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Rice is one of the most crucial food crops globally, feeding more than half of the world's population. However, the environmental challenges posed by traditional rice cultivation methods are becoming increasingly evident. The demand for sustainable agriculture practices has never been more urgent, as we strive to meet the nutritional needs of a growing population while preserving the health of our planet.

This research bulletin, *"Sustainable Rice-Based Cropping Systems: Strategies to Minimize Environmental Impact,"* emerges from a concerted effort to address these challenges by exploring innovative and sustainable approaches to rice farming. It is designed to serve as a comprehensive guide for researchers, practitioners, and policymakers committed to advancing environmentally responsible agricultural practices.

In compiling this bulletin, we have drawn upon a wealth of research and field studies that highlight the most effective strategies for reducing the environmental footprint of rice-based cropping systems. The topics covered range from water-efficient irrigation practices and reduced chemical input systems to the integration of crop diversification and soil health management. These strategies not only aim to enhance the sustainability of rice production but also to improve the resilience of farming systems against the backdrop of climate change.

The contributions within this bulletin reflect the collaborative spirit of the global agricultural research community, united by a common goal: to create farming systems that are both productive and environmentally sustainable. The insights provided here are intended to inform and inspire action, helping to guide the transition towards more sustainable agricultural practices.

As we present this bulletin, we hope it will serve as a valuable resource for those engaged in the ongoing effort to balance the demands of food production with the need for environmental conservation. By adopting and promoting the sustainable practices discussed herein, we can work towards a future where rice farming contributes not only to food security but also to the long-term health of our ecosystems.

We extend our sincere gratitude to the authors, researchers, and practitioners whose contributions have made this bulletin possible. Their dedication and expertise are the foundation of the sustainable solutions presented in this bulletin.

Authors


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CONTENTS

1. Introduction

Rice is an important food source for over half of the global population and is vital for the food security and livelihoods of millions in India. The country's varied agro-climatic zones support rice farming in diverse settings, positioning India as one of the leading rice producers worldwide. Nevertheless, traditional rice cultivation methods have substantial environmental impacts, such as excessive water use, greenhouse gas emissions, soil erosion, and loss of biodiversity (Shahid *et al.,* 2021). Tackling these environmental issues is essential for achieving sustainable rice farming that can accommodate the needs of a growing population while preserving ecological balance.

In India, rice is grown mainly through two systems, irrigated and rainfed. The irrigated system, which covers roughly 60% of the rice-growing area, depends on water from canals, reservoirs, and groundwater (Pathak et al., 2018). This method is productive but also requires a significant amount of water, leading to groundwater depletion and water resource strain. Conversely, rainfed rice, which makes up about 40% of the rice area, relies on monsoon rains and typically yields less while being more susceptible to climate variability. Both systems face challenges related to resource efficiency and environmental sustainability. Rice is the primary staple and is integral to rice-based cropping systems (RBCS), which are major contributors to food production. In irrigated regions, common cropping systems include rice-wheat and rice-rice, while in lowland rainfed areas, the rice-pulse system is prevalent, with land often left fallow during the pre-kharif/summer season.

The environmental impact of rice cultivation in India is complex. Traditional practices such as continuous flooding in rice fields consume large amounts of water, exacerbating the depletion of freshwater resources. Moreover, rice paddies are significant methane sources, a potent greenhouse gas produced by anaerobic decomposition of organic material under flooded conditions (Pathak et al., 2018). Methane emissions from rice fields significantly contribute to global warming and climate change. Additionally, rice cultivation often involves heavy use of chemical fertilizers and pesticides, which can degrade soil health, cause nutrient imbalances, and pollute water sources.

To address these environmental challenges, various management practices and innovative technologies have been introduced. Methods like direct seeding of rice (DSR) and non-puddled transplanted rice (NPTR) show promise for reducing water use and labor demands. Water management strategies such as the System of Rice Intensification (SRI), alternate wetting and drying (AWD), and aerobic rice systems are designed to improve water efficiency and lower methane emissions. Other practices like laser land levelling and mid-season drainage also enhance water management and soil health.

Promoting soil health and fertility through integrated nutrient management and organic farming is crucial for sustainable rice production. Crop diversification and integrated pest management (IPM) strategies are important for reducing environmental impacts by boosting biodiversity and minimizing chemical use. Proper management of rice residues, such as utilizing rice straw and other residues for mulching and conservation agriculture, can further mitigate environmental effects and improve soil health.

Efforts to reduce greenhouse gas emissions from rice farming include employing methane suppression techniques and cultivating climate-resilient rice varieties. Addressing the relationship between food waste and greenhouse gas emissions is also important, as reducing food waste can significantly diminish the overall environmental impact of the rice-based food system.

This bulletin aims to present a thorough analysis of rice-based cropping systems in India, investigating the environmental impacts of traditional practices and exploring management strategies and technological innovations that could alleviate these effects. By emphasizing sustainable practices, this bulletin seeks to support the development of resilient and environmentally friendly rice production systems in India.

2. Overview of Rice-Based Cropping Systems in India

Rice-based cropping systems involve farming practices where rice is the primary crop, followed by the cultivation of various other crops. In India, rice-based cropping systems are widely utilized across various states, reflecting diverse agricultural practices and regional preferences. The survey though conducted in 2001 (Yadav and Rao, 2001), provide a great insight to this diverse system. Under rice based cropping system, largest area is dedicated to the rice-wheat system, encompassing approximately 10,357.3 thousand ha, with Uttar Pradesh leading at 4,122.7 thousand ha and Punjab contributing significantly with 2,103.0 thousand ha. The rice-rice systems, prevalent in states like Tamil Nadu with 2,145.2 thousand ha, Andhra Pradesh with 1,393.0 thousand ha, Assam with 1131.0 thousand ha, Karnataka with 684.7 thousand ha, Gujarat with 257.3 thousand ha, Kerala with thousand ha and Odisha with 139.5 thousand ha, cover 5,894.0 thousand ha in total. Other prominent systems include rice-fallow, covering a substantial 4,419.9 thousand ha, with Madhya Pradesh being the major contributor at 2,038.1 thousand ha. The rice-black gram system, significant in Andhra Pradesh and Odisha, covers 598.9 thousand ha, while the rice-groundnut system, largely found in Tamil Nadu, spans 1,022.9 thousand ha. The data highlights the extensive use of rice-based systems in Indian agriculture, emphasizing the dominant role of rice in crop rotations and intercropping practices across the country.

Rice-based cropping systems currently facing several challenges including decreasing productivity, rising production costs, resource depletion, and increased greenhouse gas emissions, all contributing to a significant environmental impact. For instance, traditional rice cultivation methods like puddling, which aim to prevent water percolation, facilitate manual transplanting, and control weeds, have led to adverse effects on soil health. Long-term use of these methods can result in soil degradation, such as the destruction of soil aggregates, subsurface compaction, poor root growth, and limited aeration (Nandan et al., 2021; Hossain et al., 2021; Saurabh et al., 2021).

Another environmental issue associated with rice-based cropping systems is the burning of rice residues. This practice contributes to air pollution and nutrient loss from the soil, exacerbating environmental damage (Kumar et al., 2019). In North India, the high-water usage in rice-wheat systems has led to groundwater depletion and a lowered water table, which negatively impacts crop and land productivity as well as water efficiency.

Research in rice-based cropping systems should focus on mitigating environmental impacts. Key areas for investigation include the development of new crop establishment techniques, effective weed management (including herbicide resistance studies), nutrient management practices, soil health improvement, and crop rotation strategies aimed at reducing the environmental footprint.

3. Environmental footprint of rice cultivation

Rice cultivation serves as a basis of global agriculture, providing sustenance for billions of people while shaping ecosystems worldwide. Rice is a staple diet for half of the global population, but it also comes with its own set of environmental challenges (Pathak et al., 2018). The environmental footprint of rice farming is substantial, encompassing areas such as large quantity of water usage, emissions of greenhouse gas especially methane, and the use of chemical inputs including fertilizers and pesticides.

3.1. Water footprint

One key challenge in addressing the environmental impact of rice cultivation is the issue of water usage. Rice paddies require large amounts of water for irrigation, leading to water scarcity in many regions and ground water depletion especially in *Rabi* season. The traditional flooding method leads to high water consumption per kg of rice which vary from 3500-4000 L. As half of the rice-growing area is irrigated, it causes significant water consumption (Surendran et al., 2021). In a study the product water footprint for rice in India was reported to 3.52 $m^3\ kg^{-1}$ while for wheat (1.59 $m^3\ kg^{-1}$) and maize (2.06 $m^3\ kg^{-1}$) this value was less (Nayak et al., 2023). The green water footprint of rice was highest in Meghalaya ($8.80 \times 10^3\ m^3\ ha^{-1}$) (Fig. 1a). The blue water footprint is highest in the rice crop in western India (Fig. 1b). In western India, especially in Punjab and Haryana, groundwater is being extracted on a large scale for irrigation, leading to a significant decline in groundwater levels. The grey water footprint of rice was highest in Bihar (772.3 $m^3\ t^{-1}$) (Fig. 1c). Sustainable water management practices are essential to maintain a healthy balance. Exploring alternative water management techniques such as intermittent irrigation and aerobic rice cultivation are being adopted to conserve water and minimize water footprint. Water vapour flux measured in the rice ecosystem is an important factor that controls the microclimate of rice cultivation (Chatterjee et al., 2019). The latent heat of vaporization, net radiation, air temperature, soil temperatures, and water temperature are some of the important factors that control the water vapour flux in rice ecosystem.

