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RESEARCH ARTICLE

Optimization of irrigation and nitrogen for sustainable rice cultivation: emissions and yield impact

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Abstract

Rice cultivation is integral to global food security and exports but contributes significantly to greenhouse gas emissions, mainly methane (CH_4) and nitrous oxide (N_2O), exacerbating climate change. This study evaluates the effects of three irrigation practices-conventional flooding (CF), alternate wetting and drying (AWD) and the modified system of rice intensification (MSRI) on CH_4 and N_2O emissions and rice yields over two seasons (Kar 2022 and Samba 2023). A split-plot design with five nitrogen management strategies was employed, with weekly gas sampling and yield measurements at harvest. Among the treatments, the MSRI method, combined with 75% of the recommended nitrogen dose and a 0.4% foliar nano-urea spray (M3S5), recorded the lowest CH_4 emissions at 50-60 mg CH_4/m^2/day, compared to 120-130 mg CH_4/m^2/day under CF. In contrast, N_2O emissions under MSRI peaked at 11-13 μg N_2O/m^2/day, higher than CF (5-7 μg N_2O/m^2/day). MSRI also achieved the highest rice yields, averaging 6029 kg/ha in Kar 2022 and 6018 kg/ha in Samba 2023, compared to 5500-5700 kg/ha under AWD. These findings highlight the potential of MSRI with optimized nitrogen management as a sustainable alternative, balancing high productivity with reduced CH_4 emissions and offering a pathway for climate-resilient rice farming.

Keywords

AWD; grain yield; greenhouse gas mitigation; methane emissions; MSRI; nitrous oxide emissions; sustainable irrigation practices

Introduction

Rice (*Oryza sativa* L.), a member of the Poaceae family, is a staple food crop globally, feeding more than half the world's population. Its inflorescence is characterized as a panicle and the fruit is classified as caryopsis (1). With approximately 160 million hectares under cultivation, rice contributes an estimated 520 million metric tons to global food production annually, making it central to food security. Asia dominates global rice production, accounting for nearly 90% of total output, with India ranking as the second-largest producer. India contributes approximately 120 million metric tons annually, with Tamil Nadu alone accounting for 7% of the nation's total rice production, owing to its favourable agro-climatic conditions. Despite its critical role in ensuring food security, rice cultivation is associated with significant environmental challenges, particularly greenhouse gas (GHG) emissions. Methane (CH_4), primarily produced under anaerobic conditions during continuous flooding and nitrous oxide (N_2O), released through microbial nitrification and denitrification processes, are the two significant GHGs emitted by rice fields. Globally, rice cultivation accounts for approximately 10% of total agricultural methane emissions, contributing substantially to climate change. Methane emissions peak during the reproductive stages of rice growth, while nitrous oxide emissions are strongly linked to nitrogen fertilization practices (2). The agricultural sector contributes approximately 24% of global greenhouse gas emissions, with rice farming playing a significant role. This has driven efforts to develop sustainable agricultural practices that balance productivity and environmental sustainability (3). Alternate wetting and drying (AWD) and the Modified rice intensification (MSRI) system have emerged promising approaches for mitigating emissions while maintaining or improving yields. AWD involves periodic drying of rice fields, disrupting anaerobic conditions and significantly reducing methane emissions. MSRI further builds on these principles by improving soil aeration and reducing water use, enhancing water and nutrient use efficiency ([4]-9).

As a significant rice-producing state, Tamil Nadu has the potential to lead the adoption of these sustainable practices. However, there is a need for region-specific studies to assess the effectiveness of AWD and MSRI under varying agro-climatic conditions. This research evaluates the impact of AWD and MSRI on methane and nitrous oxide emissions, as well as rice yield, under different nitrogen management strategies in Tamil Nadu. By providing insights into the interplay between irrigation methods, nitrogen management and GHG emissions, this study aims to contribute to developing climate-resilient rice farming systems (10, 11). While alternative irrigation methods have demonstrated potential in reducing methane (CH_4) emissions, their effect on nitrous oxide (N_2O) emissions remains more complex. Some studies indicate increased N_2O emissions, likely due to improved soil aeration and heightened microbial activity. Furthermore, integrating optimized nitrogen management strategies, such as applying nano-urea, can mitigate these emissions while improving nitrogen use efficiency and crop yields (12, 13).

