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Rice and Climate: Unveiling Greenhouse Gas Emissions and Sustainable Mitigation Strategies

Sushil Kumar
Associate Professor, Botany Department, RKSD College, Kaithal

Abstract: Over 2 billion people rely on rice for their nourishment, which provides 20% of the world's caloric consumption. But it also contributes significantly to the emissions of greenhouse gases (GHGs), namely nitrous oxide (N_2O) and methane (CH_4). In flooded rice fields, methane is generated anaerobically, where as nitrogen fertilizer and water management techniques are associated with N_2O emissions. The environmental impact of rice cultivation has been addressed through a variety of mitigation techniques, including effective water and fertilizer management, the use of biochar, and cultivar selection. Mid-season drainage (MSD) and alternate wetting and drying are efficient water management strategies that lower CH_4 emissions by 10.62% to 100%, but they may also raise N_2O emissions because of improved nitrification. Both CH_4 and N_2O emissions can be reduced by fertilizer management, which includes the use of tailored fertilizers and appropriate nitrogen rates. By changing microbial structures and improving nutrient retention, the use of biochar not only lowers CH_4 and N_2O emissions but also enhances soil health. There is considerable promise for lowering GHGs while preserving agricultural yields using bacterial inoculation techniques and cultivar selection, especially for drought-resistant rice types. Although, there are still issues with residue management and long-term sustainability, using rice straw for bioenergy production or soil integration presents more chances to reduce emissions. In order to balance agricultural production and environmental sustainability and pave the road for a rice cultivation industry that is climate resilient, this review emphasizes the necessity of integrated methods that include many mitigation techniques.

Keywords: Biochar, Fertilizer management, Greenhouse gases, Rice cultivation, Sustainable agriculture.

Introduction:

About 16% of the nation’s total greenhouse gas emissions come from agriculture, which either directly or indirectly contributes to climate change (MOEF 2018; Panchasara et al. 2021). The need for more sustainable intensification of food production is indicated by the growing recognition of climate change and food security as two of the most urgent and interconnected issues confronting mankind in the twenty-first century (Godfray et al., 2011). More over 2 billion people depend on rice farming for their livelihoods, and it provides 20% of the world's calories (FAO, 2020). However, it comes at a hefty cost to the environment: 2.1% of worldwide agricultural N_2O emissions and 10–12% of anthropogenic methane emissions come from rice fields (IPCC, 2019). Anaerobic conditions in flooded rice fields are the primary source of methane, which has a global warming potential (GWP) 28–34 times that of CO_2 (Neue et al., 1990). On the other hand, the usage of nitrogen fertilizer and water management techniques are associated with N_2O emissions (Aulakh et al., 1992). The main greenhouse gases (GHGs) that cause global warming are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute 60%, 15%, and 5%, respectively (Watson et al., 1996). N_2O not only contributes to global warming but also destroys stratospheric ozone (Li et al., 2004). These greenhouse gases, which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), trap infrared radiation that leaves the earth's surface and raise its temperature. Due to the buildup of greenhouse gases in the atmosphere, the average yearly temperature of the world has risen by 0.4 to 0.76 degrees Celsius since the end of the 19th century (IPCC, 2007).

A rice field’s methane emission pattern demonstrates how the soil’s moisture content determines the flux’s peaks. When compared to intermittent wetness and drying soil conditions, continuously saturated rice fields produced greater methane emissions (Pathak et al., 2003). Methane emissions are greatly influenced by the soil's texture, cation exchange capability, organic carbon concentration and total nitrogen content (Mitra et al., 2002). One of the most complicated variables influencing methane emissions is water management. Anaerobic conditions are ideal for the production of CH4. The microbial processes of nitrification and denitrification, which occur in aerobic and anaerobic environments, respectively, create N2O in soil (Islam et al. 2020). The largest quantity of CH4 is released in rice fields during flooding conditions, and a significant amount of N_2O is generated during periods of crop transition and intermittent flooding (Zhao et al. 2011). Emissions of both GHGs are predicted to rise by 35–60% by 2030 (Smith et al. 2007). To fulfill the demands of the constantly expanding population, rice output must be raised by 40% until 2030 (FAO 2009), which might cause major environmental issues. One of the largest rice producers, India, contributes significantly to global emissions. Flooding in Indian rice fields is projected to create 1.07-1.10 Tg CH_4-C annually, with a GWP of 272.83 Tg CO_2 (Pathak et al., 2005). To address this challenge, targeted mitigation approaches and an in-depth understanding of emission patterns are required.

