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Environmental Impacts of Different Rice Cultivation Systems: A Comparative Analysis

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Abstract Rice cultivation is a critical agricultural activity with significant environmental impacts. This study aims to assess these impacts across various rice cultivation systems, including traditional paddy cultivation, the System of Rice Intensification (SRI), direct-seeded rice (DSR), organic rice farming, and other emerging systems. The research focuses on key environmental categories such as water usage and management, soil health and fertility, greenhouse gas emissions, biodiversity, and agrochemical use. Through comparative analysis and case studies, the report highlights differences in environmental impacts among these cultivation systems. Sustainable practices and innovations, including water-saving techniques, soil conservation methods, emission reduction strategies, biodiversity enhancement, and integrated pest and nutrient management, are explored. The study also discusses policy and regulatory implications, emphasizing the need for national and international policies, incentives for sustainable practices, and effective compliance and monitoring mechanisms. Future directions for research, technology adoption, collaborative efforts, and long-term environmental monitoring are proposed. The findings underscore the importance of adopting sustainable rice cultivation practices to mitigate environmental impacts and ensure agricultural sustainability.
Keywords Rice cultivation; Environmental impact; Sustainable agriculture; Greenhouse gas emissions; Soil health

1 Introduction

Rice is a staple food for more than half of the world's population, playing a crucial role in global food security and nutrition. The cultivation of rice, however, is not without its environmental challenges. Traditional rice farming methods, particularly those involving continuous flooding, are significant sources of greenhouse gas (GHG) emissions, including methane (CH_4) and nitrous oxide (N_2O) (Jiang et al., 2019; Hariz et al., 2019). These emissions contribute to global warming and climate change, making it imperative to explore and assess alternative rice cultivation systems that can mitigate these environmental impacts (Maraseni et al., 2018; Arunrat et al., 2021).

Assessing the environmental impacts of rice cultivation is essential for developing sustainable agricultural practices (Mali et al., 2023). Life cycle assessment (LCA) is a comprehensive method used to evaluate the environmental burdens associated with all stages of a product's life, from cradle to gate. This approach has been applied to rice farming to quantify GHG emissions and other environmental impacts, such as terrestrial toxicity, fossil fuel scarcity, and human health risks (Hariz et al., 2019; Alphonso and Thirumani, 2023). By understanding these impacts, policymakers and farmers can make informed decisions to adopt practices that reduce the environmental footprint of rice production.

This study evaluates and compares conventional rice farming, organic rice farming, and innovative practices such as the system of rice intensification (SRI) and alternate wetting and drying (AWD). By analyzing data from various studies, this study identifies the most sustainable rice cultivation methods that can reduce GHG emissions, improves soil health, and enhance overall sustainability. The findings provides valuable insights for farmers, researchers, and policymakers to promote environmentally friendly rice farming practices. This study explores the environmental impacts of different rice cultivation systems, emphasizing the need for sustainable practices to mitigate the adverse effects of traditional rice farming on the environment. Through a systematic comparative analysis, this research aims to contribute to the development of more sustainable and eco-friendly rice production methods.

2 Overview of Rice Cultivation Systems

Rice cultivation is a critical agricultural practice that supports the livelihoods of millions of people worldwide. Various cultivation systems have been developed to enhance productivity, sustainability, and environmental impact.

2.1 Traditional paddy cultivation

Traditional paddy cultivation, also known as conventional transplanting, involves growing rice seedlings in a nursery and then transplanting them into flooded fields. This method is labor-intensive and requires significant water resources. Despite its widespread use, traditional paddy cultivation has several environmental drawbacks, including high methane emissions and water consumption (Li et al., 2019; Nirmala et al., 2021; Kumar et al., 2023).

2.2 System of rice intensification (SRI)

The System of Rice Intensification (SRI) is an innovative method that aims to increase rice yields while reducing water usage and environmental impact. SRI involves planting fewer seedlings with wider spacing, intermittent irrigation, and the use of organic fertilizers. Studies have shown that SRI can significantly enhance grain yield, water productivity, and soil health compared to traditional methods. Additionally, SRI has been associated with reduced greenhouse gas emissions and improved economic returns for farmers (Katti and Ch, 2022).

2.3 Direct-seeded rice (DSR)

Direct-Seeded Rice (DSR) is a method where rice seeds are sown directly into the field, eliminating the need for nursery raising and transplanting. DSR is gaining popularity due to its lower labor and water requirements. However, it presents challenges such as higher weed infestation and potential increases in methane emissions. Despite these challenges, DSR has been shown to improve water productivity and reduce overall cultivation costs, making it a viable alternative to traditional methods (Kakumanu et al., 2019; Bandyopadhyay et al., 2019; Bhandari et al., 2020; Hazra et al., 2021).

2.4 Organic rice farming

Organic rice farming emphasizes the use of natural inputs and sustainable practices to cultivate rice. This method avoids synthetic fertilizers and pesticides, promoting biodiversity and soil health. Organic farming can lead to lower yields compared to conventional methods, but it offers significant environmental benefits, including reduced chemical runoff and enhanced ecosystem services. The adoption of organic rice farming is growing as consumers become more aware of the environmental and health benefits of organic products (Phụ et al., 2021).

2.5 Other emerging systems

Several other emerging rice cultivation systems are being explored to address the challenges of traditional methods. These include alternate wetting and drying (AWD), aerobic rice, and modified SRI (MSRI). AWD involves periodic drying of the field, which can reduce water usage and methane emissions. Aerobic rice is grown in non-flooded, well-drained soils, which can save water and reduce labor. MSRI is a variation of SRI that incorporates mechanization to reduce labor requirements while maintaining the benefits of SRI. These emerging systems show promise in enhancing the sustainability and efficiency of rice cultivation (Devi, 2023).

In conclusion, the comparative analysis of different rice cultivation systems highlights the potential for innovative practices to improve productivity, sustainability, and environmental impact. Each system has its advantages and challenges, and the choice of method depends on local conditions, resource availability, and specific goals of the farmers.

3 Environmental Impact Categories

3.1 Water usage and management

Water management practices in rice cultivation significantly influence environmental impacts. Non-continuous flooding methods, such as alternate wetting and drying (AWD), have been shown to reduce methane (CH_4) emissions by 53% compared to continuous flooding, although they increase nitrous oxide (N_2O) emissions by 105% (Jiang et al., 2019). AWD also saves water, reducing water usage by 10% in the dry season and 19% in the wet season (Win et al., 2021). However, intermittent irrigation can increase net greenhouse gas emissions and decrease rice yield (Shang et al., 2021).