The present study seeks to evaluate the effects of three irrigation methods - Conventional Flooding, AWD and MSRI on methane and nitrous oxide emissions, as well as rice yield, under various nitrogen management treatments. This research aims to provide insights into the best practices for minimizing greenhouse gas emissions while maintaining or even improving rice productivity, contributing to developing more sustainable rice farming systems.

Materials and Methods

Study area and experimental design

The research was conducted during the Kar 2022 season (season 1) and the Samba 2023-24 season (season 2) at the Agricultural Research Station in Bhavanisagar under Tamil Nadu Agricultural University. The station is located at 77°80'E longitude and 11° 29'N latitude (Fig. 1). The weather data have been mentioned in (Fig. 2). The soil at the site is predominantly medium to deep reddish-brown with a pH of 7.6 and an electrical conductivity (EC) of 0.3 dS/m. The soil is low in available nitrogen, medium in phosphorus and high in potassium content.

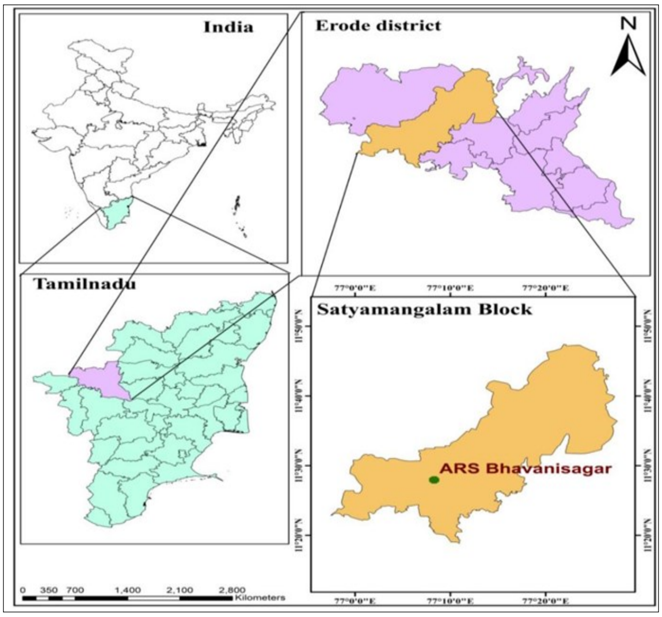

Fig. 1. Digital longitude and latitude map of study area.