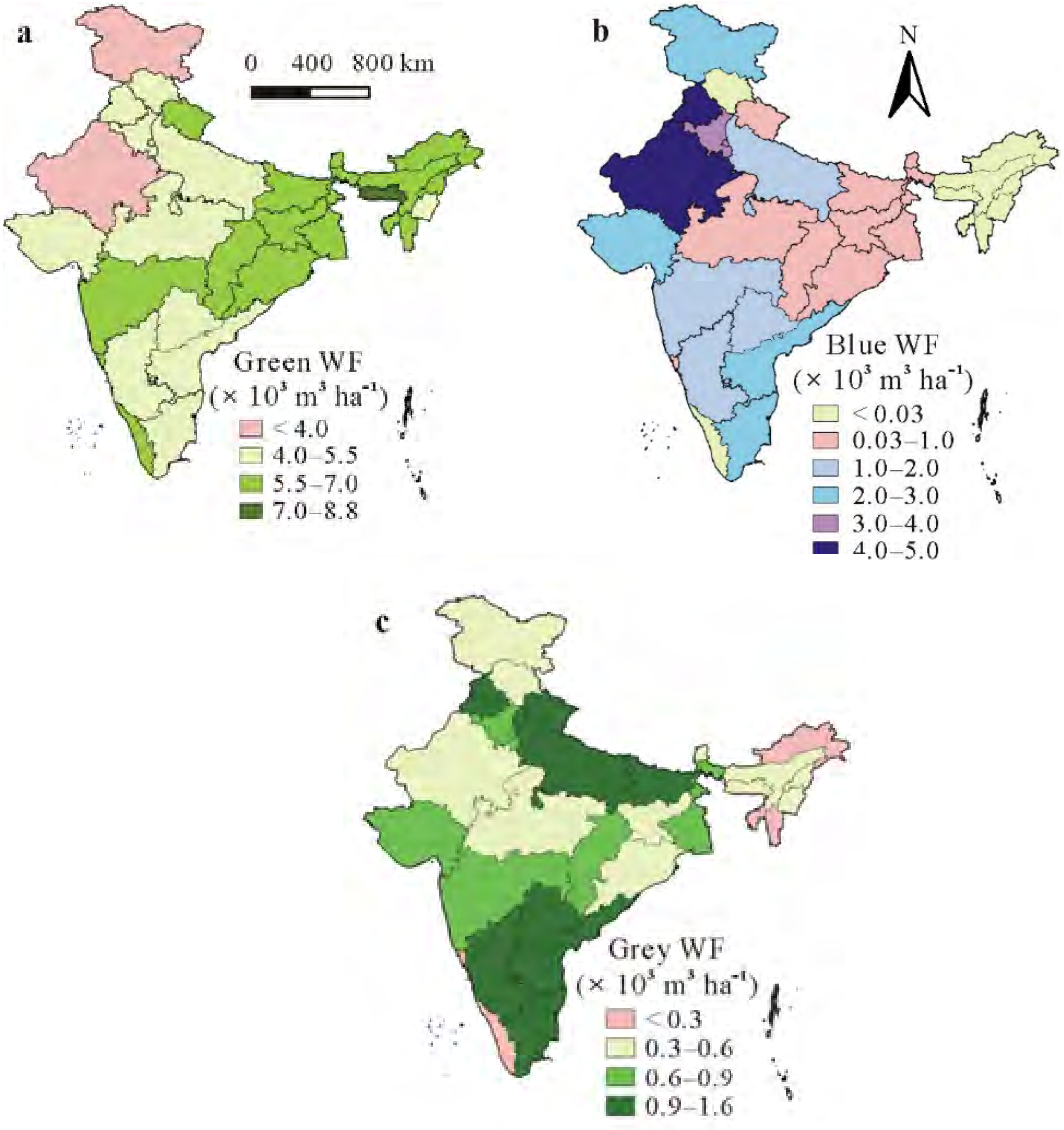


Fig. 1. Water footprint (WF) of rice in India a. Green WF; b. Blue WF; c. Grey WF (Nayak et al., 2023)

3.2. Carbon footprint

Rice paddies are a significant source of methane emissions, a potent greenhouse gas (GHG). The anaerobic conditions in flooded rice fields promote methane production by methanogenic microorganisms. Rice cultivation contributes about 10-12% of total agricultural methane emissions worldwide. Implementing practices like alternate wetting and drying, and adopting improved rice varieties can help reduce methane emissions from rice paddies. Total carbon footprints of rice, wheat, and maize in India were estimated to be 2.44, 1.27, and 0.80 t CO_2 equivalent ha^{-1}, respectively (Nayak et al., 2023). Highest product carbon footprint was found in Maharashtra (Fig. 2).

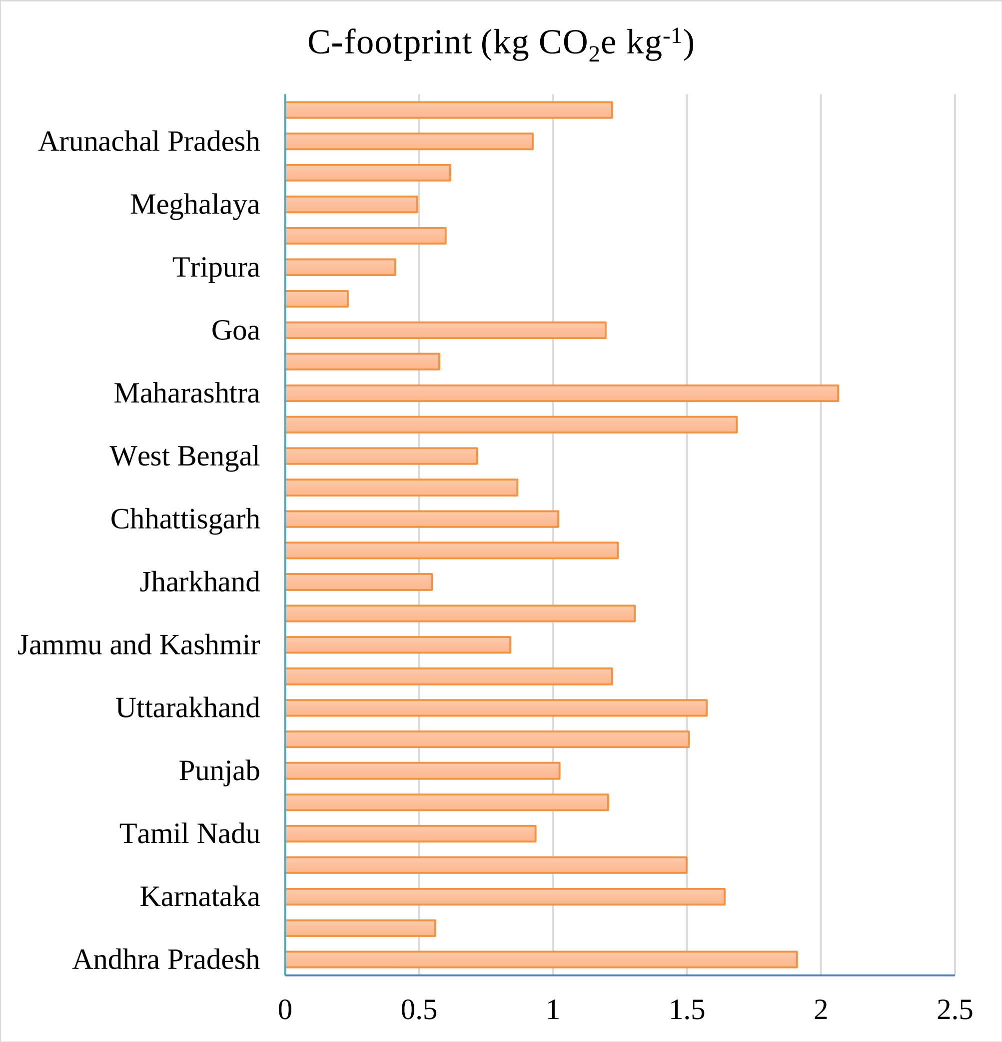


Fig. 2: Product carbon footprints of rice in different states of India (Nayak et al., 2023)

3.3. Nitrogen footprint

Nitrogen is an essential element for plant growth and productivity, but excessive nitrogen in the environment can lead to harmful effects such as air pollution (NH_3), eutrophication (NO_3), ground water pollution (NO_3) and greenhouse gas emissions (N_2O). The use of nitrogen fertilizers in rice cultivation can lead to nitrous oxide emissions, especially if the fields are alternately flooded and dried. In a rice-rice ecosystem at Cuttack, total N losses from NH_3 volatilisation, N_2O emissions and NO_3 leaching were 0.06–4.73, 0.32–2.14 and 0.25–1.93 kg ha^{-1}, corresponding to 0.06–5.84%, 0.11–2.20% and 0.09–1.81% of total applied N, respectively (Chatterjee et al., 2024). The N footprint of paddy rice ranged 0.46-2.01 kg N-eq. t^{-1} during both seasons under various N management (Fig. 3).