3.2 Soil health and fertility

Soil health and fertility are critical for sustainable rice production. The incorporation of organic amendments, such as straw and manure, can enhance soil organic carbon stocks and improve soil fertility (Janz et al., 2019). For instance, the eco-rice system (ER) in China improved soil fertility by increasing organic matter, total nitrogen, and available potassium content (Yang et al., 2019). However, the use of organic amendments can also lead to higher greenhouse gas emissions, particularly CH_4, during the decomposition process.

3.3 Greenhouse gas emissions

Rice cultivation is a significant source of greenhouse gas emissions, primarily CH_4 and N_2O. Different rice cultivation systems and management practices have varying impacts on these emissions. Ecological rice-cropping systems (ERSs) can reduce CH_4 emissions by 12.5% but increase N_2O emissions by 11.3% compared to traditional systems (Sun et al., 2021). Diversified cropping systems, such as rice-maize rotations, can lower annual yield-scaled global warming potential (GWP) compared to traditional rice-rice systems (Janz et al., 2019). Additionally, replacing synthetic nitrogen with organic fertilizer can decrease net greenhouse gas emissions and improve rice yield (Shang et al., 2021).

3.4 Biodiversity and ecosystem services

Biodiversity and ecosystem services are essential for maintaining the ecological balance in rice cultivation systems. Integrated systems, such as rice-fish (Figure 1), rice-duck and rice-crayfish, have been shown to enhance biodiversity and provide ecosystem services, such as pest control and nutrient cycling (Sun et al., 2021). These systems can also reduce the global warming potential and greenhouse gas intensity. The use of vegetated drainage ditches in eco-rice systems can further improve nutrient removal efficiency and support biodiversity (Yang et al., 2019).

Arunrat and Sereenonchai (2022) compare the ecosystem service contributions of rice-fish co-culture and rice monoculture systems. In the rice-fish co-culture system (a), maintaining soil nutrients and climate control are the primary services, accounting for 49.11% and 47.83%, respectively. Pest control constitutes a minor 1.93%. The detailed breakdown shows significant contributions to gas regulation (CO_2 fixation) at 0.71% and air purification at 0.07%. In contrast, the rice monoculture system (b) places a greater emphasis on maintaining soil nutrients (51.07%) and climate control (47.16%), but with a notably lower pest control contribution at 0.44%. Gas regulation (CO_2 fixation) is higher at 1.03%, and air purification remains consistent at 0.07%. While both systems prioritize soil nutrient maintenance and climate control, the rice-fish co-culture system offers slightly more balanced ecosystem services, including enhanced pest control and water storage benefits. This comparison highlights the potential environmental advantages of integrated agricultural practices.

3.5 Agrochemical use and pollution

The use of agrochemicals, particularly nitrogen fertilizers, has significant environmental impacts. High nitrogen rates can lead to increased acidification and terrestrial eutrophication (Tayefeh et al., 2018). Transgenic rice cultivars, which require fewer insecticides, can reduce the environmental and human health impacts associated with chemical inputs (Dastan et al., 2019). Additionally, integrated systems that utilize biogas production from cattle manure can reduce methane emissions and energy consumption, contributing to lower environmental impacts (Ogino et al., 2021).

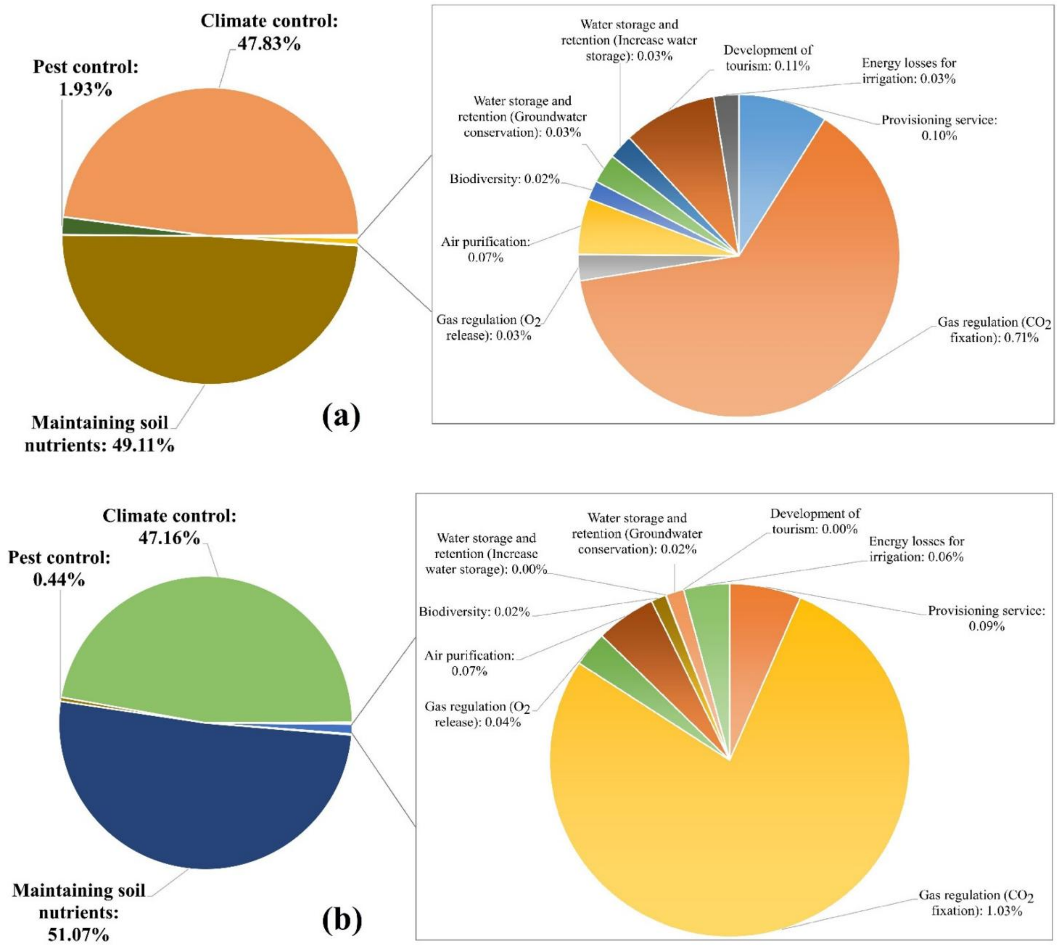


Figure 1 Proportion of service types (Adopted from Arunrat and Sereenonchai, 2022)
Image caption: (a) rice-fish co-culture system, (b) rice monoculture system (Adopted from Arunrat and Sereenonchai, 2022)

4 Comparative Analysis of Cultivation Systems

4.1 Water consumption

Water consumption varies significantly across different rice cultivation systems. Lowland rice fields have the highest water footprint (WF) at 1,701.6 m^3 per ton, followed by terraced rice (1,422.1 m^3 per ton) and upland rice (1,283.2 m^3 per ton) (Toolkiattiwong et al., 2023). Water-saving irrigation techniques, such as alternate wetting and drying (AWD), have been shown to reduce water use by 15% compared to continuous flooding (Islam et al., 2020). These methods not only conserve water but also impact greenhouse gas emissions and crop yields.

