Field Crop 2024, Vol.7, No.5, 243-251
http://cropscipublisher.com/index.php/fc

Systematic Review **Open Access**

Greenhouse Gas Emissions from Rice Paddies: Strategies for Reduction and Climate Change Mitigation

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Field Crop, 2024, Vol.7, No.5 doi: 10.5376/fc.2024.07.0024
Received: 01 Jul., 2024
Accepted: 12 Aug., 2024
Published: 01 Sep., 2024

Preferred citation for this article:
Sun W.J., and Qian Q.S., 2024, Greenhouse gas emissions from rice paddies: strategies for reduction and climate change mitigation, Field Crop, 7(5): 243-251 (doi: 10.5376/fc.2024.07.0024)

Abstract Rice cultivation is a staple of global agriculture, supporting the livelihoods of millions, but it is also a significant source of greenhouse gas (GHG) emissions, particularly methane and nitrous oxide. These emissions contribute to climate change, necessitating the development of effective mitigation strategies. This study explores the mechanisms of GHG emissions from rice paddies, including methane production pathways and the factors influencing nitrous oxide emissions. Various strategies for reducing emissions are analyzed, such as water management techniques like alternate wetting and drying (AWD), soil fertility management through integrated nutrient approaches, and crop management practices that enhance sustainability. Furthermore, the role of rice paddies in carbon sequestration is examined, alongside policy frameworks and incentive programs to support emission reduction. A case study highlights successful implementations of these strategies and the associated outcomes. The study concludes with a discussion on the challenges to widespread adoption and the need for future research to enhance both mitigation and climate resilience in rice production systems.

Keywords Rice cultivation; Greenhouse gas emissions; Methane reduction; Water management; Climate change mitigation

1 Introduction

Rice (*Oryza sativa* L.) is a staple food for nearly half of the world's population, playing a crucial role in global food security and nutrition (Jiang et al., 2019). It is predominantly cultivated in lowland irrigated systems, which are essential for maintaining high yields necessary to meet the growing demand for this vital crop (Thanuja and Karthikeyan, 2020). The significance of rice extends beyond its nutritional value, as it also supports the livelihoods of millions of farmers worldwide, particularly in Asia, where the majority of rice is produced and consumed.

Despite its importance, rice cultivation is a major source of anthropogenic greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O) (Zhao et al., 2019). Rice paddies contribute significantly to global CH_4 emissions due to the anaerobic conditions prevalent in flooded fields, which promote methanogenesis (Gupta et al., 2021). Additionally, the use of nitrogen fertilizers and organic amendments can increase N_2O emissions, further exacerbating the global warming potential (GWP) of rice systems (Shang et al., 2021). The combined emissions of CH_4 and N_2O from rice paddies are a critical concern for climate change mitigation efforts (Linquist et al., 2012).

Mitigating GHG emissions from rice paddies is essential for reducing the agricultural sector's impact on climate change while ensuring food security (Kumar et al., 2019). Various management practices, such as alternate wetting and drying, intermittent irrigation, and the use of plant growth regulators, have been explored to reduce CH_4 and N_2O emissions without compromising rice yields (Cho et al., 2021). These strategies are crucial for achieving sustainable rice production systems that balance the trade-offs between high yields and low GHG emissions (Hussain et al., 2015). Understanding the interactions between different management practices and site-specific conditions is vital for developing effective mitigation approaches (Jiang et al., 2018).

This study integrates existing strategies for greenhouse gas emission reduction in rice paddies and their effectiveness in mitigating climate change, evaluates the impacts of various management measures on CH_4 and

N_2O emissions, assesses their potential to balance yield and emissions reduction, and identifies knowledge gaps and future research needs, aiming to provide decision-makers and stakeholders with information on best practices for sustainable rice cultivation in the context of climate change.

2 Mechanisms of Greenhouse Gas Emissions from Rice Paddies

2.1 Methane emissions: sources and pathways

Methane CH_4 emissions from rice paddies primarily result from microbial methanogenesis, which occurs under anaerobic conditions in waterlogged soils. Methanogenesis is the final step in the anaerobic degradation of organic matter, where methanogens utilize substrates such as acetate (aceticlastic methanogenesis) or hydrogen plus carbon dioxide (hydrogenotrophic methanogenesis) (Conrad, 2020). Additionally, methane can be oxidized anaerobically in the presence of alternative electron acceptors like nitrate, ferric iron, or sulfate, which can mitigate CH_4 emissions (Fan et al., 2020). The presence of rice plants also influences methane emissions by providing pathways for methane transport through aerenchyma and by supplying substrates for methanogenesis, although they can also suppress emissions by delivering oxygen to the rhizosphere, which enhances methane oxidation (Oda and Chiếm, 2019).