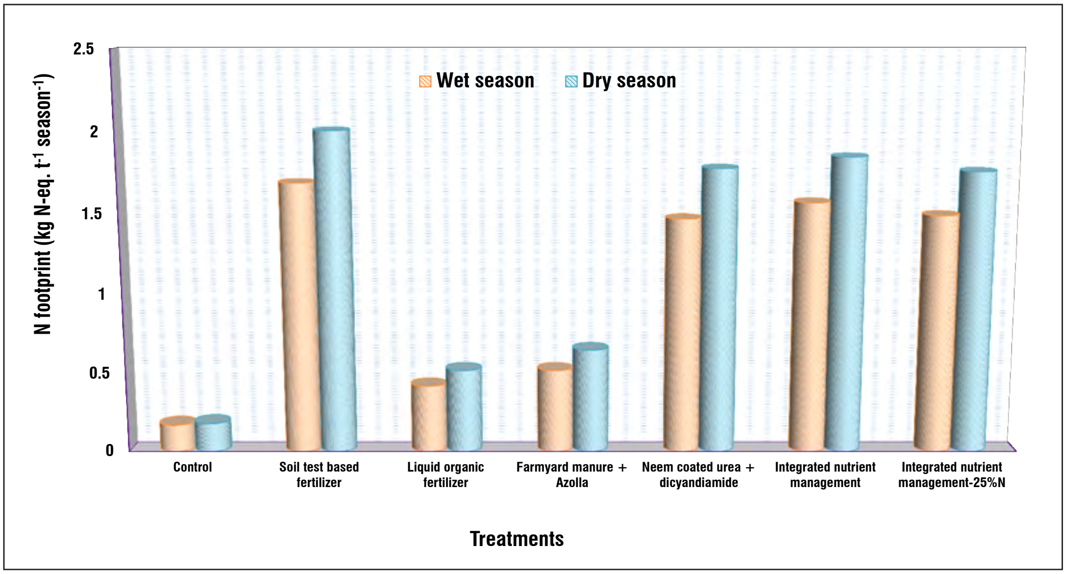


Fig. 3. Nitrogen footprint of rice under various N management (Chatterjee et al., 2024)

3.4. Pollution from pesticides and eutrophication

Pesticides and herbicides play a significant role in managing pests and weeds in rice cultivation. However, the excessive use of these chemicals over and above the recommendation has adverse effects on the environment. Runoff from the unbunded or improperly bunded fields can contaminate water sources, harming aquatic life and posing risks to human health. Chemical fertilizers especially nitrogenous and phosphatic fertilizers in rice cultivation can also lead to soil and water pollution. Excessive nitrogen and phosphorus from fertilizers can leach into water bodies, leading to eutrophication and harming ecosystems. Implementing practices like precision agriculture and utilizing organic fertilizers can help reduce these environmental impacts. Use of slow release, smart release or super granules can help to improve use efficiency of nutrient applied and reduce their loss to the environment (Fig. 4) (Chatterjee et al., 2018, 2023).

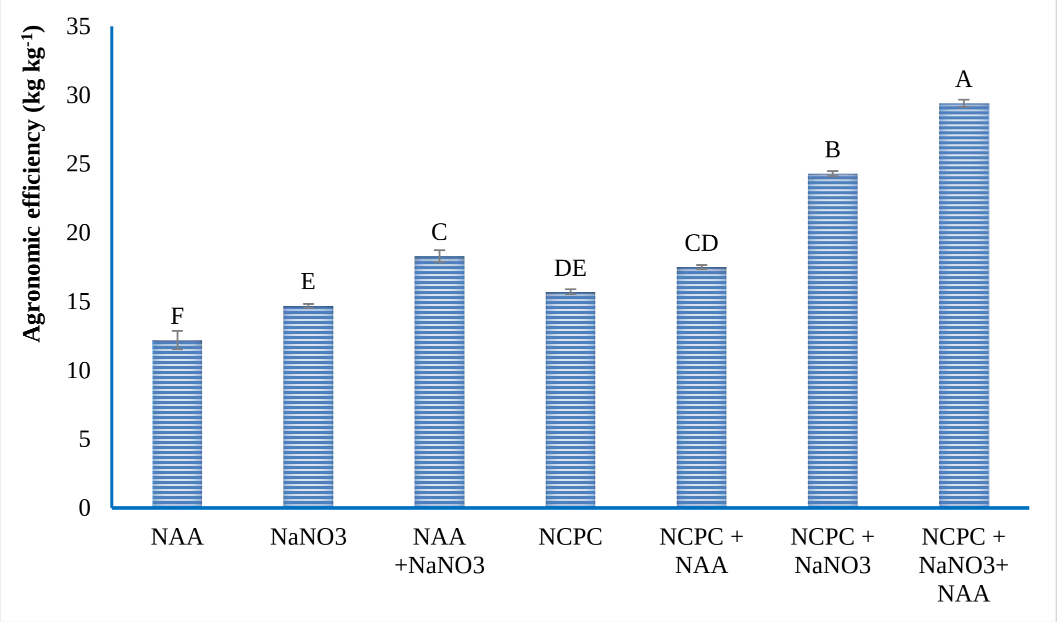


Fig. 4. Agronomic efficiency of applied nano-clay polymer composites (NCPCs) impregnated with synthetic auxin (NAA) and sodium nitrate ($NaNO_3$) in rice for smart-N fertilizer management (Chatterjee et al., 2023).

3.5. Adverse impact on biodiversity

Rice cultivation can impact local wildlife, habitats, and land use patterns. Intensive rice farming with excessive use of agrochemicals may lead to habitat loss, water pollution, and biodiversity decline. Promoting agroecological approaches, preserving natural habitats within rice landscapes, and integrating biodiversity-friendly practices enhance ecosystem resilience in rice farming areas.

4. Strategies to Minimize Environmental Impacts of rice cultivation

4.1. Crop Establishment Techniques

Conventional transplanted rice (TPR) is known for its intensive resource requirements, including high energy, water, and labor inputs. The practice of puddling the soil creates anaerobic conditions, which significantly contribute to greenhouse gas emissions and nitrogen losses, thereby increasing the environmental footprint. To address these issues, there is a growing need to explore and implement alternative crop establishment methods such as direct seeded rice (DSR) and non-puddled transplanting.

4.1.1. *Direct Seeded Rice (DSR)*

Direct seeded rice (DSR) involves planting rice seeds directly into the field rather than starting them in a separate seedbed and then transplanting the seedlings. This method avoids the puddling and continuous flooding typical of traditional TPR, leading to reduced overall water use and a lower environmental impact. Research indicates that DSR can substantially decrease the environmental footprint of rice cultivation. For instance, DSR requires less labor and water compared to traditional methods and results in a shorter crop cycle due to earlier flowering, which reduces the carbon footprint. Studies have shown that DSR in a no-till system can save 48.5% of energy and reduce greenhouse gas emissions by 16.5% (Yadav et al., 2020). Furthermore, the DSR-wheat cropping system has been found to have a smaller water and carbon footprint compared to the TPR-wheat system (Jin et al., 2024). A DSR-wheat-mungbean system under zero tillage achieved a 64% reduction in environmental impact compared to the conventional TPR-wheat system (Ghosh et al., 2022). Additionally, modifications in nitrogen management, such as using nitrogen-efficient cultivars, adopting appropriate fertilizer application methods, and employing coated nitrogen fertilizers, can further lower the carbon footprint associated with DSR (Ali et al., 2003; Jat et al., 2019).

4.1.2. *Non-Puddled Transplanted Rice*

Non-puddled transplanted rice is emerging as an alternative to traditional puddling practices, which are often seen as necessary but problematic due to their environmental and economic downsides. In non-puddled transplanting, rice seedlings are planted in saturated soil using a mechanical transplanter, eliminating the need for puddling. This approach can reduce cultivation costs and the environmental footprint while maintaining or even enhancing yields compared to conventional puddled methods. Research has demonstrated that non-puddled methods can lead to significant energy savings. For example, zero-till non-puddled transplanted rice has been reported to save 32% of energy compared to conventional tillage practices (Munda et al., 2022). Singh et al., (2020) found that non-puddled transplanting results in reduced cultivation costs and comparable or higher yields compared to puddled transplanting. Sharma et al., (2005) compared minimum tillage, which involves a single pass of puddling, with traditional TPR and found no significant yield differences between the two methods. Other studies, such as those by Haque et al., (2016), noted water savings and cost reductions with non-puddled transplanting without compromising yields. Rashid et al., (2018) also reported that yields in non-puddled transplanting were similar to those in puddled transplanting. Early research suggests that zero-till non-puddled rice could offer improved agronomic efficiency and reduced environmental impacts, making it a promising alternative to conventional practices (Chaki et al., 2021).