4.2 Soil degradation and erosion

Soil degradation and erosion are critical issues in rice cultivation. Terraced rice fields, while effective in reducing erosion, have a higher carbon footprint (CF) compared to upland and lowland systems. Reduced tillage practices can mitigate soil degradation by maintaining soil structure and organic matter content, which is beneficial for long-term soil health (Islam et al., 2020).

4.3 Methane and nitrous oxide emissions

Methane (CH_4) and nitrous oxide (N_2O) emissions are major concerns in rice cultivation. Continuous flooding is associated with high CH_4 emissions, while intermittent flooding increases N_2O emissions significantly. For instance, N_2O emissions from intermittently flooded rice fields can be 30-45 times higher than those from continuously flooded fields (Kritee et al., 2018). However, non-continuous flooding practices can reduce the global warming potential (GWP) by 44% (Jiang et al., 2019). The use of modified nitrogen fertilizers and water-saving irrigation can further reduce CH_4 emissions by up to 31% and increase N_2O emissions by 42%-52% (Li et al., 2018).

4.4 Impact on local flora and fauna

Different rice cultivation systems impact local flora and fauna differently. Lowland rice fields, with their high water and pesticide use, have the most significant negative impact on human health and freshwater ecotoxicity. The use of biochar and wood vinegar has been shown to mitigate these impacts by reducing N_2O and CH_4 emissions and improving soil health (Feng et al., 2020).

4.5 Pesticide and fertilizer impact

Pesticide and fertilizer use in rice cultivation systems have varying environmental impacts. Lowland rice fields have the highest pesticide residues, including chlorpyrifos and glyphosate, which are harmful to both human health and the environment (Toolkiattiwong et al., 2023). Integrated nutrient management, combining inorganic fertilizers with organic amendments like Azolla compost, can enhance soil carbon storage and reduce the global warming potential, although it may increase CH_4 emissions (Bharali et al., 2018). The co-application of wood vinegar and biochar has also been effective in reducing GHG emissions and improving rice yield (Feng et al., 2020).

In summary, the comparative analysis of different rice cultivation systems highlights the trade-offs between water use, soil health, greenhouse gas emissions, and environmental impacts. Effective management practices, such as water-saving irrigation, reduced tillage, and integrated nutrient management, can mitigate these impacts and promote sustainable rice cultivation.

5 Case Studies

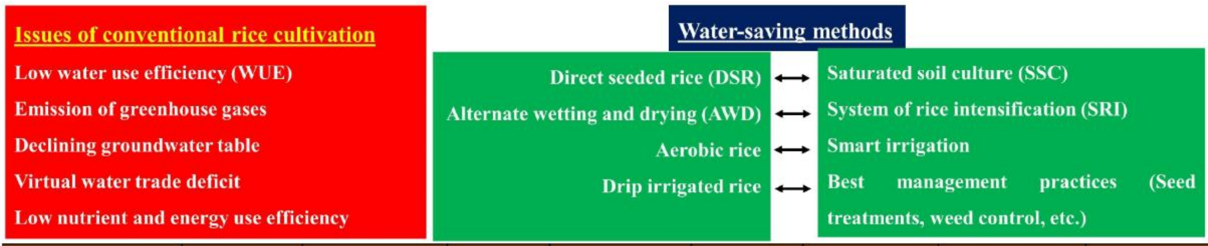
5.1 Case study of traditional paddy cultivation

Traditional paddy cultivation, often referred to as conventional transplanting of rice (CTF), involves the flooding of fields and transplanting seedlings. This method has been widely practiced due to its simplicity and effectiveness in weed control. However, it is associated with high water usage and significant greenhouse gas (GHG) emissions, particularly methane (CH_4) (Nirmala et al., 2021; Kumar et al., 2023). Studies have shown that traditional paddy fields can emit substantial amounts of CH_4 due to anaerobic conditions created by continuous flooding (Li et al., 2019). Additionally, the conventional method has been found to have lower water productivity and soil microbial activity compared to more modern techniques.

5.2 Case study of system of rice intensification (SRI)

The system of rice intensification (SRI) is an innovative method that aims to increase rice yields while reducing water usage and environmental impact. SRI involves planting fewer seedlings, maintaining soil aeration through intermittent drying, and using organic fertilizers. Research in India has demonstrated that SRI can significantly enhance grain yield, water productivity, and soil health compared to traditional methods (Figure 2) (Nirmala et al., 2021). SRI has also been shown to reduce GHG emissions by 21% compared to conventional methods, making it a more environmentally friendly option (Kumar et al., 2023). Furthermore, SRI management has been associated with higher soil microbial populations and beneficial nematodes, contributing to improved soil health.

The research of system of Mallareddy et al. (2023) shows that rice intensification (SRI) demonstrates notable advantages in water-saving rice production methods. SRI achieves 20-40% water savings, making it efficient in water use. It maintains low percolation rates and effectively controls weed growth compared to other methods. SRI is suitable for a variety of soil types, particularly loamy to clay soils, and operates well in irrigated ecosystems. In terms of environmental impact, SRI shows low emissions of both methane (CH_4) and nitrous oxide (N_2O), contributing to a reduced global warming potential (GWP). The irrigation strategy involves maintaining soil moisture in field capacity, with an irrigation depth of less than 5 cm, which helps in conserving water. Additionally, SRI is characterized by low energy input and cost, making it a sustainable and economical choice for farmers. The method also has low labor requirements, further enhancing its practicality and attractiveness as a water-saving rice cultivation practice.