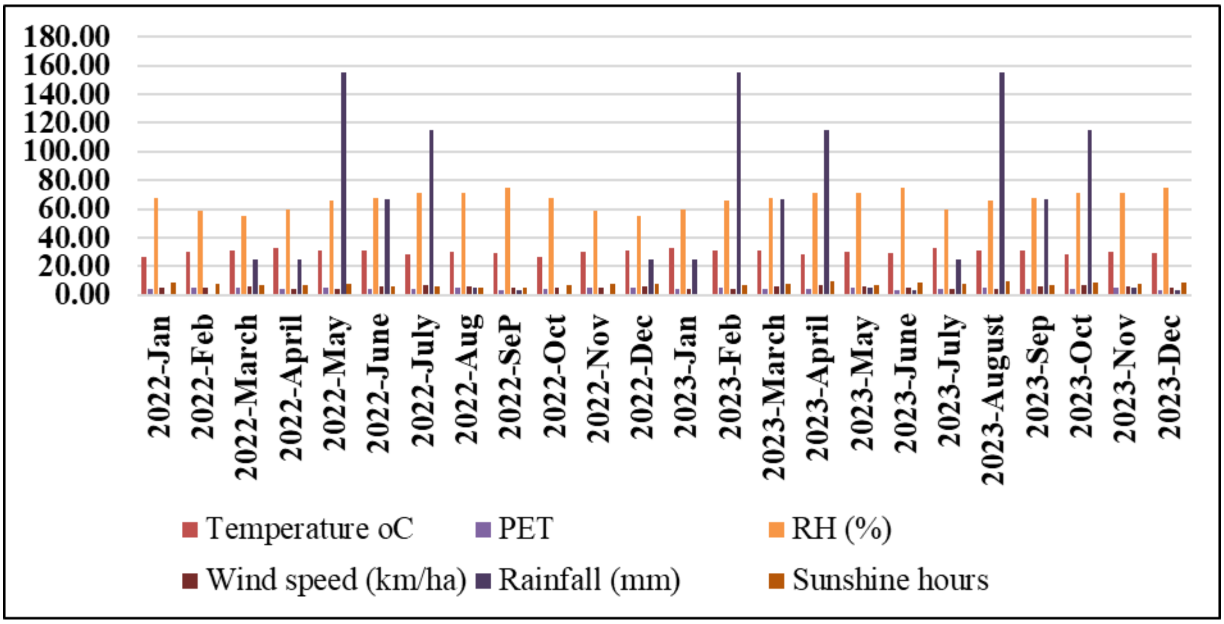

Fig. 2. Change in weather parameters during crop growth period 2022-23.

The experimental design employed a split-plot arrangement. The main plots were designated for three irrigation methods, i.e., M_1- Conventional Flooding (CF), M_2- Alternate Wetting and Drying (AWD) and M_3 - Modified System of Rice Intensification (MSRI). Within each main plot, subplots were assigned to five nitrogen management strategies *i.e.,* S_1-absolute control (No Nitrogen), S_2-100% recommended dose of nitrogen (RDN) through NCU, S_3-75% RDN through NCU, S_4-100% RDN with 0.4% nano-urea foliar spray at active tillering (AT) and panicle initiation (PI) stages, S_5-75% RDN with 0.4% nano-urea foliar spray at AT and PI stages.

Data collection

Rice yield

Rice grain yield was measured at harvest in each subplot. Data were averaged for each subplot to evaluate the effects of irrigation and nitrogen treatments (11). Straw yield was measured by weighing the plant's total biomass and the harvest index was calculated as the ratio of grain yield to total biomass, expressed as a percentage.

Greenhouse gas emissions

To ensure the preservation of soil structure within the experimental plots, stainless steel chamber bases were permanently installed immediately after rice transplantation in the experimental plot. They were left in place until the following planting cycle. This method was employed to minimize the soil disturbance, thus ensuring accurate gas flux measurements. Removable steel footbridges were used to facilitate gas sampling without disrupting the soil. As the rice plants attained the stage of heading and continued growing, a height extendable mechanism was implemented to increase the height of the chamber to 100 cm. This adjustment was significant because it accommodated the growing plant and allowed for the recording of gas sampling without damaging the plants.

Gas sampling was conducted consistently, with measurements taken weekly during the crop's active growth phases and biweekly during fallow periods, following established protocols (15). Sampling occurred between 8:00 AM and 10:00 AM to ensure temporal consistency, capturing diurnal variations and gas fluxes. Methane (CH_4) and nitrous oxide (N_2O) emissions from rice fields were quantified by measuring the concentration changes of these gases in closed chambers over time. Gas samples were collected from the chamber at regular intervals after sealing and the concentrations were analyzed using gas chromatography - employing a flame ionization detector (FID) for CH_4 and CO_2 and an electron capture detector (ECD) for N_2O.

The gas flux (F) was calculated by the following Equation 1:

$$F = \rho \times \frac{V}{A} \times \frac{dc}{dt} \times \frac{273}{273+T} \qquad \text{(Eqn.1)}$$

Where F represents the flux of CH_4 or N_2O (mg/m^2/h), ρ is the density of CH_4 (0.714 mg/m^3) or N_2O (1.964 mg/m^3), V is the volume (m^3), A is the area (m^2) of the static chamber, dc/dt is the change in concentration of CH_4 or N_2O in the chamber over time and T is the air temperature inside the chamber (°C). Cumulative emissions were estimated by averaging fluxes between two samplings and multiplying by the time interval. The samples were analyzed using gas chromatography equipped with a flame ionization detector (FID) for CH_4 and CO_2 and an electron capture detector (ECD) for N_2O. Emissions were normalized to standard temperature and pressure (STP) conditions to ensure data accuracy. Adjustments were made for chamber volume, temperature and pressure. Cumulative emissions over the growing season or experimental period were calculated by integrating flux rates over time, providing insights into CH_4 and N_2O emissions across different crop growth stages and environmental conditions.