By adopting DSR and non-puddled transplanting methods, rice cultivation can move towards more sustainable practices that mitigate environmental damage while maintaining productivity. These innovations present viable solutions for addressing the ecological challenges associated with traditional rice farming practices.

In an on-station trial conducted at ICAR-National Rice Research institute, Cuttack, the grain yields rice and green gram, and the system productivity were significantly influenced by Non puddled transplanted rice (Fig. 5) and it recorded yields at par with conventional tillage DSR (CT-DSR) (Munda et al., 2021).

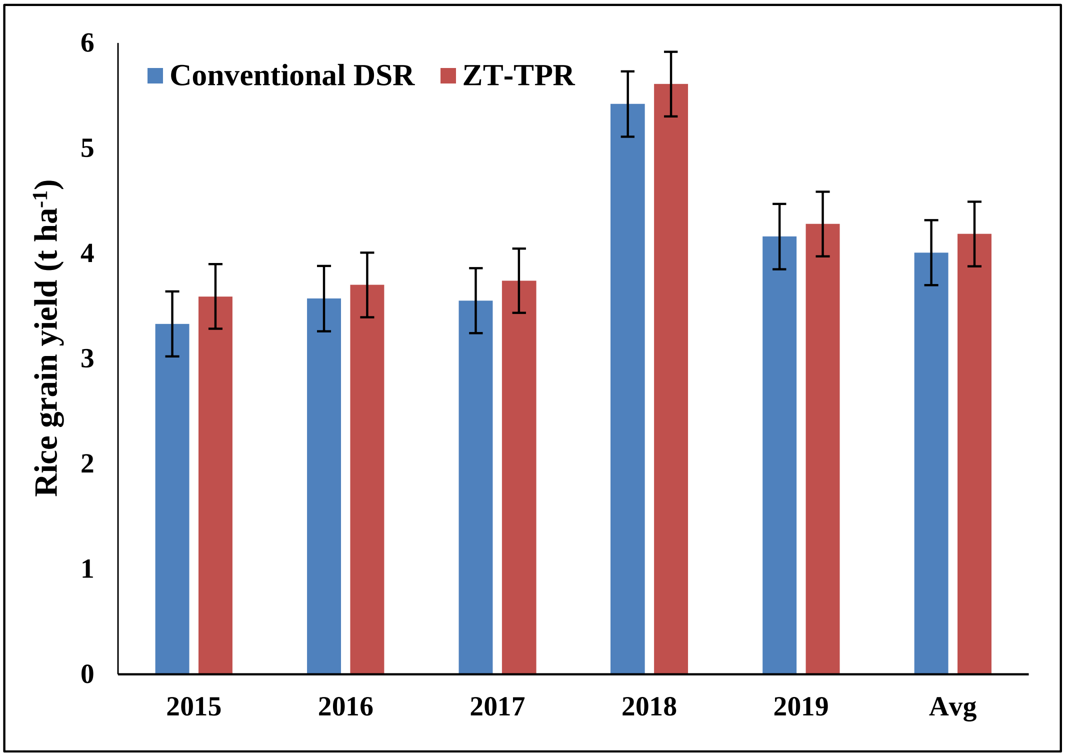


Fig. 5. Rice yield (t ha^{-1}) under zero-tillage transplanting (ZT- TPR) and conventional-tillage direct sowing (CT-DSR)

The total energy requirement in CT-DSR and ZT-TPR system was 12,111 MJ ha^{-1} and 11,763 MJ ha^{-1}, respectively (Munda et al., 2021). Among the all the inputs fertilizer consumed highest energy (7350 MJ ha^{-1}) followed by diesel (3829 MJ ha^{-1}) in CT. Among the tillage systems zero tillage saved considerable energy over CT, especially in machinery and diesel use leading to around 31% total energy saving. Energy use efficiency and energy productivity was ~20% higher in ZT-TPR system over CT-DSR.

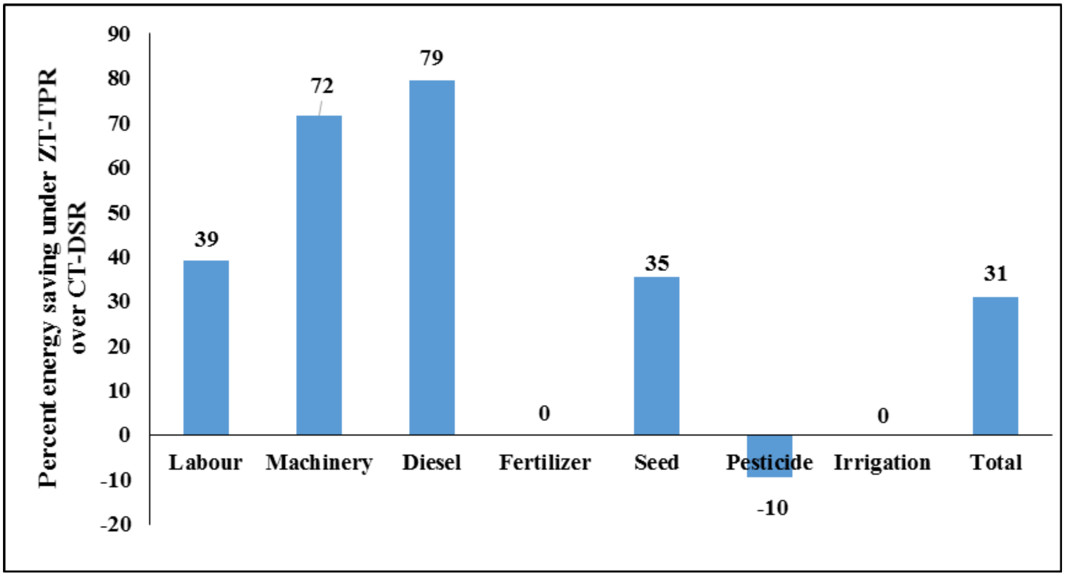


Fig. 6. Percentage energy saving under zero tillage transplanted rice (ZT-TPR) over conventional tillage direct seeded rice (CT-DSR)

With regard to the emission of greenhouse gases, the soil N_2O emission was significantly influenced by zero-tillage and conventional tillage practices under rice-green gram cropping system (Munda et al., 2023). The effect of DSR and TPR on CH_4 and N_2O emission is different under tillage practices. The cumulative seasonal emission of N_2O was recorded highest in conventional-tillage-direct-sown-rice followed by conventional-tillage-green gram system (CT-DSR-CT-GG) (1.11 kg ha^{-1}). Less emission was observed under zero tillage-transplanted rice followed by zero-tillage-green gram system (ZT-TPR-ZT-GG) (0.64 kg ha^{-1}). Daily N_2O flux rates were significantly higher (20.7%) under CT-DSR-CT-GG than that of by ZT-TPR-ZT-GG. Regardless of treatments, higher release was observed immediately after fertilizer application. Seasonal CH_4 emission recorded a different trend with highest emissions in CT-DSR-CT-GG (58.41 kg ha^{-1}) followed by ZT-TPR -ZT-GG (44.14 kg ha^{-1}) (Fig. 7).

4.2. Crop diversification

Crop diversification is a vital agricultural practice for enhancing agroecosystem productivity and lowering the carbon footprint. In West Bengal, approximately 40% of the land remains fallow after the wet season rice cultivation. This fallow period results in higher N_2O emissions, decreasing the soil's C: N ratio and increasing its global warming potential (GWP). Introducing short-duration pulse or oilseed crops followed by jute cultivation can mitigate GHG emissions by balancing system productivity and GWP (Munda et al., 2023). Crop diversification also helps control weeds, suppress plant diseases, and boost economic yield (Munda et al., 2023). Crop diversification along with zero tillage practice can reduce N_2O emissions about 20% lower in maize (Lal et al., 2022).