	AWD	SSC	DSR	Aerobic rice	SRI	Drip	Smart Irrigation	CF
Water saving (%)	~ 25	25-30	~ 15	20-30	20-40	>50	30	-
Percolation	Low	Very low	Low	Low	Low	Very low	Low	More
Weed	More	More	More	More	More	Low	More	Low
Suitable ecosystem	I	I	R	I	I	I	I	I/R
CH_4 emission	Low	Low	Low	Low	Low	Low	Low	More
N_2O emission	More	More	More	More	More	Low	More	Low
GWP	Low	Low	Low	Low	Low	Very low	Low	More
Irrigation	WT <15 cm in tube	Shallow irrigation	Normal irrigation	Maintain SM in field capacity	Hair like crack	2-days interval	Based on SM	4 to 7 days interval
Irrigation depth (cm)	<5	3	<5	<5	<5	No flooding	<5	>10
Suitable soil	Loamy	Loamy	All	Loam to clay	All	Sandy	All	Clay
Labour requirement	Low	Low	Low	Low	More	Very low	Very low	More
Energy input	Low	Low	Low	Low	Low	Low	Low	More
Cost	Low	Low	Low	Low	Low	More	More	More

GWP – Global warming potential; CF – Conventional flooding; I – Irrigated; R – Rainfed; WT – Water Table; SM –Soil moisture

Figure 2 A comparison of water-saving rice production methods (Adopted from Mallareddy et al., 2023)

5.3 Case study of direct-seeded rice (DSR)

Direct-seeded rice (DSR) is a method where seeds are sown directly into the field, eliminating the need for transplanting. This method is gaining popularity due to its labor-saving benefits and potential for water conservation. However, studies have shown mixed results regarding its environmental impact. For instance, a study in southeast China found that DSR systems had 25% higher cumulative CH_4 emissions compared to traditional transplanting systems, primarily due to higher gross ecosystem productivity and rice plant density (Li et al., 2019). On the other hand, DSR has been shown to reduce energy consumption and GHG emissions in some regions, such as Karnataka, India, where it demonstrated higher energy use efficiency and lower on-farm emissions compared to puddled transplanted rice (PTR) (Basavalingaiah et al., 2020).

5.4 Case study of organic rice farming

Organic rice farming emphasizes the use of natural inputs and sustainable practices to enhance soil health and reduce environmental impact (Figure 3). This method avoids synthetic fertilizers and pesticides, relying instead on organic matter and biological pest control. Research has shown that organic rice farming can improve soil nutrient dynamics and reduce chemical residues in the environment (Gamaralalage et al., 2021). Additionally, organic practices can enhance biodiversity and natural enemy populations, contributing to pest management and ecosystem health (Katti and Ch, 2022). However, organic farming may face challenges such as lower yields and nutrient deficiencies, which need to be addressed through careful management (Hazra et al., 2021).

The research of system of Sarkar et al. (2020) highlights the numerous benefits of crop residue retention for enhancing soil fertility and health. By maintaining crop residues on the soil surface, better moisture conservation is achieved, reducing the need for additional irrigation. This practice also moderates soil temperature, creating a more stable environment for plant growth. Crop residue retention minimizes soil erosion by inhibiting runoff, which helps maintain soil structure and composition. Additionally, it results in lower greenhouse gas emissions, contributing to a more sustainable agricultural practice. Beneath the surface, retained residues improve soil aggregation and hydraulic conductivity, facilitating better water infiltration and root growth. The presence of high-quality organic matter increases soil carbon stocks, enhancing nutrient recycling and availability. This, in turn, supports higher microbial activity, which is crucial for nutrient cycling and soil fertility. Overall, crop residue retention promotes better root proliferation, leading to healthier and more resilient crops.

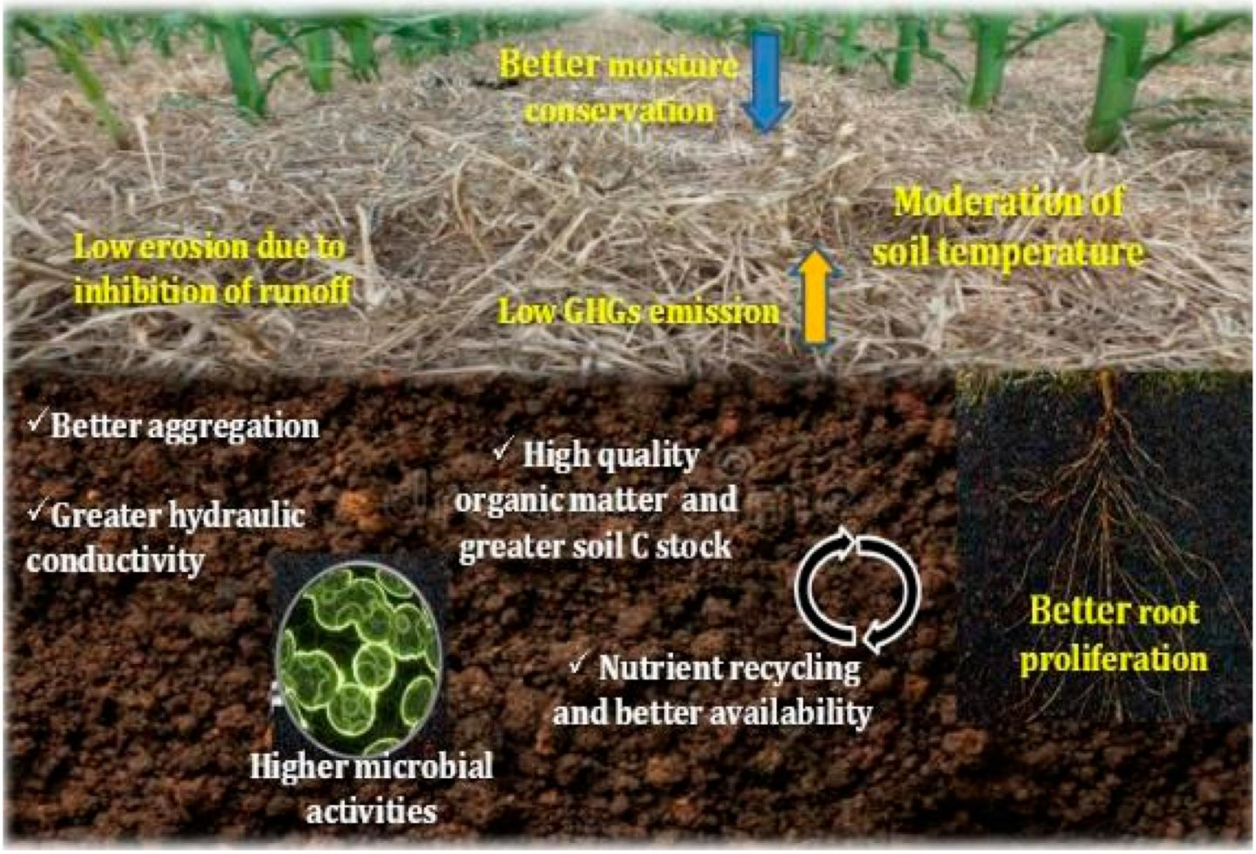


Figure 3 Advantages of crop residue retention for improving soil fertility (Adopted from Sarkar et al., 2020)

5.5 Comparative insights

Comparing these different rice cultivation systems reveals a complex interplay of benefits and trade-offs. Traditional paddy cultivation, while effective in weed control, is associated with high water usage and GHG emissions. SRI offers significant advantages in terms of yield, water productivity, and environmental impact, making it a promising alternative (Nirmala et al., 2021; Kumar et al., 2023). DSR, although labor-saving and potentially more energy-efficient, can result in higher CH_4 emissions under certain conditions (Li et al., 2019; Basavalingaiah et al., 2020). Organic rice farming promotes environmental sustainability and biodiversity but may require more intensive management to address yield and nutrient challenges. Overall, the choice of cultivation system should consider local conditions, resource availability, and environmental goals to achieve sustainable rice production.