2.2 Nitrous oxide emissions: mechanisms of production

Nitrous oxide N_2O emissions from rice paddies are primarily produced through microbial processes such as nitrification and denitrification. Nitrification occurs under aerobic conditions where ammonia is oxidized to nitrate, while denitrification happens under anaerobic conditions where nitrate is reduced to N_2O and nitrogen gas. The intermittent wetting and drying cycles in rice paddies create fluctuating aerobic and anaerobic conditions that favor these processes (Gupta et al., 2021). The application of nitrogen fertilizers can significantly influence N_2O emissions by providing substrates for nitrification and denitrification (Liu et al., 2016).

2.3 Factors influencing emission levels

Several factors influence the levels of greenhouse gas emissions from rice paddies, including water management, soil type, and agricultural practices. Water management practices, such as intermittent flooding, can reduce methane emissions by promoting aerobic conditions that inhibit methanogenesis and enhance methane oxidation (Malyan et al., 2016). Soil type also plays a crucial role, as soils with higher organic matter content tend to produce more methane due to the availability of substrates for methanogens (Sun et al., 2018). Additionally, the use of fertilizers and amendments can impact emissions; for instance, nitrate-based fertilizers can enhance anaerobic methane oxidation, thereby reducing methane emissions. The presence of specific microbial communities, such as sulfate-reducing bacteria and methane-oxidizing bacteria, can also mitigate methane production through competitive and mutualistic interactions. Furthermore, the conversion of rice paddies to other land uses, such as aquaculture, has been shown to reduce both methane and nitrous oxide emissions significantly.

3 Strategies for Reduction of Greenhouse Gas Emissions

3.1 Water management techniques

Alternate wetting and drying (AWD) is a water management technique that involves the periodic drying and re-flooding of rice paddies (Figure 1). This method has been shown to significantly reduce methane (CH_4) emissions, which are a major contributor to greenhouse gas emissions from rice fields. Studies have demonstrated that AWD can reduce CH_4 emissions by up to 95% compared to continuous flooding (CF) systems, while also conserving water by 25%~70% (Runkle et al., 2018). Additionally, AWD has been found to maintain or even improve rice yields under certain conditions, making it a viable alternative to traditional irrigation methods (Sriphirom et al., 2019; Malumpong et al., 2020).

Synchronous irrigation involves coordinating the irrigation schedules of multiple fields to optimize water use and reduce greenhouse gas emissions. This technique can be particularly effective when combined with AWD, as it allows for more efficient water distribution and reduces the overall water footprint of rice cultivation. Studies have shown that synchronous irrigation can further enhance the benefits of AWD by improving water productivity and reducing the global warming potential (GWP) of rice paddies.

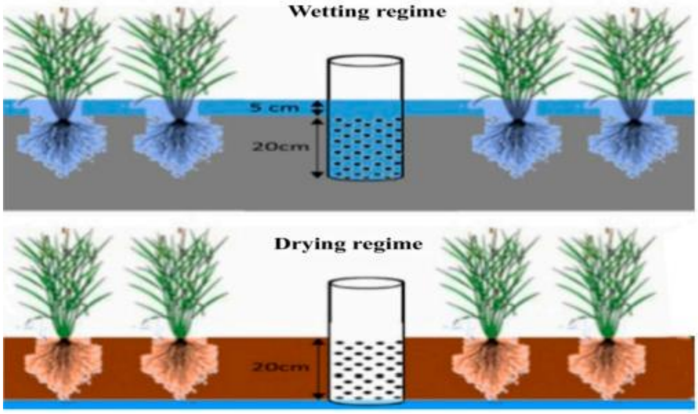

Figure 1 Wetting and drying regimes during the AWD irrigation (Adopted from Haque et al., 2021)

3.2 Soil fertility management

Integrated nutrient management (INM) involves the combined use of organic and inorganic fertilizers to optimize soil fertility and reduce greenhouse gas emissions. This approach can enhance the efficiency of nutrient use, thereby reducing the need for chemical fertilizers, which are a significant source of nitrous oxide (N_2O) emissions. Studies have shown that INM can reduce N_2O emissions by up to 66% when combined with water-saving irrigation techniques like AWD (Islam et al., 2020).

The use of organic amendments, such as biochar and compost, can improve soil health and reduce greenhouse gas emissions from rice paddies (Liang, 2024). Biochar, in particular, has been shown to reduce CH_4 emissions by up to 40.6% when applied to rice fields. Additionally, organic amendments can enhance soil organic carbon (SOC) stocks, which can further mitigate climate change by sequestering carbon in the soil (Sriphirom et al., 2020).