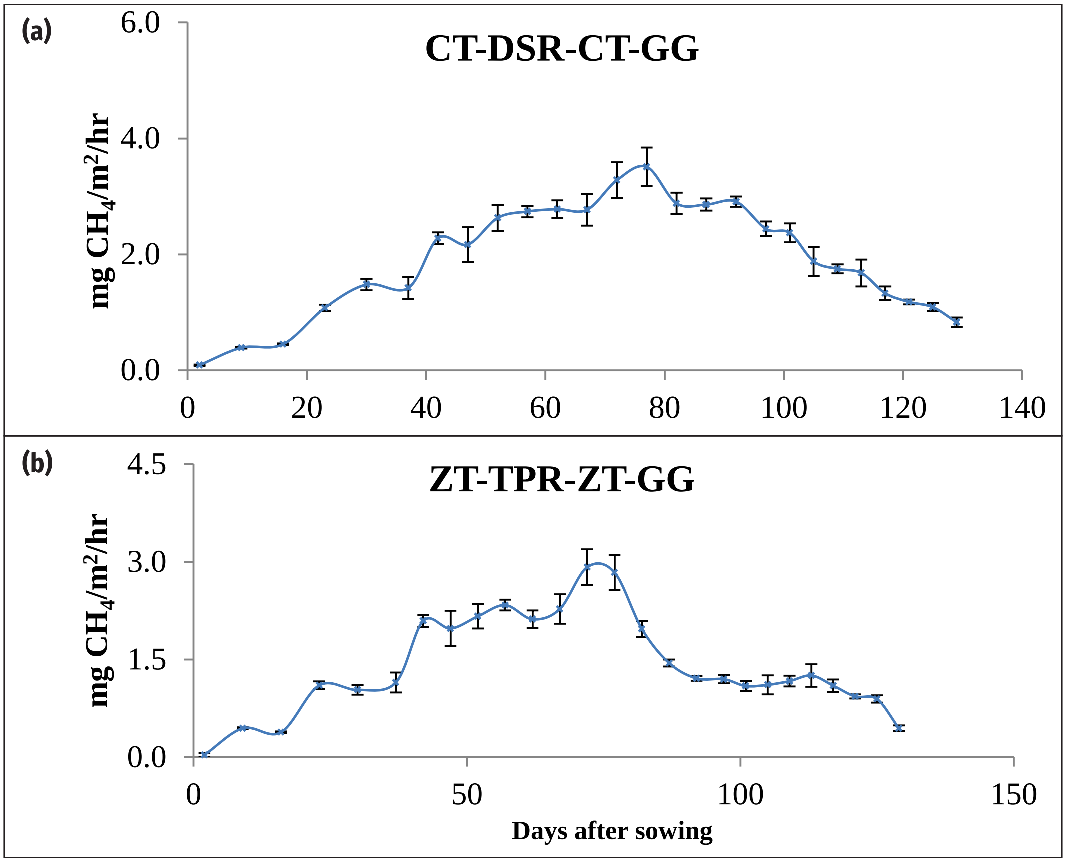


Fig. 7. CH_4 emissions observed in rice-green gram cropping system under conservation and conventional tillage after five years of experiment influenced by CT-DSR: conventional tillage-direct seeded rice and ZT-TPR: zero tillage-transplanted rice

Further, Tripathy et al., (2022) described diversification of rice fallows by inclusion of maize in the cropping system improves soil structure and physical properties and helps in soil organic carbon buildup. Integrated cropping systems, coupled with best agronomic practices such as line sowing, optimal plant establishment methods (e.g., System of Rice Intensification in rice), soil test-based fertilizer use, and proper crop sequencing, can enhance crop productivity without increasing farm inputs or GHG emissions.

4.3. Water Management in Rice Cultivation

The intricate water management of rice cultivation is further complicated by the adverse impacts of climate change, resulting in water abundance in some regions and water scarcity in others. Insufficient water levels also hinder plant growth and crop yield. Excessive evapotranspiration during periods of moisture stress disrupts nutrient flow to the roots, reducing the availability of essential plant nutrients. Excessive water from heavy rainfall at the start of the growing season delays plant growth, accelerates the loss of surface-applied fertilizers and harms rice crops through oxygen-deprived conditions under submergence. Various water-efficient technologies, such as the System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD), aerobic rice systems, laser land levelling, and mid-season drainage, are essential for enhancing productivity and resilience in rice cultivation amidst the challenges of climate change. Implementing these water-efficient technologies is crucial for adapting to the changing climate and ensuring sustainable rice production.

4.3.1. System of rice intensification (SRI)

System of Rice Intensification (SRI) was developed in Madagascar in the 1980s by French Jesuit priest Henri de Laulanié, but it has since spread to other countries in Asia, Africa, and Latin America. SRI focuses on enhancing the productivity of rice plants through changes in planting techniques, water management, weed management and soil health. One of the key principles of SRI is to plant only 1-2 number of seedlings of about 10-15 days old in widely spaced square fashioned rows, allowing each plant more room to grow and develop a stronger root system (Lal et al., 2016). This prevents overcrowding and competition for nutrients, enhance nutrient uptake, resulting in healthier and more productive plants. This technique follows intermittent watering, which involves flooding and then draining the field, rather than keeping it continuously submerged in water. This helps to improve root growth and encourages aerobic conditions in the soil, which are beneficial for rice plants. This technique also emphasizes application of organic amendments and gradual replacement of chemical fertilizers to improve soil structure and functioning (Lal et al., 2016). Weeding is practiced through the use of mechanical weeders, especially cono weeder due to its wider spacing. The SRI has been shown to be more resilient to climate change, as the increased root growth and plant vigour help rice plants withstand droughts, floods, and other environmental stresses. The benefits of SRI is listed in Table 1.

4.3.2. Alternate wetting and drying (AWD)

This water management technique involves alternating flooded and non-flooded conditions in rice fields. This method has gained significant attention in recent years due to its potential to reduce water use, greenhouse gas emissions, and production costs while maintaining crop yields (Table 1). The AWD relies on the principle that rice plants do not need to be continuously submerged in water and can survive periodic dry spells without a significant impact on yield. By allowing the soil to dry out periodically, significant reduction of water usage and saving of costs associated with irrigation can be achieved (Table 1). This technique helps to reduce methane emissions and improves soil health due to increased aeration. The AWD is implemented by using perforated field water pipe inserted inside the ground to monitor the water depth in the field. The irrigation water is applied when the water level drops to about 15 cm below the soil surface after irrigation. However, field is kept about 5 cm under standing water at flowering stage (Nayak et al., 2020).

4.3.3. Aerobic rice

Unlike traditional flooded rice cultivation, this technology involves growing nutrient-sensitive and high-yielding varieties under unsaturated soils irrigated intermittently. This method requires significantly less water than traditional rice cultivation, making it a more sustainable option for regions facing water scarcity or drought conditions. Aerobic rice utilizes oxygen-rich conditions to enhance root growth and nutrient absorption. It is more resilient to pests and diseases, as the aerobic conditions suppress the growth of harmful pathogens. CR Dhan 200 series, Sahbhagi Dhan are suitable varieties under aerobic rice conditions.

4.3.4. Laser land levelling

It is a technique to level the fields (±2 cm) for even distribution of irrigation water using precision global positioning system (GPS) with laser-guided technology. This method improves water use efficiency, reduces labour costs, saves time and fuel, facilitates the sowing of seeds at a uniform depth, resulting in uniform germination, and improves crop yields (Table 1; Anonymous, 2024).

4.3.5. Mid-season drainage

Mid-season drainage is executed during mid to late ripening phase of rice crop in which standing water is removed for about a week to aerate the soil and reduce methane emission (Table 1). It can increase nitrous oxide emission, but overall net global warming potential is still mitigated.

Table 1. Benefits of various water smart technologies practiced in rice cultivation

Technology	Benefits	Reference
System of rice intensification (SRI)	• Saves up to 20-25% water • Water requirement for irrigation is only 1200-1400 ha-mm • Water use efficiency is about 5.7-5.8 kg ha-mm^{-1}. • Rice productivity can be increased by 35-40% • Reduces seed requirement by about 5 kg ha^{-1}, Shortens time to maturity by 1-3 weeks Protects against biotic stress factors such as pests/ diseases • Reduces methane emission by about 50-60%	Lal et al., 2016 Nayak et al., 2020 Thakur et al., 2013

Alternate wetting and drying (AWD)	• Water savings of up to 15-30% • Irrigation water requirement is 1000-1200 ha mm • Water use efficiency is 5.4-5.5 kg ha-mm^{-1} • Reduce methane emissions by up to 48% compared to continuous flooding	Nayak et al., 2020 Rejesus et al., 2011 Sahu et al., 2023
Aerobic rice	• Increase water productivity • Uses up to 30% less water • Yield losses ~20-40%, which can be minimized through suitable varieties • Requires less labour and energy • Reduces greenhouse gas emissions	Nie et al., 2012 Farooq et al., 2023 Nayak et al., 2021
Laser land levelling	• Optimize water use efficiency • Prevent waterlogging • Increasing rice productivity by 8%	Anonymous 2024
Mid-season drainage	• Decreased seasonal methane emissions by 20–77%.	Perry et al., 2024