6 Sustainable Practices and Innovations

6.1 Water-saving techniques

Water-saving techniques are crucial for sustainable rice cultivation, especially in the context of water scarcity and climate change. Alternate wetting and drying (AWD) is one such technique that has shown promise in reducing water usage while maintaining or even increasing rice yields. AWD involves periodic drying of the field, which reduces the total water input by 19% in the wet season and 39% in the dry season, thereby improving water productivity by 46% and 77%, respectively (Maneepitak et al., 2019). Another study highlights the potential of water-saving ground cover rice production systems (GCRPSs) in reducing water requirements and greenhouse gas emissions, particularly when integrated nutrient management is employed (Yao et al., 2019). However, the long-term impacts of these techniques on soil health need further investigation (Livsey et al., 2019).

6.2 Soil conservation methods

Soil conservation is vital for maintaining soil fertility and ensuring long-term agricultural productivity. Practices such as crop rotation, the incorporation of legumes, and the use of mycorrhizal associations can significantly improve soil health (Mali et al., 2023). The co-culture of rice and aquatic animals has also been shown to enhance soil quality by increasing biodiversity and improving nutrient cycling (Bashir et al., 2020). Additionally, the use of rice-specific harvesters can help manage rice residues more effectively, reducing the need for residue burning and its associated environmental impacts (Ullah et al., 2021).

6.3 Emission reduction strategies

Reducing greenhouse gas emissions from rice cultivation is essential for mitigating climate change. Integrated nutrient management in GCRPSs has been shown to reduce nitrous oxide (N_2O) and nitric oxide (NO) emissions by approximately 77% and 50%, respectively, compared to conventional methods (Yao et al., 2019). The adoption of direct-seeded rice instead of transplanted rice can also reduce methane emissions, a significant greenhouse gas (Ullah et al., 2021). Furthermore, AWD has been found to reduce methane emissions by 52.3%, although it may increase carbon dioxide emissions (Livsey et al., 2019).

6.4 Enhancing biodiversity

Enhancing biodiversity within rice cultivation systems can lead to more resilient and sustainable agricultural practices. The co-culture of rice and aquatic animals not only improves farm productivity but also increases biodiversity, which can enhance ecosystem services such as pest control and nutrient cycling (Bashir et al., 2020). Crop rotation and companion planting are other methods that can contribute to biodiversity, thereby improving soil health and reducing the need for chemical inputs (Mali et al., 2023).

6.5 Integrated pest and nutrient management

Integrated pest and nutrient management (IPNM) is a holistic approach that combines various agricultural practices to optimize crop yields while minimizing environmental impacts. The use of synthetic and organic fertilizers in GCRPSs has been shown to reduce N_2O and NO emissions significantly, making it an eco-friendly strategy (Yao et al., 2019). Precision agriculture techniques, such as the use of artificial intelligence for nutrient management, can further enhance the efficiency of IPNM (Mali et al., 2023). Additionally, the incorporation of allelopathic crops in rotation systems can help manage weeds, reducing the need for chemical herbicides (Ullah et al., 2021).

By adopting these sustainable practices and innovations, rice cultivation can become more environmentally friendly, economically viable, and socially acceptable, ensuring food security for future generations.

7 Policy and Regulatory Implications

7.1 National and international policies

National and international policies play a crucial role in shaping the environmental impacts of rice cultivation systems. Policies that promote sustainable agricultural practices can significantly reduce the carbon footprint (CF), water footprint (WF), and other environmental impacts associated with rice farming. For instance, the restriction of harmful pesticides like glyphosate and chlorpyrifos in Thailand highlights the importance of regulatory measures in mitigating long-term health effects and environmental toxicity (Toolkiattiwong et al., 2023). Additionally, the development of farming technologies and standards, as seen in China, can help avoid the disorder of agricultural production and promote better economic performance and environmental sustainability (Chen et al., 2021).

7.2 Incentives for sustainable practices

Incentives for sustainable practices are essential to encourage farmers to adopt eco-friendly methods. For example, the introduction of cleaner production technologies in China has shown that eco-rice systems can improve soil fertility and increase net economic benefits despite a slight reduction in grain yield (Yang et al., 2019). Similarly, organic rice farming in Thailand has demonstrated a lower carbon footprint and higher value of carbon sequestration ecosystem services compared to conventional farming, indicating the potential benefits of incentivizing organic practices (Arunrat et al., 2021). Providing financial incentives, subsidies, and technical support can motivate farmers to transition to sustainable rice cultivation systems.

7.3 Compliance and monitoring

Effective compliance and monitoring mechanisms are necessary to ensure that farmers adhere to sustainable practices and regulatory requirements. Monitoring the use of restricted pesticides and assessing the environmental impacts of different rice cultivation systems can help identify areas for improvement and enforce compliance (Toolkiattiwong et al., 2023). Life cycle analysis (LCA) and other integrated assessment methods can provide valuable data on pollution emissions, greenhouse gas (GHG) emissions, and other environmental factors, aiding in the development of targeted policies and monitoring strategies (Alphonso and Thirumani, 2023; Hu et al., 2023).

7.4 Role of government and non-governmental organizations

Both government and non-governmental organizations (NGOs) have a pivotal role in promoting sustainable rice cultivation. Governments can implement policies, provide incentives, and establish monitoring frameworks to support sustainable practices. NGOs can complement these efforts by conducting research, raising awareness, and providing education and training to farmers. For instance, the adoption of rice-animal co-culture systems, which offer ecological, economic, and social benefits, can be facilitated through strong extension programs and policy guidance from both government and NGOs (Bashir et al., 2020). Collaborative partnerships between these entities can drive the widespread adoption of sustainable rice farming practices and contribute to environmental conservation and food security.