Production of GHGs in paddy fields:

Although rice paddy mostly contributes to CH_4 emissions, it also releases some N_2O during floods because of the anaerobic conditions of the soil (Pittelkow et al. 2013). Under continuous cycles of flooding and drainage from rice cropping systems, N_2O emissions significantly increased (Yao et al. 2012). As a result, the rice-based cropping system demonstrated a notable trade-off between CH_4 and N_2O emissions, and the availability of water in the crop's root zone had a major impact on the generation of both gases. The primary causes of CH_4 and N_2O generation and emissions in rice paddies are soil microorganisms. Methanogenic archaea in rice paddies produce CH_4, and methanotrophic bacteria oxidize some of it. Microbial nitrification and denitrification together account for roughly 70% of N_2O emissions (Braker and Conrad 2011).

1. CH_4 production in rice paddy:

The process of methanogenesis, in which organic matter with a redox potential of less than 150 mV decomposes in the absence of oxygen, produces CH_4 in paddy soils. When soil is exposed to an aerobic atmosphere, carbon dioxide is released and decomposition takes place in the presence of oxygen. The process of methanogenesis begins when the redox potential suddenly lowers. The pathways by which CH_4 is released to the atmosphere after production are diffusion loss of dissolved CH_4 across the water-air and soil-water interfaces, ebullition loss by the release of gas bubbles, and plant transport into the roots by diffusion and conversion to CH_4 gas in the aerenchyma and cortex of rice plants, as well as concurrent release to the atmosphere through plant micropores (Davamani et al. 2020). Standing water in low-lying rice fields produces anaerobic conditions in the soil that promote methanogenesis and denitrification, producing CH_4 and N_2O at the same time.

2. CO_2 production in rice paddy:

The amount and characteristics of organic matter added to soil, environmental factors, and soil processes all affect the generation and release of CO_2. The organic components start to break down based on microbial activity, which releases various gases, including CO_2 (Hossain et al. 2017). Accordingly, a major factor in soil CO_2 emissions is the carbon mineralization of organic materials that are returned to the soil (Rahman 2013). Through the respiration of roots and other plants and animals, CO_2 is released onto the surface soil (Hossain et al., 2017). CO_2 emissions are further increased by urea fertilizer application, residue burning, and tillage techniques in rice fields. About 13–35% of CO_2 and 94–97% of CH_4 are contributed via ebullition, respectively. The amount of crop waste and litter, root activity, and microbial processes all affect carbon dioxide emissions because soil microorganisms transform the soil's carbon pool into CO_2. Urea fertilizer sprayed in the fields is transformed to NH4+, OH−, and HCO3 in the presence of water and urease enzymes; this bicarbonate ultimately transforms into $CO_2$and water (Hussain et al. 2015).

3. N_2O production in rice paddy:

In soils, nitrogen (N) undergoes microbial metabolism to create N_2O. This conversion of N to N_2O has been linked to two biological processes: the reduction of NO_{3-} to N_2 during the denitrification process and the loss of N as N_2O during the aerobic nitrification of NH_{4+}. Anaerobic conditions predominate during the denitrification process, which results in the creation of N_2O as an intermediate product.

The primary determinants of N_2O emission in paddy soil are water management and the amount of nitrogen fertilizer (Ali et al. 2019). Ammonium N is nitrified and NO3− is created when fertilizer is given to the paddy fields in the oxidized layer at the water–soil interface. As it approaches the reduced layer, the NO_{3-} generated in the oxidized layer is denitrified, resulting in the intermediate product of N_2O (Xing et al. 2009). N_2O is created during the rice-growing season as a result of the subterranean saturated soil layer's alternating wetness and drying periods as well as the rice-winter upland crop cycle. It may also rise with water evaporation and add to atmospheric N_2O. Rice plants serve as a route for dissolved gases from the root zone to the atmosphere, and during flooding conditions, they are the primary source of considerable N_2O emissions (Yan et al. 2000). Since, N_2O is a water-soluble molecule, it may be absorbed by plant roots and moved by the transpiration stream to the leaves.

