the yield and farmers' income. Similarly, Rice Crop Manager (RCM) was integrated in rice cultivation, and it has been found that RCM recommendations could increase the yield better than traditional fertilization practice by about 19% coupled with less GHG emission (Chaudhary *et al*., 2025).

Deep placement of fertilizer and nitrification inhibitors

Fertilizer nutrients are placed, drilled, or inserted in the soil about 10 cm or deeper (Chen *et al*., 2021) to supply nutrients either before planting the crop or on a standing crop. In rice systems, urea is formed into briquettes of 2.7 to 3.4 g in size (Sharna *et al*., 2021) and is placed deep into the reduced zone with special equipment. Applying nitrogen fertilizer deep into the soil gives better yield than surface-applied lowland rice, along with less environmental pollution, as the nitrification–denitrification process is limited, resulting in low N_2O emission and decreased NH_3 volatilization loss (Mohanty *et al*., 1999). The N fertilizer applied under reduced zone remains for a long period in the form of ammonium (NH_4^+) for crop uptake, without converting into nitrate (NO_3^-) due to the absence of oxygen.

Deep placement of N fertilizer in direct-seeded rice, compared to surface broadcasting, could mitigate the N_2O emission to the tune of 24% (Li *et al*., 2021). Production of N_2O primarily occurs near the soil surface due to increased microbial nitrification and denitrification compared to deeper soil layers (Venterea and Stanenas, 2008). Deep placement of N fertilizer in a reduced zone will retain N as NH_4^+ form, which aids in slowing the pace of diffusion of NH_4^+- N to the surface soil from the reduced zone; otherwise, it is subjected to microbial process at the soil surface and emission as N_2O (Rochette *et al*., 2014).

Nitrification inhibitors are the chemicals used to control nitrogen transformations in the soils (Kanter and Searchinger, 2018). Due to their toxic effect on nitrifying bacteria (*Nitrosomonas*), they temporarily inhibit the production of nitrate (Elrys *et al*., 2020). Dicyandiamide, nitrapyrin, N-serve, potassium azide, *etc*., are examples of nitrification inhibitors. In a study conducted by Gaihre *et al*., (2020), application of N fertilizers as urea deep placement (UDP) and urea with dicyandiamide @ 3% helped to lower the N_2O emissions by 95% and 73%, respectively, over urea and potassium nitrate topdressing. Further, grain yield and N recovery efficiency were improved by 19% and 40% respectively, over urea.

Direct seeded rice

Direct Seeded Rice (DSR) is the direct sowing of seeds into saturated/unsaturated, non-puddled soil, as an alternative to puddled transplanted rice (PTR) for saving water, labour, fuel, and time, and gives comparable yield to PTR, provided weeds are controlled effectively with herbicides (Liu *et al*., 2015; Xu *et al*., 2019). It reduces the volume of water required for land preparation and puddling, and reduces the overall water demand of the PTR (Kaur and Singh, 2017; Ishfaq *et al*., 2020). Moreover, the duration of field submergence under DSR is less compared to transplanted flooded rice, hence chances for CH_4 emission are significantly reduced (Chaudhary *et al*., 2023).

Liu *et al*., (2022) have conducted a field experiment to evaluate the rate of CH_4 emission under direct-seeded flooded rice (DSF), direct-seeded alternate wetting and drying (DSA), and transplanted flooded rice (TFR) systems and found that both DSF and DSA could benefit root physiological traits and significantly reduce CH_4 emission at all growth stages of rice to the extent of 96% compared to TFR. A similar conclusion was made by Li *et al*., (2021), as direct-seeded rice favoured to the effective utilization of applied fertilizer N and reduced N_2O emissions by 24% due to altered root morphological traits like larger root length, mean root diameter, and total root volume per hill.

Transplanting age of seedlings

Transplanting age of seedlings will influence the methane emission from the system, as planting with young seedlings will produce more tillers and less root damage compared to aged seedlings, which further creates an improved channel to transport GHG from the soil through aerenchyma tissues. Higher tiller production by young-aged seedlings influences the proliferation of methanogens due to the availability of more withered plant residues after their senescence/death, and consequently increased GHG production. Planting with aged seedlings will reduce the number of days of submergence in the main field, which also delays plant-mediated GHG transport from soil to the atmosphere due to damaged roots and their recouping time. This results in reduced GHG emissions with transplanting of aged seedlings without affecting yield

(Aulakh *et al*., 2000; Pattar *et al*., 2001; Nayak *et al*., 2006). The quantum of solar radiation received by the crop will also influence the GHG emissions, as the photosynthesis and activity of plants are comparatively high under an extended period of solar radiation. The crop that received a higher quantum of solar radiation due to transplanting with young-aged seedlings emitted more CH_4 than with the more aged seedlings (Sass and Fisher, 1991).