8 Future Directions

8.1 Research and development needs

Future research should focus on developing and optimizing sustainable rice cultivation practices that minimize environmental impacts while maintaining or improving yield. This includes investigating the long-term effects of different rice cultivation systems on soil health, water usage, and greenhouse gas emissions. For instance, studies have shown that organic rice farming significantly reduces carbon footprint compared to conventional farming, highlighting the need for further exploration into organic practices and their scalability (Arunrat et al., 2021). Additionally, the integration of life cycle assessment (LCA) methodologies can provide comprehensive insights into the environmental impacts of various rice cultivation systems, as demonstrated in multiple studies (Motevali et al., 2019; Chen et al., 2021).

8.2 Adoption of sustainable technologies

The adoption of sustainable technologies such as high-yielding varieties (HYV) and advanced irrigation systems can significantly reduce the environmental footprint of rice cultivation. For example, the use of HYV in Bangladesh has been shown to improve both economic and environmental welfare by increasing rice production efficiency and reducing greenhouse gas emissions (Shew et al., 2019). Moreover, the implementation of integrated systems, such as rice-beef-biogas or rice-animal co-culture, can enhance resource utilization and reduce environmental impacts (Bashir et al., 2020; Ogino et al., 2021). Promoting these technologies through government policies and farmer education programs is crucial for widespread adoption.

8.3 Collaborative efforts and knowledge sharing

Collaboration between researchers, policymakers, and farmers is essential to develop and implement sustainable rice cultivation practices. Knowledge sharing platforms and extension programs can help disseminate best practices and innovative technologies. For instance, the co-culture of rice and aquatic animals has shown potential for improving farm productivity and environmental sustainability, but its adoption is limited by the lack of extension programs and farmer awareness (Bashir et al., 2020). Establishing strong networks for knowledge exchange can facilitate the adoption of such sustainable practices.

8.4 Long-term environmental monitoring

Long-term environmental monitoring is necessary to assess the sustainability of different rice cultivation systems and their impacts on ecosystems. Continuous monitoring can help identify trends and inform adaptive management strategies. For example, monitoring the carbon footprint and water usage of various rice cultivation systems can provide valuable data for improving practices and reducing environmental impacts (Firouzi et al., 2018; Alphonso and Thirumani, 2023). Additionally, tracking the use and effects of pesticides and fertilizers can help mitigate their negative impacts on human health and freshwater ecosystems (Motevali et al., 2019; Toolkiattiwong et al., 2023).

By addressing these future directions, researchers can move towards more sustainable and environmentally friendly rice cultivation systems that ensure food security while protecting our natural resources.

9 Concluding Remarks

This comparative analysis of different rice cultivation systems has highlighted significant variations in environmental impacts across various methods. The study found that terraced rice cultivation in Northern Thailand exhibited the highest carbon footprint (CF) intensity, while upland rice had the lowest. Similarly, lowland rice fields had the highest water footprint (WF) and the most significant human health and freshwater ecotoxicity impacts. In China, the rice-crayfish rotation system showed higher environmental pressure and lower sustainability compared to rice-wheat and rice-fallow rotations. In Iran, the rice ratooning agro-system was found to be more environmentally beneficial than single cropping, particularly in terms of fossil fuel depletion and global warming. Ecological rice-cropping systems, such as rice-duck and rice-crayfish, were effective in reducing greenhouse gas emissions, although they increased N_2O emissions. The environmental impact of rice production was also influenced by the type of rice cultivar and the use of nitrogen fertilizers, with higher N rates leading to increased acidification and terrestrial eutrophication.

Sustainable rice cultivation is crucial for mitigating the adverse environmental impacts associated with traditional farming practices. The findings underscore the need for adopting integrated and ecological rice-cropping systems that balance productivity with environmental sustainability. For instance, the rice-duck system has been identified as a promising approach for reducing greenhouse gas emissions and enhancing soil health. Similarly, the integration of rice and livestock systems, such as the rice-beef-biogas system in Vietnam, has shown potential in reducing environmental impacts while increasing food production. The use of transgenic rice cultivars can also contribute to sustainability by reducing the need for chemical inputs and associated environmental pollutants. These sustainable practices not only help in conserving natural resources but also ensure long-term food security and farmer livelihoods.

In conclusion, the comparative analysis of different rice cultivation systems reveals that sustainable practices can significantly reduce environmental impacts. Policymakers and farmers should prioritize the adoption of integrated and ecological rice-cropping systems to achieve environmental sustainability. Specific recommendations include: Promoting Ecological Systems: Encourage the use of ecological rice-cropping systems like rice-duck and rice-crayfish, which have demonstrated lower greenhouse gas emissions and better soil health. Integrated Farming Practices: Implement integrated crop-livestock systems, such as the rice-beef-biogas system, to optimize resource use and reduce environmental impacts. Use of Transgenic Cultivars: Support the cultivation of transgenic rice varieties to minimize the need for chemical inputs and reduce environmental pollution. Efficient Water and Fertilizer Management: Develop and promote efficient water and fertilizer management practices to reduce the water footprint and mitigate the adverse effects of nitrogen fertilizers. Policy and Education: Formulate policies and educational programs to raise awareness among farmers about sustainable practices and provide incentives for adopting advanced farming techniques. By implementing these recommendations, it is possible to achieve a more sustainable and environmentally friendly rice cultivation system that meets the growing food demands while preserving the ecosystem.

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Conflict of Interest Disclosure

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

References

Alphonso R., and Thirumani Devi A., 2023, Environmental impact of conventional rice cultivation using life cycle analysis, pp.224-234.
https://doi.org/10.21048/IJND.2023.60.2.34215

Arunrat N., Sereenonchai S., and Wang C., 2021, Carbon footprint and predicting the impact of climate change on carbon sequestration ecosystem services of organic rice farming and conventional rice farming: a case study in Phichit province, Thailand, Journal of Environmental Management, 289: 112458.
https://doi.org/10.1016/j.jenvman.2021.112458
PMid:33823412

Arunrat N., and Sereenonchai S., 2022, Assessing ecosystem services of rice–fish co-culture and rice monoculture in Thailand, Agronomy, 12(5): 1241.
https://doi.org/10.3390/agronomy12051241

Bandyopadhyay K., Sarangi A., Kumar D., and Singh D., 2019, Effect of puddling and direct sowing of rice on soil physical health and water productivity of rice-wheat cropping system under different irrigation regimes, Journal of the Indian Society of Soil Science, 67(2): 160-173.
https://doi.org/10.5958/0974-0228.2019.00017.3