3.3 Crop management practices

Selecting rice varieties that are more efficient in water and nutrient use can significantly reduce greenhouse gas emissions. Varieties that have shorter growing periods or are more resistant to drought and pests can reduce the need for water and chemical inputs, thereby lowering CH_4 and N_2O emissions. Research has shown that certain rice varieties can maintain high yields under AWD conditions, making them suitable for sustainable rice production (Ishfaq et al., 2020; Wang et al., 2020).

Crop rotation and diversification involve alternating rice cultivation with other crops to improve soil health and reduce greenhouse gas emissions (Sun and Qian, 2024). This practice can break pest and disease cycles, reduce the need for chemical inputs, and enhance soil fertility. Studies have indicated that crop rotation can reduce CH_4 emissions by altering the microbial activity in the soil, which is responsible for methane production. Additionally, diversifying crops can improve the resilience of farming systems to climate change, further contributing to greenhouse gas mitigation.

4 Climate Change Mitigation Strategies

4.1 Role of rice paddies in carbon sequestration

Rice paddies play a significant role in carbon sequestration, which is crucial for mitigating climate change. The incorporation of organic fertilizers and the adoption of no-till practices have been shown to enhance soil organic carbon (SOC) sequestration. For instance, replacing synthetic nitrogen with organic fertilizers in rice paddies can significantly decrease net greenhouse gas emissions and improve rice yield, thereby contributing to carbon sequestration (Shang et al., 2021). Additionally, no-till practices, especially when combined with residue retention, have been found to reduce methane emissions and enhance SOC sequestration, although the increase in nitrous oxide emissions needs to be managed carefully (Zhao et al., 2016). Integrated management practices, such as reduced water usage, tillage with residue management, and reduced mineral nitrogen fertilizer, have also demonstrated potential in increasing SOC stocks in rice paddies (Figure 2) (Begum et al., 2018; Dheri and Nazir, 2021).

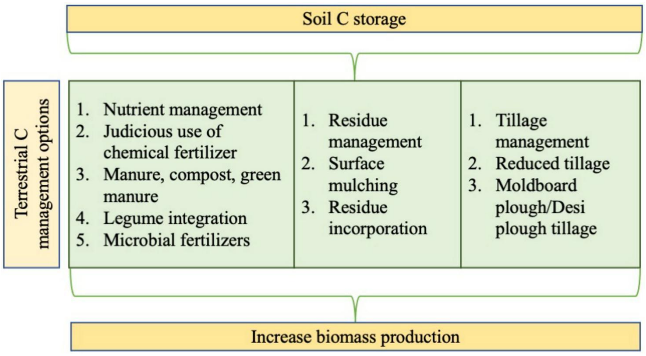

Figure 2 Management practices of C sequestration (Adopted from Dheri and Nazir, 2021)

4.2 Policy and incentive frameworks for emission reduction

Effective policy and incentive frameworks are essential for encouraging farmers to adopt practices that reduce greenhouse gas emissions from rice paddies. Policies that promote the use of water-saving irrigation techniques, such as alternate wetting and drying (AWD) and intermittent irrigation, can significantly reduce methane emissions while maintaining rice yields (Islam et al., 2020. Additionally, providing incentives for the adoption of improved rice varieties that are more efficient in nitrogen uptake and less dependent on continuous flooding can further reduce emissions (Zhao et al., 2019). Policymakers should also consider supporting the use of biochar amendments, which have been shown to decrease methane and nitrous oxide emissions while increasing crop yields (Wu et al., 2019). These frameworks should be designed to balance the trade-offs between reducing emissions and ensuring food security.

4.3 Education and awareness programs for farmers

Education and awareness programs are critical for equipping farmers with the knowledge and skills needed to implement greenhouse gas mitigation strategies effectively. Training programs that focus on the benefits and techniques of water-saving irrigation practices, such as intermittent irrigation and AWD, can help farmers reduce methane emissions from their rice paddies (Jiang et al., 2019; Lansing et al., 2023). Additionally, educating farmers about the advantages of using organic fertilizers and biochar amendments can promote practices that enhance soil carbon sequestration and reduce overall greenhouse gas emissions. Awareness campaigns should also highlight the importance of adopting improved rice varieties and no-till practices to achieve sustainable rice production with lower emissions (Xu et al., 2015). By providing farmers with the necessary information and resources, these programs can facilitate the widespread adoption of climate-smart agricultural practices.