4.4. *Integrated Nutrient Management*

Lowland rice cultivation, which relies heavily on nitrogen (N) fertilizers, poses a significant risk of nitrous oxide (N_2O) emissions, a potent greenhouse gas with a global warming potential 265 times higher than carbon dioxide (CO_2). Additionally, N fertilizers contribute to atmospheric ammonia (NH_3) pollution, leading to environmental concerns. Excessive fertilizer use also leads to nitrate leaching, groundwater contamination, eutrophication, and biodiversity loss in surface water bodies. To address these environmental concerns, a balanced nutrient management strategy is crucial for sustainable rice production. This approach involves optimizing fertilizer use by combining organic and inorganic sources, reducing N application through integrated nutrient management (INM) practices, and mitigating the adverse effects of reactive N species on the environment. A combined approach using organic manures (like FYM, crop residues, and biofertilizers) and chemical fertilizers has been recommended to manage soil fertility and nutrients in intensive rice-based cropping systems, helping to address yield stagnation. High-quality, easily decomposable, and locally sourced organic materials are crucial for effective INM. Studies have shown that poultry manure (PM) outperforms sheep and cattle manure in terms of rice grain yield. Additionally, blue-green algae (BGA) significantly contribute to the nitrogen economy of lowland rice through biological N fixation. Analysis of nutrient management practices on rice, wheat, and sustainable yield indices across various locations in the Gangetic plains revealed that unfertilized plots showed a negative yield trend, while NPK fertilized and NPK with organics plots showed increasing or stable trends (Nayak et al., 2012). The declining yield trend in unfertilized plots was attributed to reduced soil organic carbon (SOC) and nutrient supply. Study emphasized the importance of applying recommended fertilizer doses with partial substitution of organics for sustaining rice-wheat system productivity (Nayak et al., 2012). Combining NPK fertilizers with farmyard manure (FYM) significantly increased rice yield and enhanced sustainability in a 39-year-old rice-rice system (Fig. 8; Shahid et al., 2013).

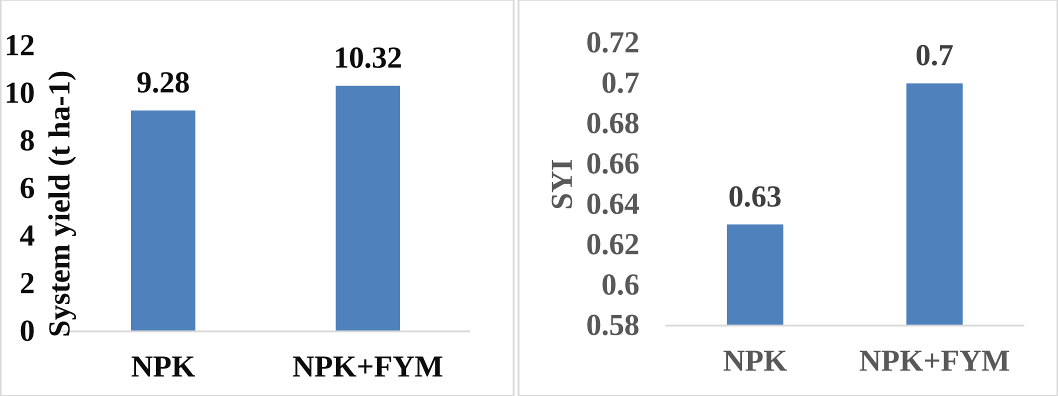


Fig. 8. Long term Impact of INM on yield and sustainability of rice-rice system (Shahid et al., 2013).

Integrated nutrient management strategy including 50% RDN–urea and 50% RDN as poultry manure or FYM produced similar yield as that of 100% RDN as urea in the second season and maintained higher microbial activity and labile C fractions. (Mohanty et al., 2020).

Table 2. Rice grain yield under different integrated nutrient management practices (Mohanty et al., 2020)

Treatments	Yield (t ha^{-1})	
	Dry Season	Wet Season
Control (No N applied)	3.2d	3.03c
100 % recommended dose of N (RDN) from urea	5.1a	4.96a
50 % RDN from urea + 50% RDN from FYM	4.6b	4.86a
50 % RDN from urea + 50 % RDN from poultry manure	4.5b	4.89a
50% RDN from urea + 25% RDN from rice straw + 25 % RDN from FYM	4.1c	4.16b
50 % RDN from urea + 25 % RDN from blue green algae (BGA) + 25 % N from FYM	4.5b	5.01a

4.5. Soil Amendments for Reducing Greenhouse Gas Emissions

Rice cultivation is a notable source of methane (CH_4) emissions, accounting for about 11% of human-induced CH_4 emissions globally. To address these emissions, several strategies have been implemented, including use of soil amendments and microbial interventions. Nitrification inhibitors such as dicyandiamide (DCD) can indirectly influence CH_4 emissions by slowing nitrification, which in turn reduces nitrous oxide (N_2O) emissions and affects CH_4 production.

Soil amendments, including organic matter, biochar, and sulfate-based compounds, can also reduce CH_4 emissions. Biochar improves soil aeration and stimulates methanotrophic activity, while sulfate-based compounds inhibit methanogen activity. Moreover, industrial by-products like fly ash, basic slag and phosphogypsum can decrease the availability of methanogen substrates and increase electron acceptors, thereby reducing methane formation. Additionally, application of value-added soil amendment like basic slag (waste of steel industries) and use of efficient methanotroph formulation is an environmental and eco-friendly option to reduce GHGs emissions. The application of basic slag along with methanotrophs significantly reduced GWP by %14.9 and %14 in the wet and dry seasons paddy (Swain et al., 2023).

4.6. Microbial Interventions for Reducing Greenhouse Gas Emissions

Microbial approaches, such as methanotrophic inoculation and bioaugmentation with specific microbial consortia, can decrease CH_4 emissions by 20-30% and improve soil health. These techniques introduce bacteria that consume CH_4, reducing emissions and enhancing soil fertility (Dash et al., 2021). It has been observed that by the use of methane-oxidising bacteria-based formulation product containing MT-22 by ICAR-NRRI offers a promising solution to reduce methane emissions by 10 to 12% (PIB, 2024). Due to competition between sulfate reducers and methanogens for the same substrates, sulfate amendment is a mitigation approach to lower methane emissions from rice fields. Filamentous bacteria called cable bacteria are known to raise sulfate levels through the process of electrogenic sulfide oxidation. Scholz et al., (2020) have demonstrated that, in comparison to control pots devoid of cable bacteria, a single inoculation of rice-vegetated soil pots with cable bacteria raises the sulfate inventory five times and reduces methane emissions by 93%. Thus, encouraging cable bacteria in rice fields through enrichment or prudent management could turn into a tactic to lower emissions of methane. The combination of these strategies can greatly diminish CH_4 emissions from rice paddies, fostering more sustainable rice cultivation and reducing environmental impacts.

4.7. Organic farming practices

Rice farming is a major contributor to greenhouse gas (GHG) emissions, with field emissions accounting for 65-95% of total life cycle emissions. These emissions are predominantly due to anaerobic soil conditions and the excessive use of chemical nitrogen fertilizers. In contrast, organic rice farming practices are increasingly recognized for their lower environmental impact, which includes reduced GHG emissions and minimized ecosystem degradation.

Research indicates that organic rice farming (OF) has a significantly lower carbon footprint compared to conventional rice farming (CF). Specifically, OF has a carbon footprint of -0.13 kg CO_2 equivalent per kilogram of rice yield, and it boasts a higher value of carbon sequestration ecosystem services (VCSES), reaching $541,196 per hectare per year, compared to CF (Arunrat et al., 2021). These metrics suggest that organic farming not only reduces GHG emissions but also enhances the ecosystem's ability to sequester carbon, making it more effective in mitigating climate change. In addition to reducing GHG emissions, organic farming practices also address groundwater contamination and enhance microbial biodiversity. By avoiding synthetic fertilizers and pesticides, organic farming minimizes the risk of groundwater pollution.

At NRRI, Cuttack, the effects of long-term organic additions on soil carbon (C) storage and functional microbial activities were examined in relation to greenhouse gas (GHG) emissions from rice fields. It was observed that the farm yard manure + green manure (FYM+GM) treatment raised the global warming potential (GWP) by 110% and decreased the C efficiency ratio by 24% as compared to the unamended control (Bhattacharyya et al., 2012). However, the soil's organic matter and total carbon content increased significantly with the rice straw + green manure (RS+GM) treatment, by 34% and 53%, respectively. The study concluded that the optimal soil amendment to sequester soil organic carbon is RS+GM at a 1:1 ratio (based on nitrogen (N)). In flooded tropical rice soil systems, these amendments may not only increase yield capacity but also reduce greenhouse gas emissions.

Although organic farming may initially result in higher GHG emissions due to substantial applications of organic manure, these emissions typically decrease over time as soil organic matter stabilizes. Long-term studies demonstrate that organic farming consistently leads to lower overall environmental impact indices compared to conventional methods, which are associated with higher environmental indices and greater harm (Amirahmandi et al., 2022).