Bashir M., Liu J., Geng Y., Wang H., Pan J., Zhang D., Rehim A., Aon M., and Liu H., 2020, Co-culture of rice and aquatic animals: an integrated system to achieve production and environmental sustainability, Journal of Cleaner Production, 249: 119310.
https://doi.org/10.1016/j.jclepro.2019.119310

Bharali A., Baruah K., Baruah S., and Bhattacharyya P., 2018, Impacts of integrated nutrient management on methane emission, global warming potential and carbon storage capacity in rice grown in a northeast India soil, Environmental Science and Pollution Research, 25: 5889-5901.
https://doi.org/10.1007/s11356-017-0879-0
PMid:29235029

Bhandari S., Khanal S., and Dhakal S., 2020, Adoption of Direct Seeded Rice (DSR) over puddled-Transplanted Rice (TPR) for resource conservation and increasing wheat yield, Journal of Cleaner Production, 1(2): 44-51.
https://doi.org/10.26480/rfna.02.2020.59.66

Basavalingaiah K., Ramesha Y., Paramesh V., Rajanna G., Jat S., Misra S., Gaddi A., Girisha H., Yogesh G., Raveesha S., Roopa T., Shashidhar K., Kumar B., El-Ansary D., and Elansary H., 2020, Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: a case study from puddled transplanted rice and direct-seeded rice system of Karnataka, India, Sustainability, 12(16): 6439.
https://doi.org/10.3390/su12166439

Chen Y., Liu C., Chen J., Hu N., and Zhu L., 2021, Evaluation on environmental consequences and sustainability of three rice-based rotation systems in Quanjiao, China by an integrated analysis of life cycle, emergy and economic assessment, Journal of Cleaner Production, 310: 127493.
https://doi.org/10.1016/j.jclepro.2021.127493

Dastan S., Ghareyazie B., and Pishgar S., 2019, Environmental impacts of transgenic Bt rice and non-Bt rice cultivars in northern Iran, Biocatalysis and Agricultural Biotechnology, 20: 101160.
https://doi.org/10.1016/j.bcab.2019.101160

Devi B., 2023, Direct seeded rice as resource efficient technology, International Journal of Environment and Climate Change, 13(8): 1169-1174.
https://doi.org/10.9734/ijecc/2023/v13i82056

Feng Y., Li D., Sun H., Xue L., Zhou B., Yang L., Liu J., and Xing B., 2020, Wood vinegar and biochar co-application mitigates nitrous oxide and methane emissions from rice paddy soil: a two-year experiment, Environmental Pollution, 267: 115403.
https://doi.org/10.1016/j.envpol.2020.115403
PMid:33254598

Firouzi S., Nikkhah A., and Aminpanah H., 2018, Rice single cropping or ratooning agro-system: which one is more environment-friendly? Environmental Science and Pollution Research, 25: 32246-32256.
https://doi.org/10.1007/s11356-018-3076-x
PMid:30225691

Gamaralalage N., Yadav S., Propper C., Kumar V., Dayawansa N., and Singleton G., 2021, Assessing potential environmental impacts of pesticide usage in paddy ecosystems: a case study in the Deduru Oya River Basin, Sri Lanka, Environmental Toxicology and Chemistry, 41(2): 343-355.
https://doi.org/10.1002/etc.5261
PMid:34818438 PMCid:PMC9306700

Hariz A., Chen S., Razak P., Bakar N., Shahrun M., Zawawi N., Mujab A., Abdullah F., Jumat F., Kamaruzaman R., Saidon S., and Talib S., 2019, Life cycle assessment in conventional rice farming system: estimation of greenhouse gas emissions using cradle-to-gate approach, Journal of Cleaner Production, 212: 1526-1535.
https://doi.org/10.1016/j.jclepro.2018.12.062

Hazra K., Swain D., and Singh S., 2021, Crop performance and soil-plant nutrient dynamics in rice-lentil system altered with rice cultivation practices in alkaline soil, European Journal of Agronomy, 130: 126352.
https://doi.org/10.1016/j.eja.2021.126352

Hu W., Bai Z., Hu R., Diao Y., Xu X., and Wang H., 2023, Effects of different management patterns on greenhouse gas emissions from single-season rice fields, International Agrophysics, 37(4): 365-376.
https://doi.org/10.31545/intagr/163343
PMid:18552943

Islam S., Sander B., Quilty J., Neergaard A., Groenigen J., and Jensen L., 2020, 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.
https://doi.org/10.1016/j.scitotenv.2020.140215
PMid:32758960

Janz B., Weller S., Kraus D., Racela H., Wassmann R., Butterbach-Bahl K., and Kiese R., 2019, Greenhouse gas footprint of diversifying rice cropping systems: impacts of water regime and organic amendments, Agriculture, Ecosystems & Environment, 270: 41-54.
https://doi.org/10.1016/j.agee.2018.10.011

Jiang Y., Carrijo D., Huang S., Chen J., Balaine N., Zhang W., Groenigen K., 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.
https://doi.org/10.1016/j.fcr.2019.02.010

Kakumanu K., Kotapati G., Nagothu U., Kuppanan P., and Kallam S., 2019, Adaptation to climate change and variability: a case of direct seeded rice in Andhra Pradesh, India, Journal of Water and Climate Change, 10(2): 419-430.
https://doi.org/10.2166/wcc.2018.141

Katti G., and Ch P., 2022, Impact of rice cultivation methods on insect pest incidence and their management, Journal of Rice Research, 15(Special Issue): 84-89.
https://doi.org/10.58297/XHFF3294

Kritee K., Nair D., Zavala-Araiza D., Proville J., Rudek J., Adhya T., Loecke T., Esteves T., Balireddygari S., Dava O., Ram K. R A., Madasamy M., Dokka R., Anandaraj D., Athiyaman D., Reddy M., Ahuja R., and Hamburg S., 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 of the United States of America, 115(39): 9720-9725.
https://doi.org/10.1073/pnas.1809276115
PMid:30201704 PMCid:PMC6166800

Kumar R., Chintalapati P., Rathod S., Singh T., Kuchi S., Mannava P., Latha P., Somasekhar N., Nirmala B., Madamsetty S., Prasad J., Kumar S., Srinivas D., Sreedevi B., Tuti M., Arun M., Sailaja B., and Sundaram R., 2023, Comparison of system of rice intensification applications and alternatives in India: agronomic, economic, environmental, energy, and other effects, Agronomy, 13(10): 2492.
https://doi.org/10.3390/agronomy13102492