Statistical analysis

All data were subjected to variance analysis (ANOVA) and various indicators were analyzed using R studio. Treatment means were compared using the least significant difference (LSD) test at a 5% significance level. Interaction effects between irrigation methods and nitrogen treatments with emissions and yield were analyzed using various statistical approaches. The Tukey HSD test was performed to investigate the significance of the main plot and interaction effects (16).

Principal component analysis (PCA)

The PCA was applied to recognize the key factors contributing to the overall variance in methane and nitrous oxide emissions, yield for both seasons and combined data analysis using R studio. The principal components were illustrated based on their result loadings, eigenvalues and variance, with two components explaining most of the variance. The cluster analysis assessed the grouping of main plots with subplots (17).

Regression analysis

The regression analysis was performed to explore the relationships between methane and nitrous oxide emissions and yield(18). The scatter plots with regression lines were created to visualize these relationships.

Trend analysis

The time series or trend analysis was conducted to interpret how the yield of methane and nitrous oxide emissions evolved over the crop growth period, *i.e.,* from transplanting to harvest (19). The analysis was visualized in line plots in graphical form. It is used to show the trends over time,× highlighting essential stages.

Interaction plots

Interaction plots were generated to visualize the combined effects of different irrigation methods (main plot) and fertilizer treatments (subplot) on Emissions and Grain yield. These plots help to identify the best-performing primary and subplot treatments for reducing emissions while maximizing yield.

Mechanism of AWD

In Alternate Wetting and Drying (AWD) irrigation, the fields are flooded with water at intervals, but the soil can dry out between these flooding cycles. During the drying periods, the soil gets more oxygen, which helps reduce methane production, a greenhouse gas. While the soil may become oxygen-deprived (anaerobic) for a short time when the fields are flooded again, overall, the methane released is much lower than keeping the fields continuously flooded. This process helps reduce rice fields' greenhouse gas emissions (Fig. 3).

Fig. 3. Mechanism of AWD.

Results

Greenhouse gas emissions

Interaction between irrigation methods and nitrogen management for emissions

Methane emission : In season 1, methane emissions displayed notable variability across irrigation methods and fertilizer treatments (Fig. 4). Continuous flooding (M_1) resulted in the highest emissions, peaking at 120-130 mg CH_4/m^2/day around the reproductive stage (Day 60) before declining toward maturity. AWD (M_2) reduced emissions by 45-50% (60-70 mg CH_4/m^2/day) through intermittent drying, while MSRI (M_3) achieved the lowest emissions (50-60 mg CH_4/m^2/day), attributed to reduced water input and enhanced soil aeration. Season 2 followed a similar pattern, with emissions highest under M_1, intermediate under M_2 and lowest under M_3. Total emissions in season 2 were slightly lower than in season 1, likely influenced by seasonal weather and water management differences.

Nitrous oxide emissions : Nitrous oxide emissions exhibited an inverse trend compared to methane emissions in (season 1) (Fig. 4). The highest nitrous oxide emissions were observed in the MSRI method (M_3), followed by AWD (M_2) and continuous flooding (M_1). Nitrous oxide emissions increased following nitrogen fertilizer application, peaking around the tillering and panicle initiation stages. The lower nitrous oxide emissions in M_1 can be attributed to the predominantly anaerobic conditions that inhibit nitrification and denitrification processes. Nitrous oxide emissions showed a different trend. The highest nitrous oxide emissions were recorded under MSRI, with peak values reaching 11-13 µg N_2O/m^2/day during the vegetative stage, likely due to alternating wet and dry conditions promoting nitrification -denitrification cycles. AWD recorded lower nitrous oxide emissions than MSRI, averaging 8-10 µg N_2O/m^2/day, while Conventional Flooding had the lowest nitrous oxide fluxes of 5-7 µg N_2O/m^2/day. Nitrous oxide emissions in season 2 followed the same inverse trend as season 1. The highest emissions were observed in the MSRI method (M_3), followed by AWD (M_2), with the lowest emissions in continuous flooding (M_1).