4.8. Managing Rice Residues

Globally, rice production generates approximately 731 million tons of lignocellulosic straw annually, with an average yield of 1.0-1.5 kg of straw per kilogram of harvested rice. This straw could potentially supply 6.5 million tons of NPK annually if half of it were utilized as fuel and animal feed. However, in India, about 16% of crop residues are burned, with 60% of these being paddy straw. This practice significantly contributes to air pollution, with recent estimates attributing around 70% of the air pollution in New Delhi and other areas during November and December to straw burning (Bhattacharyya and Barman, 2018). Burning straw releases harmful gases like CO_2, CO, SOx, NOx, particulate matter, and CH_4, exacerbating air pollution and increasing greenhouse gas emissions. The widespread burning of rice residues not only represents a loss of valuable renewable resources but also contributes to environmental degradation and higher greenhouse gas emissions.

Rice straw and residues have considerable potential for use in conservation agriculture, mulching, and the production of products like manure, ethanol, biodiesel, and biochar. If 20% of the world's rice straw were utilized for ethanol production, it could generate about 40 billion liters of ethanol annually, replacing 25 billion liters of gasoline derived from fossil fuels. Paddy straw can also be effectively used in composting, bioenergy production, and as animal feed. Microbial composting, which utilizes cellulolytic and ligninolytic bacteria to break down lignocellulosic materials such as paddy straw, represents a promising approach for managing agricultural waste (Panneerselvam et al., 2024).

Breeding new varieties that produce high-quality straw for animal feed and biofuel production, alongside high-quality grains, is another innovative strategy (Bhattacharyya et al., 2020). Expanding the use of technologies for composting, ethanol and biochar production, and power generation from rice residues is crucial for maximizing their benefits and minimizing environmental impacts.

4.9. Integrated Pest Management (IPM)

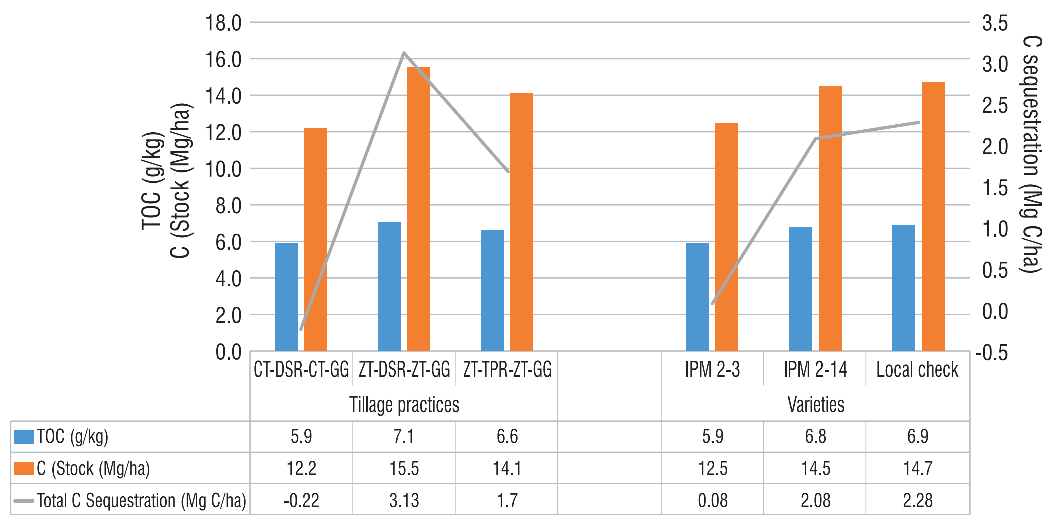
With the advancement of agriculture, pesticides have become crucial for safeguarding crops and enhancing productivity. These chemicals, including nematicides, insecticides, fungicides, herbicides, rodenticides, and molluscicides, help mitigate losses due to pests and diseases while boosting crop yields and maintaining affordability. Globally, approximately two million metric tons of pesticides are used annually, with herbicides comprising 47.5%, insecticides 29.5%, and fungicides 17.5% (Sharma et al., 2019). Notably, cotton and rice account for 57% of total pesticide use. In rice-growing regions of South and Southeast Asia, pests, weeds, and diseases can cause a 15-25% loss in potential rice production due to the favorable conditions for pest proliferation. However, the widespread application of pesticides often results in significant portions reaching non-target areas, with over 98% of insecticides and 95% of herbicides failing to hit their intended targets (Rath et al., 2018). This not only causes pollution of air and water but also contributes to ecosystem damage and health risks. Excessive pesticide use has led to the emergence of resistant pest strains, necessitating more toxic chemicals. To address these issues, integrating biopesticides and adopting Integrated Pest Management (IPM) strategies which combine biological, physical, and chemical controls can provide more sustainable pest management solutions. IPM techniques, such as using pheromone traps, biological control agents, and pest-resistant rice varieties, can help reduce pesticide dependency, lessen environmental contamination and enhance biodiversity.

4.10. Conservation Agriculture (CA)

Conservation agriculture (CA) aims to achieve sustainable and profitable farming by integrating soil, water, and biological resource management. Its core principles include minimal soil disturbance, maintaining soil cover, and crop rotation. These practices enhance soil health, water retention, and biodiversity, leading to more resilient farming systems. In India, where rice farming is essential, adopting CA practices is increasingly recognized as a key strategy for reducing the environmental footprint of rice farming and addressing challenges related to resource depletion and climate change (Shahid et al., 2021; Bala et al., 2023; Jat et al., 2023).

Growing rice-green gram under conservation agriculture system helped in improving the soil fertility, increased rice-green gram system yield by 2.5-5.0% and income of the farmer by 22-25% over the farmers' practice. It also helped to save energy by 21.4% and soil organic carbon stabilization by 17% over conventional practice (Shahid et al., 2021).

In another experiment, after five years of continuous cropping, the annual cumulative C-sequestration into the experimental soils by conservation treatments ranged from 1.70 Mg C ha^{-1} in the zero-tillage-transplanted-rice followed by zero tillage-transplanted rice followed by zero-tillage-green gram system (ZT-TPR-ZT-GG) to as high as 3.13 Mg C ha^{-1} in the zero tillage-direct seeded rice followed by zero-tillage-green gram system (ZT-DSR-ZT-GG) (Fig. 9).



	CT-DSR-CT-GG	ZT-DSR-ZT-GG	ZT-TPR-ZT-GG		IPM 2-3	IPM 2-14	Local check
	Tillage practices				Varieties		
🟦 TOC (g/kg)	5.9	7.1	6.6		5.9	6.8	6.9
🟧 C (Stock (Mg/ha)	12.2	15.5	14.1		12.5	14.5	14.7
— Total C Sequestration (Mg C/ha)	-0.22	3.13	1.7		0.08	2.08	2.28

Fig. 9. Total carbon and carbon stock in soil as influenced by tillage, residue management and green gram varieties after 5 years of conservation agriculture practice

On the other hand, conventional-tillage-direct-sown-rice followed by conventional-tillage-green gram system (CT-DSR-CT-GG) showed a negative C sequestration potential (−0.22 Mg C ha^{-1}). The ZT-DSR-ZT-GG system demonstrated a greater rate of C sequestration (3.13 Mg C ha^{-1}) in comparison to conventional management techniques. Similarly, under conservation agriculture system (ZT-DSR-ZT-GG) methane emission is reduced as compared to the conventional system (Fig. 10).