Li J., Li Y., Wan Y., Wang B., Waqas M., Cai W., Guo C., Zhou S., Su R., Qin X., Gao Q., and Wilkes A., 2018, Combination of modified nitrogen fertilizers and water saving irrigation can reduce greenhouse gas emissions and increase rice yield, Geoderma, 315: 1-10.
https://doi.org/10.1016/j.geoderma.2017.11.033

Li H., Guo H., Helbig M., Dai S., Zhang M., Zhao M., Peng C., Xiao X., an Zhao B., 2019, Does direct-seeded rice decrease ecosystem-scale methane emissions, a case study from a rice paddy in southeast China, Agricultural and Forest Meteorology, 272: 118-127.
https://doi.org/10.1016/J.AGRFORMET.2019.04.005

Livsey J., Kätterer T., Vico G., Lyon S., Lindborg R., Scaini A., Da C., and Manzoni S., 2019, Do alternative irrigation strategies for rice cultivation decrease water footprints at the cost of long-term soil health, Environmental Research Letters, 14(7): 074011.
https://doi.org/10.1088/1748-9326/ab2108

Mallareddy M., Thirumalaikumar R., Balasubramanian P., Naseeruddin R., Nithya N., Mariadoss A., Eazhilkrishna N., Choudhary A.K., Deiveegan M., Subramanian E., Padmaja B., and Vijayakumar S., 2023, Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies, Water, 15(10): 1802.
https://doi.org/10.3390/w15101802

Mali M., Meghalatha K., Anuradha K., Kumar V., Lakshmi P., Karmakar S., Lakra D., Rudraboyina S., and Chandrakar G., 2023, The Future of rice farming: a review of natural and eco-friendly practices, International Journal of Environment and Climate Change, 13(11): 4240-4249.
https://doi.org/10.9734/ijecc/2023/v13i113604

Maneepitak S., Ullah H., Paothong K., Kachenchart B., Datta A., and Shrestha R., 2019, Effect of water and rice straw management practices on yield and water productivity of irrigated lowland rice in the Central Plain of Thailand, Agricultural Water Management, 211: 89-97.
https://doi.org/10.1016/J.AGWAT.2018.09.041

Maraseni T., Deo R., Qu J., Gentle P., and Neupane P., 2018, An international comparison of rice consumption behaviours and greenhouse gas emissions from rice production, Journal of Cleaner Production, 172: 2288-2300.
https://doi.org/10.1016/J.JCLEPRO.2017.11.182

Motevali A., Hashemi S., and Tabatabaeekoloor R., 2019, Environmental footprint study of white rice production chain-case study: Northern of Iran, Journal of Environmental Management, 241: 305-318.
https://doi.org/10.1016/j.jenvman.2019.04.033
PMid:31028968

Nirmala B., Tuti M., Kumar R., Waris A., Muthuraman P., Parmar B., and Singh T., 2021, Integrated assessment of system of rice intensification vs. conventional method of transplanting for economic benefit, energy efficiency and lower global warming potential in India, Agroecology and Sustainable Food Systems, 45(5): 745-766.
https://doi.org/10.1080/21683565.2020.1868648

Ogino A., Thu N., Hosen Y., Izumi T., Suzuki T., Sakai T., Ando S., Osada T., and Kawashima T., 2021, Environmental impacts of a rice-beef-biogas integrated system in the Mekong Delta, Vietnam evaluated by life cycle assessment, Journal of environmental management, 294: 112900.
https://doi.org/10.1016/j.jenvman.2021.112900
PMid:34111596

Phụ H., Linh H., and Trà L., 2021, The advantages of the system of rice intensification (SRI) in environmental protection and climate change mitigation in rice production-a review, International Rice Congress, 226(9): 11-21.
https://doi.org/10.34238/TNU-JST.4343

Sarkar S.; Skalicky M.; Hossain A.; Brestic M.; Saha S.; Garai S.; Ray K., and Brahmachari K., 2020, Management of crop residues for improving input use efficiency and agricultural sustainability, Sustainability, 12(23): 9808.
https://doi.org/10.3390/su12239808

Shang Z., Abdalla M., Xia L., Zhou F., Sun W., and Smith P., 2021, Can cropland management practices lower net greenhouse emissions without compromising yield, Global Change Biology, 27(19): 4657-4670
https://doi.org/10.1111/gcb.15796
PMid:34241939

Shew A., Durand-Morat A., Putman B., Nalley L., and Ghosh A., 2019, Rice intensification in Bangladesh improves economic and environmental welfare, Environmental Science & Policy, 95: 46-57.
https://doi.org/10.1016/J.ENVSCI.2019.02.004

Sun G., Sun M., Du L., Zhang Z., Wang Z., Zhang G., Nie S., Xu H., and Wang H., 2021, Ecological rice-cropping systems mitigate global warming - a meta-analysis, Science of the Total Environment, 789: 147900.
https://doi.org/10.1016/j.scitotenv.2021.147900
PMid:34323843

Tayefeh M., Sadeghi S., Noorhosseini S., Bacenetti J., and Damalas C., 2018, Environmental impact of rice production based on nitrogen fertilizer use, Environmental Science and Pollution Research, 25: 15885-15895.
https://doi.org/10.1007/s11356-018-1788-6
PMid:29589233

Toolkiattiwong P., Arunrat N., and Sereenonchai S., 2023, Environmental, human and ecotoxicological impacts of different rice cultivation systems in Northern Thailand, International Journal of Environmental Research and Public Health, 20(3): 2738.
https://doi.org/10.3390/ijerph20032738
PMid:36768102 PMCid:PMC9916391

Ullah A., Nawaz A., Farooq M., and Siddique K., 2021, Agricultural innovation and sustainable development: a case study of rice–wheat cropping systems in South Asia, Sustainability, 13(4): 1965.
https://doi.org/10.3390/SU13041965

Win E., Win K., Bellingrath-Kimura S., and Oo A., 2021, Influence of rice varieties, organic manure and water management on greenhouse gas emissions from paddy rice soils, PLoS ONE, 16(6): e0253755.
https://doi.org/10.1371/journal.pone.0253755
PMid:34191848 PMCid:PMC8244889

Yang B., Ma Y., Zhang C., Jia Y., Li B., and Zheng X., 2019, Cleaner production technologies increased economic benefits and greenhouse gas intensity in an eco-rice system in China, Sustainability, 11(24): 7090.
https://doi.org/10.3390/su11247090

Yao Z., Zheng X., Wang R., Liu C., Lin, S., and Butterbach-Bahl K., 2019, Benefits of integrated nutrient management on N_2O and NO mitigations in water-saving ground cover rice production systems, Science of the Total Environment, 646: 1155-1163.
https://doi.org/10.1016/j.scitotenv.2018.07.393
PMid:30235601