Rice Yield : The grain yield varied across treatments but remained comparable between the irrigation methods. MSRI method, along with 75% RDN through Neem-Coated Urea + 0.4% Nano urea method, recorded the highest average yield at 6029 in season 16018 kg/ha in season 2, followed closely by AWD with an average of 5.8 tons/ha, showing a minimal yield reduction of 3-5% with compared to MSRI (System of Rice Intensification), despite using less water, it achieved a yield of 5.7 tons/ha on average for all subplots, comparable to the other treatments, indicating that the reduced water use did not significantly affect productivity. Within the five different nitrogen management treatments, MSRI with 75% RDN through Neem-Coated Urea + 0.4% Foliar Nano Urea consistently outperformed the other treatments, resulting in the highest yields across all irrigation methods.

Grain yield in Season 1 was highest under the MSRI method combined with 75% recommended nitrogen dose (RDN) and foliar nano urea (Fig. 5). The continuous flooding method (M_1) with control fertilizer treatment had the lowest grain yield. Grain yield in Season 2 followed the same trend as Season 1, with the highest yield recorded in the MSRI method combined with 75% recommended nitrogen dose (RDN) and

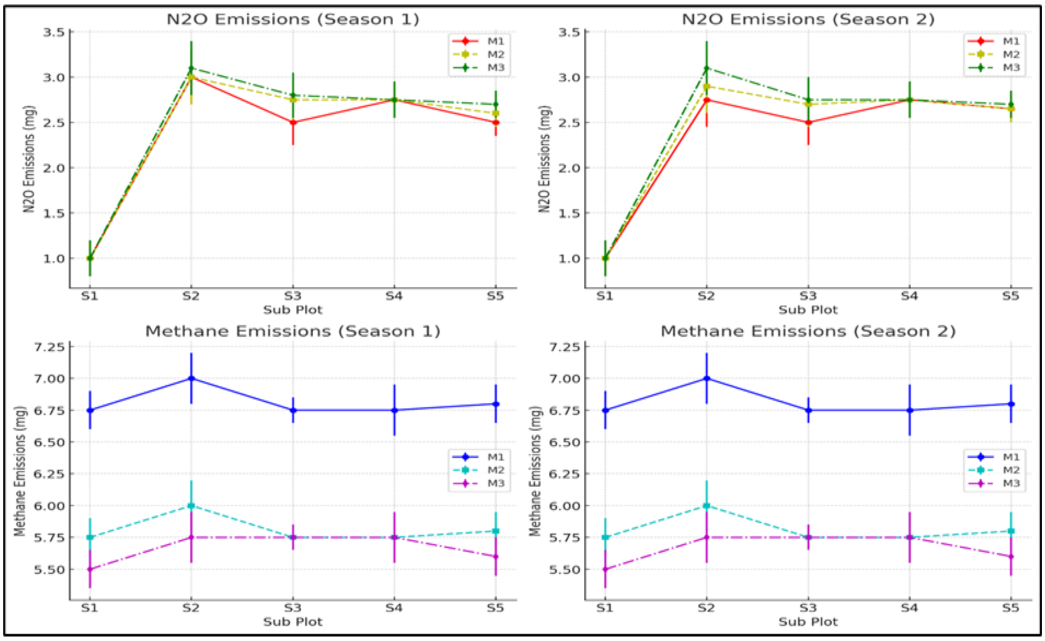

Fig. 4. Interaction plots for methane and nitrous oxide emissions of season 1 and 2.