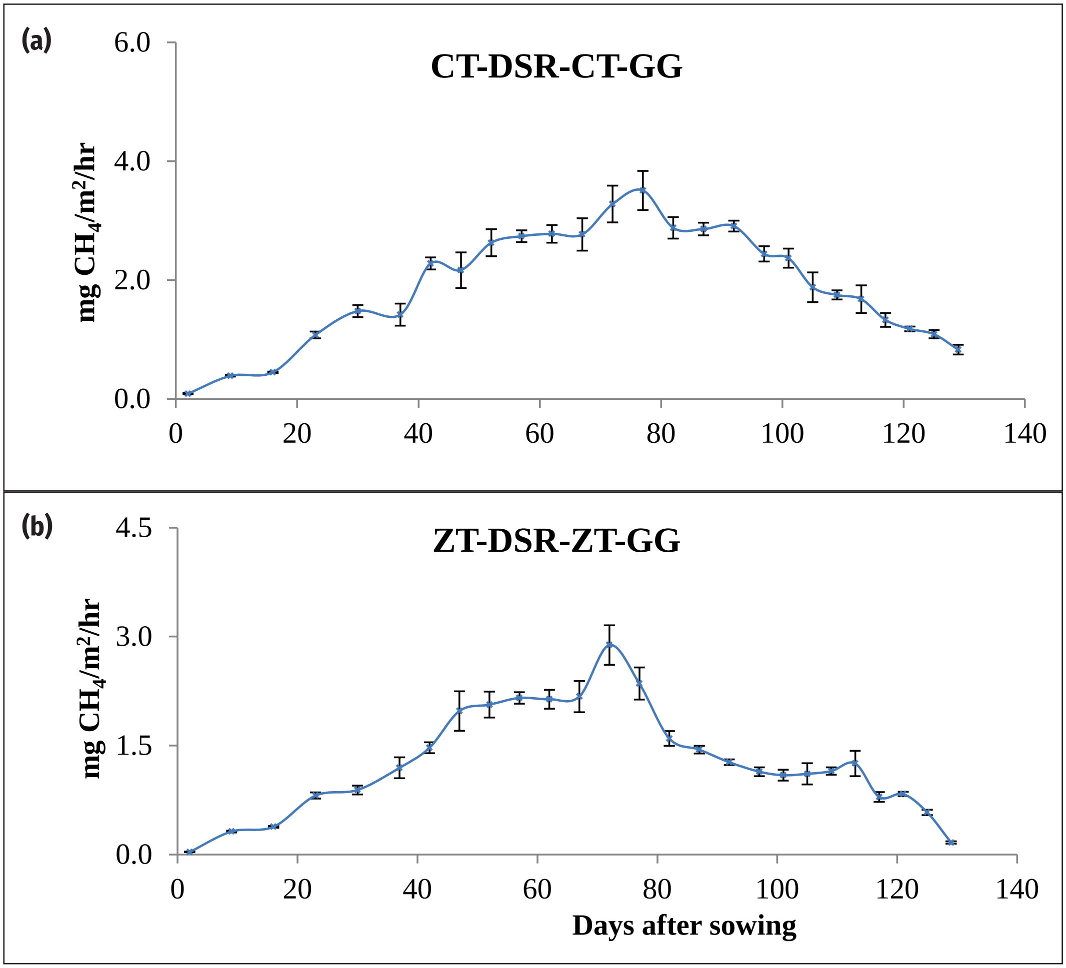


Fig. 10. CH_4 emissions observed in rice-green gram cropping system under conservation and conventional tillage after five years of experiment influenced by CT-DSR: conventional tillage-direct seeded rice and ZT-DSR: zero tillage-direct seeded rice

In a varietal screening trial under conservation agriculture practices, it was observed that there was a considerable variance in both total C stock and total C sequestration among the chosen kinds of green grams varieties (Munda et al., 2022). Results indicates that, in comparison to other types, the local check had the highest capacity for sequestering carbon (2.28 mg C ha^{-1}).

4.11. Post harvest losses in relation to GHG emission

The losses in paddy occurs in the pre-harvest, harvest and post-harvest stages. Pre-harvest losses are mostly influenced by the attack of insects, pests, weeds and rusts. Harvesting losses are due to shattering losses when the grains are left to dry in the field after cutting. Post harvest losses occur in threshing, transportation and storage which is affected by moisture content of grain, temperature and relative humidity of stored grain, fungal infection, storage insects etc.

Fig. 11. Stages of post-harvest losses in rice [compiled from Saadat et al., (2020), Saba et al., (2018), FAO Report (2007)]

The post-harvest operations as well as losses contribute to carbon emissions in terms of methane, carbon dioxide and nitrous oxide emitted out of fuel consumption for operating the post-harvest equipment. Besides the paddy loss in the field and off the field gets fermented also leading to methane emission. Research study by Mohan et al., (2022) indicated that production and post-harvest operations of rice in Thanjavur district of Tamil Nadu led to an emission of 6720.46 kg CO_2e/ha. Of which, post production processes contributed to 1851.46 kg CO_2e/ha that included activities such as harvesting (770 kg CO_2e/ha), Drying (752.1 kg CO_2e/ha), Storage (107.6 kg CO_2e/ha), Milling (99.9 kg CO_2e/ha), Packaging (5.7 kg CO_2e/ha), Transport (116.1 kg CO_2e/ha). However, the carbon economic efficiency was calculated to be 23.39 that showed the economic worth of producing rice is Rs 23.39/ kg of greenhouse gas emission.

Research study by Shashidara et al., (2022) indicated that GHG emission associated with parboiled rice obtained from 40 rice mills of Karnataka state is very high. For parboiling, usually rice husk is used in the boiler for steaming operation of parboiling. It is found that for processing one ton of paddy, parboiling process requires 200 kg of steam (Satish et al., 2019). The results indicated that the rice mills emitted 1756.37 kg/month CO_2 equivalent from electricity consumption. Burning of rice husk as fuel for boiler emitted nearly 776134.44 kg CO_2/month and for diesel utilization, the emission was 48114.33 kg CO_2/month. Apart from these, other GHG gases like methane (252.32 kg/month), nitrous oxide (34.94 kg/month), Carbon monoxide (31110.31 kg/month) were also emitted in the parboiling process. Although parboiled rice has immense health benefits (Muchlisyiyah et al., 2023), however, the parboiling process is associated with huge heat generation which significantly affects the GHG emission.

A more comprehensive framework for lowering greenhouse gas emissions related to food waste could be created, and measures or policies could be developed for the entire supply chain management process. These could include high volume storage (such as vacuum packaging, smart packaging, etc.) and processing infrastructure that uses block chain technology, as well as modifying the transport mechanism to include advanced cooling and quality-assuring indicators and shorter product travel times. To create a resilient system, mechanisms for valuing food waste at later stages of the food supply chain, such as anaerobic digestion, bioactive chemical extraction, composting, arts and crafts, and biofuel generation, must also be created. Using food waste as a resource is part of implementing the concepts of the circular economy. For instance, composting can aid in the replenishment of soil nutrients and the generation of biogas.

5. Conclusion and way forward

The imperative to balance food security with environmental sustainability is nowhere more evident than in the rice-based cropping systems that dominate India's agricultural landscape. This research bulletin has highlighted the significant environmental challenges posed by traditional rice cultivation methods, including excessive water usage, high greenhouse gas emissions, soil degradation, and biodiversity loss. Through a comprehensive analysis of sustainable practices and innovative technologies, we have identified effective strategies to mitigate these impacts. Key methods such as direct seeding of rice (DSR), non-puddled transplanted rice (NPTR), and advanced water management techniques like the System of Rice Intensification (SRI), alternate wetting and drying (AWD), and aerobic rice systems offer promising pathways to reduce water consumption and greenhouse gas emissions. Additionally, integrated nutrient management, organic farming, crop diversification, residue management, integrated pest management (IPM) and conservation agriculture are crucial for maintaining soil health and reducing reliance on chemical inputs. Practicing improved post-harvest processing may also help to reduce the emission of greenhouse gases and reduce the environment footprint of the rice based cropping system. The adoption of these sustainable practices is not only vital for reducing the environmental footprint of rice cultivation but also for enhancing the resilience of farming systems against climate change.

The way forward for achieving sustainable rice-based cropping systems in India requires a holistic and integrated approach that combines policy support, farmer education, research, and community engagement. Governments must provide incentives and create an enabling environment that promotes the adoption of sustainable practices, such as advanced water management techniques and climate-resilient rice varieties. Strengthening extension services and training programs will be crucial in equipping farmers with the knowledge and skills needed to implement these innovations. Continued research and development are essential to refine existing methods and explore new technologies that further reduce environmental impacts. A robust monitoring and evaluation framework is needed to assess the effectiveness of these practices and ensure continuous improvement. Engaging local communities and raising awareness about the environmental and economic benefits of sustainable farming will foster widespread adoption at the grassroots level. By aligning these efforts, India can significantly reduce the environmental footprint of its rice production systems, enhancing agricultural sustainability and contributing to global efforts to combat climate change. This multi-faceted approach will not only safeguard the environment but also improve the resilience and productivity of rice farming, benefiting both farmers and the broader society.

Epilogue

Rice is a fundamental component of food security in India, sustaining a significant portion of the population. However, conventional rice farming practices place considerable strain on the environment, including excessive water use, high greenhouse gas emissions, soil degradation, and biodiversity loss. This research bulletin explores sustainable strategies to mitigate these environmental impacts within India's rice-based cropping systems.

Key approaches include the adoption of direct seeding of rice (DSR) and non-puddled transplanted rice (NPTR) to reduce water use and labor demands. Advanced water management techniques, such as the System of Rice Intensification (SRI), alternate wetting and drying (AWD), and aerobic rice systems, are examined for their potential to enhance water efficiency and lower methane emissions. The bulletin also emphasizes the importance of soil health through integrated nutrient management and organic farming, which are critical for long-term sustainability.

Crop diversification and integrated pest management (IPM) are identified as effective methods for reducing chemical dependency and fostering ecological balance. Additionally, the alternate use of rice residues instead of burning and management of rice residues through conservation agriculture practices is highlighted for its role in improving soil health and minimizing environmental impacts. The bulletin also addresses strategies for reducing greenhouse gas emissions, including use of soil amendments, microbial interventions and improved post-harvest processing.

The need for policy and institutional support to promote these sustainable practices is underscored, with a call for a comprehensive approach that integrates scientific research, farmer education, and policy initiatives. By embracing these sustainable practices, India can significantly reduce the environmental footprint of its rice production systems, contributing to global efforts to combat climate change and enhance agricultural sustainability.

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