Alternate wetting and drying

Alternate Wetting and Drying (AWD) is a practice to save irrigation water, where rice fields are irrigated when surface water has disappeared for a period ranging from one day to over 7 days, and it depends on the available soil, stage of crop growth, and the prevailing climate. Alternate Wetting and Drying can be initiated two to three weeks after transplanting. The fields are then allowed to drain naturally until the level of water comes to a certain depth below the soil surface, and the fields are irrigated to a depth of 5 cm above the surface at this point. This cycle of drying and flooding is repeated for two weeks before the harvest, except during the flowering stage, when the depth of water is maintained to a depth of 5 cm for a duration of two weeks. Maintaining an AWD of 15 cm ensures substantial yield, as the root system of the rice plants still receives adequate moisture from the still-wet soil (Lampayan *et al*., 2009; Setyanto *et al*., 2018).

The practice of AWD helps in improving the aeration status of soil, eventually reducing methanogenic activity of anaerobic methane-producing archaea (Ratering and Conrad, 1998). Conversely, drainage helps in enhancing the population of aerobic methane-oxidizing methanotrophic bacteria due to the availability of oxygen in plenty at the soil rhizosphere regions, which further converts CH_4 to less harmful CO_2 and results in less GHG emissions. Additionally, drainage increases the concentrations of sulphate and ferric iron in soil, which results in increased population of sulphate and iron reducing bacteria, further inhibiting CH_4 production, even when soil falls to a low redox potential on reflooding (Sahrawat, 2004; Ma and Lu, 2011; Malyan *et al*., 2016). Applying fertilizer to moist soils, when the moisture levels between field capacity and optimal moisture, is beneficial, as it helps to ensure that root absorption of fertilizer N is at its peak, resulting in less mineral N left unabsorbed in surface soil, which in turn limits the nitrification and denitrification processes that can lead to N_2O emissions (Chapuis-Lardy *et al*., 2007; Loaiza *et al*., 2024).

The practice of intermittent irrigation reduced the cumulative CH_4 emissions by 70-100% and N_2O emissions by 10-70% with a 19-56% reduction in cumulative water use compared to traditional continuous flooding. Additionally, the yield obtained between continuous flooding and alternate wetting and drying had no significant difference (Loaiza *et al*., 2024). In a study by Sriphirom and Rossopa (2023), the different drying levels of AWD 10, 15, and 20 cm were evaluated with continuous flooding to check their effect on GHG emission, and they concluded that the AWD practice could reduce the annual GHG emissions by 48%. Among these, the deeper drying levels stood best in terms of the lowest rate of emission than the shallow drying levels. Moreover, the yield accrued in AWD was comparable with continuous flooding, with a water consumption saving of about 17%.

Application of herbicides

Chemical herbicides alleviate the drudgery associated with mechanical hand weeding and labour costs, and are gaining high momentum in the current agricultural scenario. Application of butachlor @ 1 kg/ha, a pre-emergence herbicide, altered the methane formation in rice soil as reported by Mohanty *et al*., (2001). It inhibited the activity of both aerobic and anaerobic bacteria in soil, and hence reduced the emission of methane compared to the situation without herbicide. It has also been reported that butachlor resulted in lowering the ebullition transfer of methane to the atmosphere by about 80%. Similarly, application of herbicides like bensulfuron methyl (0.6%) and pretilachlor (6.0%) had a reduced emission rate of CH_4 and N_2O in rice. This reduction was attributed to the role of herbicides in lowering the readily mineralizable carbon and microbial biomass carbon contents. Moreover, it prevented the drop of redox potential in soil; consequently the abundance of methanotrophs over methanogenic population and limited availability of mineral N (Das *et al*., 2011; Jiang *et al*., 2015).