5 Case Study

5.1 Successful implementation of emission reduction strategies

Several studies have demonstrated the successful implementation of various strategies to reduce greenhouse gas (GHG) emissions from rice paddies. For instance, a global meta-analysis highlighted that non-flooding irrigation methods, such as alternate wetting and drying (AWD), significantly reduced methane (CH_4) emissions by 53% compared to continuous flooding, although it did increase nitrous oxide (N_2O) emissions by 105% (Jiang et al., 2019). Another study in China showed that water-saving irrigation strategies, such as flooded and wet intermittent irrigation (FWI) and flooded and dry intermittent irrigation (FDI), reduced CH_4 emissions by 60% and 83%, respectively, compared to continuous flooding (Xu et al., 2015). Additionally, early-season drainage combined with mid-season drainage was found to reduce CH_4 emissions and yield-scaled global warming potential (GWP) by 85-90% compared to continuous flooding.

5.2 Analysis of outcomes

The outcomes of these strategies have been multifaceted, impacting both GHG emissions and rice yields. For example, the implementation of AWD not only reduced CH_4 emissions by 38% but also increased water use efficiency by 40%, although it led to a 34% increase in N_2O emissions (Wang et al., 2020). Similarly, the use of FWI and FDI irrigation strategies resulted in a reduction of GWP and greenhouse gas intensity (GHGI) by up to 29%, while maintaining rice yields when using drought-resistant rice varieties. In another case, replacing synthetic nitrogen with organic fertilizer in paddy rice significantly decreased net GHG emissions and improved rice yield (Shang et al., 2021). These findings suggest that while some strategies may lead to trade-offs between different types of GHG emissions, they can still achieve overall reductions in GWP and maintain or even enhance rice yields.

5.3 Lessons learned and best practices

From these case studies, several lessons and best practices have emerged. First, water management practices such as AWD and early-season drainage are effective in reducing CH_4 emissions and overall GWP, although they may increase N_2O emissions (Islam et al., 2018). Therefore, it is crucial to balance the trade-offs between different GHGs. Second, integrating organic fertilizers and optimizing nitrogen application rates can further mitigate GHG emissions while enhancing rice yields. Third, the selection of drought-resistant rice varieties can help maintain yields under water-saving irrigation regimes, making these strategies more viable for farmers. Lastly, continuous adaptation and localized management, as demonstrated by Balinese farmers, can lead to both reduced GHG emissions and increased rice yields, highlighting the importance of community-based approaches (Lansing et al., 2023).

6 Policy and Economic Considerations

6.1 Role of government and international agencies

Governments and international agencies play a crucial role in mitigating greenhouse gas (GHG) emissions from rice paddies. Effective policies and regulations are essential to promote sustainable agricultural practices and reduce emissions. For instance, regulatory bodies can formulate policies that encourage the adoption of water management practices such as alternate wetting and drying (AWD) and intermittent irrigation, which have been shown to significantly reduce methane (CH_4) emissions from rice fields (Lansing et al., 2023). Additionally, international agencies can facilitate the exchange of knowledge and technology, helping to implement best practices globally. The Intergovernmental Panel on Climate Change (IPCC) provides scaling factors for different water management practices, which can guide policymakers in setting realistic and effective emission reduction targets (Jiang et al., 2019).

6.2 Economic incentives for adoption of mitigation strategies

Economic incentives are vital to encourage farmers to adopt GHG mitigation strategies. Subsidies, tax breaks, and financial support for the adoption of sustainable practices can make a significant difference. For example, providing financial incentives for the use of organic fertilizers instead of synthetic nitrogen can help reduce net GHG emissions while maintaining or even improving rice yields (Shang et al., 2021). Similarly, promoting the use of drought-resistant rice varieties through economic incentives can help conserve water and reduce GHG emissions without compromising yield (Xu et al., 2015). These incentives can lower the initial cost barriers for farmers, making it more feasible for them to implement environmentally friendly practices.

6.3 Challenges and barriers to implementation

Despite the potential benefits, several challenges and barriers hinder the implementation of GHG mitigation strategies in rice paddies. One major challenge is the trade-off between reducing CH_4 and increasing nitrous oxide (N_2O) emissions. For instance, while non-continuous flooding practices can significantly reduce CH_4 emissions, they may lead to an increase in N_2O emissions, complicating the overall GHG mitigation efforts. Additionally, the variability in soil and climate conditions can affect the effectiveness of different management practices, making it difficult to implement a one-size-fits-all solution (Zhao et al., 2016; Zhao et al., 2019). Economic constraints also pose a significant barrier, as the initial costs of adopting new technologies and practices can be prohibitive for many farmers. Furthermore, there is often a lack of awareness and technical knowledge among farmers about the benefits and methods of GHG mitigation, which can impede the adoption of these practices (Chen et al., 2021; Gupta et al., 2021).