Mitigation of GHGs production:

Water and fertilizer control, the use of biochar, improved planting, drought-resistant rice varieties and straw management are all promising mitigation strategies.

1. Water management: Effective water management for rice farming, is essential as it affects productivity, greenhouse gas emissions and ecological sustainability. When compared to continuous flooding, practices such furrow irrigation, winter drainage, mid-season drainage, and alternating wetting and drying have a considerable influence on emissions (Loaiza et al., 2024). Alternating wetting and drying may raise N_2O emissions because of improved nitrification-denitrification cycles (Feng et al., 2021; Liao et al., 2020), but it decreases CH_4 emissions by 10.62% to 100% (Sriphirom et al., 2019). Additionally, it can maintain or marginally lower rice production while saving water by 4.52% to 63.2% (Sriphirom et al., 2019; Feng et al., 2021). According to Loaiza et al. (2024), alternating wetting and drying still reduces the total global warming potential (GWP) by 5.32% to 73%. Furthermore, by altering microbial activity, it can reduce soil phosphorus (P), which in turn reduces N_2O emissions (Adhikary et al., 2023). According to Sanders et al. (2014), dry fields produce less CH_4 than flooded fields, making fallow-season water management even more important. Ridge-furrow irrigation reduces CH_4 by 45.6%–70.3% and N_2O by 23% while increasing yields (Zeng & Li, 2021; Timm et al., 2024). Many researchers have developed the notion of utilizing wastewater in rice production in addition to regulating irrigation water. One interesting method of growing rice is to utilize treated wastewater for irrigation. This method can both lower the amount of nitrogen fertilizer used and prevent the formation of CH_4 while still increasing rice output. According to Pham et al. (2021), irrigation with treated wastewater can result in outstanding rice output and quality while lowering CH4 emissions by up to 95.6%.

2. Fertilizer management:

Nitrogen fertilizers, sulfate fertilizers, farmyard manure, and green manure make up 14.3% of the roughly 172.2 million metric tons of fertilizer consumed globally for rice cultivation (Chauhan et al., 2017). Rice crops only absorb one-third of nitrogen fertilizer; the other two-thirds are lost as a result of surface runoff, ammonia volatilization, denitrification, leaching, or soil organism immobilization (Chauhan et al., 2017). Fertilizers can reduce GHG emissions by promoting CH_4 transport via the aerenchyma, inhibiting CH_4 oxidation through NH_4^+, and increasing carbon availability for methanogens. The goal of fertilizer management is to minimize emissions by adjusting fertilizers and optimizing their quantities. An ideal rate of 225 kg N/ha was proposed by Zhong et al. (2016), however soil and meteorological circumstances may affect this. On the other hand, drastic cuts may eventually raise GHGs by reducing soil productivity and organic carbon (Snyder et al., 2009). Modified fertilizers including vermicompost, urea briquettes, organic manure, and enhanced-efficiency fertilizers have been studied to lower emissions. According to Zhao et al. (2015), organic manure raised GWP by 97.51%–219.31% while decreasing N_2O emissions by 28.34%–69.41% and increasing CH_4 emissions by 137%–310%. Ammonium sulfate replaced urea, reducing CH_4 by 40% while increasing N_2O by 24% (Hussain et al., 2022). In comparison to cow dung, vermicompost decreased GWP by 13–17% and CH_4, CO_2, and N_2O emissions by 13–19%, 17–21%, and 4–9%, respectively (Haque & Biswas, 2021).