Plant growth hormones

Plant growth hormones are also found to be a suitable means to reduce methane emissions from the submerged rice ecosystem. The application of indole-3-acetic acid (IAA), indole-3-butyric acid (IBA), and gibberellic acid (GA_3) at 20 ppm once during at tillering and also at panicle initiation stages have resulted in reduced cumulative CH_4 emission over untreated plot, and it was attributed mainly due to regulation effect of plant hormones on leaf development, xylem vessel size, and stomatal density, which further enhanced leaf photosynthetic rate, grain filling and grain yield. Similarly, soil application of cellulose acetate-mixed ethephon at a 1:1 ratio during planting the crop helped to reduce the archaeal communities and methanogens significantly in submerged paddy soils with

lower CH_4 emissions up to 90% without affecting the grain yield (Borah and Baruah, 2016; Rae Cho *et al*., 2022).

Industrial wastes

Byproducts from steel, fertilizer, and power industries, like basic slag, phosphogypsum, and fly ash, *etc*., have the potential to utilize them as soil conditioners (Kumar *et al*., 2020). Application of basic slag had a positive effect on rice yield as it is a rich source of elements such as silicates, calcium, and iron. The cumulative CH_4 emission rate was 56% lower in the plots that received slag compared to those of the control (without basic slag). Use of slag in soil increases iron content, which proliferates and increases the activity of iron-reducing anaerobic bacteria, which require electrons for their survival and compete with methanogens, resulting in low emissions (Bodegom *et al*., 2004; Wang *et al*., 2015). Silica oxide present in slag will benefit the development of aerenchyma tissues, which will improve the oxidation status of soil (Kumar *et al*., 2020; El-Okkiah *et al*., 2022). Similarly, application of phosphogypsum will improve the sulphur content in soil, hence the activity of sulphur-reducing bacteria in soil will be higher, which will compete with methanogens for carbon source; consequently, the production of methane was affected (Prasad and Shivay, 2018; Padhy *et al*., 2021). Fly-ash is a rich source of essential elements like P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Co, B, and Mo, and its alkaline nature could be effectively utilized to neutralize soil acidity apart from nutrient supplying benefits on its application (Adriano *et al*., 1980; Gorai, 2018; Kumar *et al*., 2020). Ali *et al*., (2009) has observed that application of fly-ash, phosphogypsum and slag at 10 t/ha to soil before transplanting could suppress the methane flux from rice ecosystem by 20%, 27% and 25% respectively, with a yield improvement of 17%, 15% and 23% over the control due to presence of high amount of sulphur, iron, and manganese in these amendments.

Constraints in adoption of mitigation practices

The adoption of mitigation practices to curtail GHG emissions from the rice system is facing several constraints at the farm level. Higher upfront costs associated with the practice of precision agriculture and alternate wetting and drying make the farmers not to proceed for such operations, and the mechanism of carbon credit in agriculture sector is at its infant stage, their implementation at wider scale can be complex, which make the farmers with limited financial incentives and resultant reluctance to adoption of new practices especially when such practices reduces yield compared to conventional flooded rice cultivation. Moreover, mitigation strategies cannot be universally applicable due to changes in prevailing climate, soil type, crops cultivated, and other local conditions, which necessitate more region-specific research. Similarly, farmers are at various levels of apprehension to implement and manage new mitigation techniques, and hence, effective training for them is required. Limited irrigation practices are the dominant component in emission mitigation technologies, and which demand a flourishing water management infrastructure for timely and effective irrigations; hence, the existing one has to be restructured for the smooth conduct of controlled irrigation. The potential impacts and effectiveness of developed mitigation strategies on the yield of rice and the associated cropping system also need to be fully studied, which is crucial for global food security. These constraints need to be addressed effectively for implementing the mitigations strategies for sustainable and low emission rice system.

Future perspectives

Future strategies in rice cultivation for GHG mitigation should be focused on deliberate integration of various practices like cultural operations, water management, soil amendments, and optimum nutrient management, coupled with advanced modeling techniques with machine learning digital tools to precisely predict and manage of emissions under future climate scenarios, which paves the way to a low-emission rice system. Furthermore, the policies are to be aligned to educate farmers on mitigation strategies and to encourage them by incentivizing them through efficient carbon credit auditing mechanisms.

Conclusion

Greenhouse gas (GHG) emissions from the agriculture sector, particularly from rice cultivation, significantly contribute to global warming and climate change. The role of paddy cultivation on GHG emissions calls for suitable interventions to be adopted to optimize rice production while minimizing its GHG intensity. It is essential to develop strategies for low-cost systems and management practices aimed at reducing GHG emissions from the rice ecosystem. A combination of various management practices, such as selection of varieties, tillage, liming, application of biochar and fertilizers, method of planting, irrigation management, application of herbicides and growth hormones, and use of industrial wastes, can be deliberately integrated to effectively lower GHG emissions in rice production.

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