7 Future Directions and Research Needs

7.1 Innovations in technology and practices

Innovations in technology and practices are crucial for reducing greenhouse gas (GHG) emissions from rice paddies. Several studies have highlighted the potential of various management practices to mitigate emissions. For instance, the adoption of alternate wetting and drying (AWD) irrigation has been shown to significantly reduce methane (CH_4) emissions by 25%~70% without increasing nitrous oxide (N_2O) emissions (Chirinda et al., 2018). Additionally, the use of biochar and other soil amendments can further reduce GHG emissions while enhancing rice yields (Yagi et al., 2020). The development and implementation of drought-resistant rice varieties, such as HY3, have also demonstrated effectiveness in maintaining yields and reducing GHG emissions under water-saving irrigation strategies (Xu et al., 2015). Future research should focus on optimizing these practices and developing new technologies that can be easily adopted by farmers to achieve sustainable rice production.

7.2 Enhancing climate resilience in rice production

Enhancing the climate resilience of rice production systems is essential to ensure food security while mitigating climate change. The integration of water-saving irrigation practices, such as intermittent irrigation and AWD, has shown promise in reducing GHG emissions and conserving water resources (Lansing et al., 2023). Moreover, the selection of high-yielding, low-emission rice varieties can significantly contribute to reducing the global warming potential (GWP) of rice cultivation (Zhang et al., 2019). It is also important to consider the local environmental and climatic conditions when implementing these practices, as their effectiveness can vary based on soil type, organic carbon content, and other factors (Jiang et al., 2019). Future research should aim to develop region-specific strategies that enhance the resilience of rice production systems to climate change.

7.3 Need for multi-disciplinary approaches

Addressing the complex issue of GHG emissions from rice paddies requires a multi-disciplinary approach that integrates agronomy, soil science, climate science, and socio-economic factors. Studies have shown that changes in field management practices can balance the trade-offs between high yield and low emissions of GHGs (Shang et al., 2021). However, the interactions between different management practices and site-specific conditions need to be better understood to develop effective mitigation strategies (Zhao et al., 2019). Collaborative efforts among researchers, policymakers, and farmers are essential to identify and implement the most promising practices. Additionally, there is a need for comprehensive assessments that consider the overall GWP of different management practices and their socio-economic impacts (Hussain et al., 2015). Future research should focus on developing integrated approaches that address the environmental, economic, and social dimensions of sustainable rice production.

8 Concluding Remarks

Rice paddies are significant sources of greenhouse gases (GHGs), particularly methane (CH4) and nitrous oxide (N_2O), contributing substantially to global emissions. Various studies have highlighted the critical factors influencing these emissions and potential mitigation strategies. For instance, rice paddies contribute around 30% and 11% of global agricultural CH_4 and N_2O emissions, respectively, necessitating urgent mitigation strategies. The spatial and temporal dynamics of CH4 emissions are influenced by factors such as soil properties and climate conditions, with warming climates potentially enhancing CH_4 emissions. Elevated CO_2 levels have been shown to increase CH_4 emissions from paddies, although the effects vary over time and between ecosystems. Management practices, such as alternate wetting and drying (AWD), have demonstrated significant reductions in CH4 emissions without compromising rice yields. Additionally, the conversion of rice paddies to other agricultural systems, such as aquaculture, can also reduce GHG emissions. The role of rice plants themselves in mitigating CH_4 emissions, particularly in high-emitting paddies, has been noted, suggesting that certain rice varieties could be more effective in reducing emissions.

Mitigating GHG emissions from rice paddies is crucial for climate change adaptation and requires a multifaceted approach. Effective strategies include optimizing water management practices, such as AWD, which significantly reduce CH_4 emissions while maintaining rice yields. Additionally, reducing nitrogen fertilizer application can lower N_2O emissions, contributing to overall GHG mitigation. The adoption of improved rice varieties that can suppress CH_4 emissions further enhances the potential for sustainable rice production. Integrating remote sensing and biogeochemical modeling can provide accurate assessments of GHG emissions, aiding in the development of region-specific mitigation strategies. Moreover, transitioning to alternative agricultural systems, such as aquaculture, offers a viable pathway to reduce emissions while potentially increasing agricultural income. Policymakers and regulatory bodies must prioritize these strategies to formulate effective policies that balance the need for food security with the imperative to mitigate climate change. Continued research and field studies are essential to refine these strategies and ensure their effectiveness across diverse environmental and agricultural contexts.

Acknowledgments

We are grateful to Miss Guo for critically reading the manuscript and providing valuable feedback.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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