3. Biochar application:

Burning organic waste, such rice straw, produces biochar, a material that resembles charcoal and is thought to be a viable method for reducing global warming (Lehmann et al., 2021; Wang et al., 2023). It changes soil characteristics including pH, microbial structure, and porosity, improves soil adsorption capacity, and raises nutrient content by decreasing leaching (Singh et al., 2024). The use of biochar considerably lowers emissions of CH_4 and N_2O. When paired with moderate amounts of fertilizer, increasing biochar also decreased N_2O emissions. One of the ways that biochar works is by raising the pH of the soil, which encourages methanotroph activity and lowers CH_4 emissions (Iboko et al., 2023). Returning agricultural waste as biochar might contribute to 10% of all anthropogenic reductions in CH_4 emissions (Wang et al., 2023). But the process of making biochar can release a lot of greenhouse gases, so a thorough life-cycle assessment (LCA) is necessary to weigh the trade-offs. Its efficacy also depends on high application rates, which presents financial difficulties. The necessary dose and related expenses may be decreased by increasing the efficiency of biochar production (Singh et al., 2024).

4. Cultivar selection:

The International Rice Research Institute has the largest collection of rice cultivars, with more than 100,000 accessions. Future developments include choosing or genetically altering cultivars to lower greenhouse gas emissions and improving rice for improved nutrition, such as addressing vitamin A and iron deficiencies (Gnanamanickam, 2009). There has been a lot of interest in drought-resistant rice cultivars, also known as water-saving and drought-resistant rice, because to its exceptional water-use efficiency and drought resilience. Following rigorous field testing, at least 22 of these cultivars were created and approved between 2000 and 2022 (Xia et al., 2022 According to reports, they lower N_2O emissions by 7.6% to 76.56%, and CH_4 emissions by 8.2% to 100% (Feng et al., 2021; Habib et al., 2023).

5. Rice straw utilization:

According to Yodkhum et al. (2018), there are several ways to use rice straw, including direct combustion for power, soil integration, open burning, and the creation of bioenergy. After being grown, rice straw is frequently burnt in many nations, which increases particulate matter and greenhouse gas emissions (Singh et al., 2021). GHGs may also be released during the transportation of rice straw (de Silva et al., 2021). Over 100 million tons of rice straw burned annually worldwide, open burning produces the biggest greenhouse gas emissions (Singh et al., 2024). This is probably because methanogens thrive on the extra substrate. According to Hou et al. (2013), continuous straw return raised CH_4 emissions by 185% to 289%. In order to counteract this, CH_4 emissions were decreased by breaking down rice straw using microbial substrates prior to soil absorption (Jumat et al., 2023). In contrast to soil integration, Ma et al. (2009) proposed ditch mulching as a way to reduce CH_4. Delaying the addition of straw until soil temperatures were lower also temporarily decreased CH_4 emissions by inhibiting methanogenic activity (Belenguer-Manzanedo et al., 2022).

Making value-added products from rice straw, such as bioenergy, biochemicals, and nanomaterials, is another area of attention. According to Singh et al. (2016), burning rice straw directly produces more greenhouse gas emissions than bioethanol production. However, the transportation of straw, the employment of chemicals and enzymes, the burning of byproducts, and the use of ethanol as fuel all contribute to emissions throughout the manufacturing of bioethanol, making thorough comparisons necessary. N_2O emissions can also be reduced by using rice straw.

Conclusion and future perspective:

Despite being essential to the world's food security, rice farming contributes significantly to greenhouse gas emissions, especially CH_4 and N_2O. In order to ensure sustainable farming practices and mitigate climate change, these emissions must be addressed. This analysis emphasizes how crucial it is to use mitigation techniques including using biochar, choosing low-emission rice varieties, and effectively managing fertilizer and water. Fertilizer management can further reduce emissions while preserving soil production by using improved fertilizers and nitrogen application rates. The use of biochar shows promise as an approach that can both improve soil health and reduce emissions of CH_4 and N_2O. Innovative strategies that improve water-use efficiency and lower GHG emissions without sacrificing yields include bacterial inoculation methods and drought-resistant rice cultivars. Furthermore, there is a chance to lower emissions and increase resource efficiency through the sustainable use of rice straw, which includes the manufacture of bioethanol and soil inclusion.

In order to provide region-specific solutions, future research should concentrate on combining various mitigating techniques. The long-term effects of these practices on emissions and production may be assessed with the use of sophisticated modeling techniques and life-cycle evaluations. To create rice cultivars with minimal greenhouse gas emissions, advances in genetic engineering and molecular breeding should also be utilized. Incentives for using climate-resilient technology and policies supporting sustainable rice farming methods are essential for implementing these solutions on a global scale.

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