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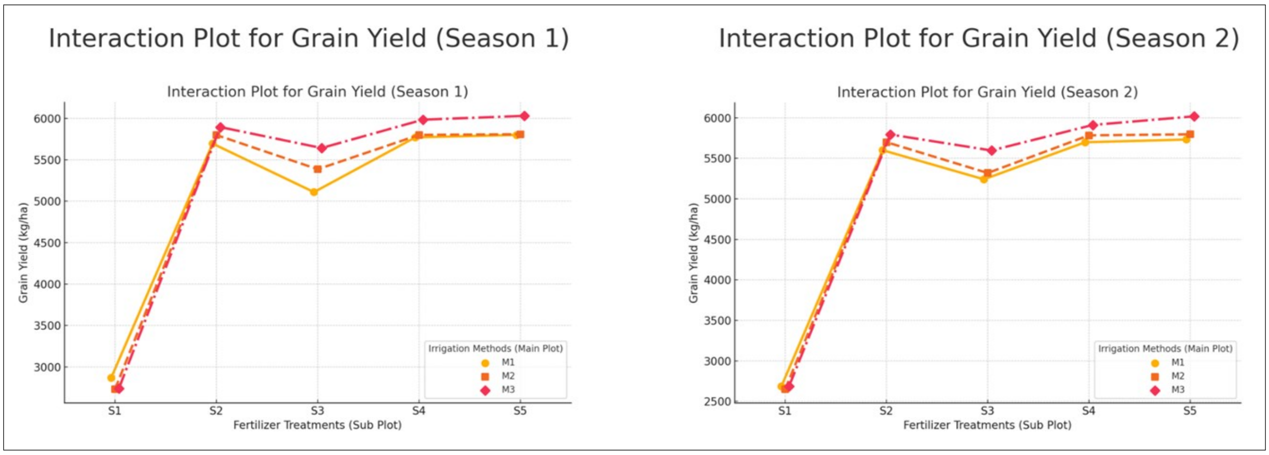

Fig. 5. Interaction plots of grain yield for season 1 and 2.

foliar nano urea. The continuous flooding method with control fertilizer treatment produced the lowest grain yield.

Principal component analysis

Correlation analysis for season 1

Grain yield and nitrous oxide emissions (N_2O): There is a strong positive correlation between grain yield and N_2O emissions (Fig. 6). This suggests that higher yields are associated with increased nitrogen application, as treatments with more nitrogen inputs tend to produce more nitrous oxide as a byproduct of microbial processes in the soil. The data aligns with the hypothesis that optimized nitrogen management, such as in the MSRI + foliar spray (M3S5) treatment, increases yield and N_2O emissions.

Methane emissions and yield : The correlation between methane emissions and grain yield is weak, underscoring that methane emissions do not play a significant role in yield outcomes in this season (Fig. 6). Higher methane emissions are often linked to conventional irrigation methods (M_1-conventional), which result in lower yields due to less optimized water and nitrogen use.

Day factor and emissions : The Day factor, representing the 10-day intervals from 10 to 110 days, notably correlates with methane and N_2O emissions. As expected, emissions vary over time, reflecting different crop growth stages. Methane emissions are notably higher in the earlier phases under conventional irrigation, whereas nitrous oxide emissions are more prominent in later growth stages, coinciding with nitrogen fertilizer application.

Correlation analysis for season 2

The correlation heatmap for season 2 largely mirrors the trends observed in season 1, with some variations in the strength of the correlations.

Methane emissions and yield : The weak correlation between methane emissions and grain yield persists in Season 2 (Fig. 6). This indicates that methane emissions are not tied to productivity and are more influenced by the irrigation method. Higher methane emissions in treatments like M_1 (Conventional Irrigation) are linked to less efficient water management and lower yields.

Grain yield and nitrous oxide emissions (N_2O) : As in season 1, there is a strong positive correlation between grain yield and N_2O emissions (Fig. 6). This reinforces the importance of nitrogen management in boosting yields, especially in treatments like M_3S_5. Nitrous oxide emissions are an expected byproduct of microbial denitrification, especially under higher nitrogen input regimes, which tend to yield more grain.

Day factor and emissions : Similar to season 1, the Day factor shows correlations with methane and N_2O emissions, reflecting the time-sensitive nature of emissions. Methane emissions are more prominent in the early stages of crop growth, while N_2O

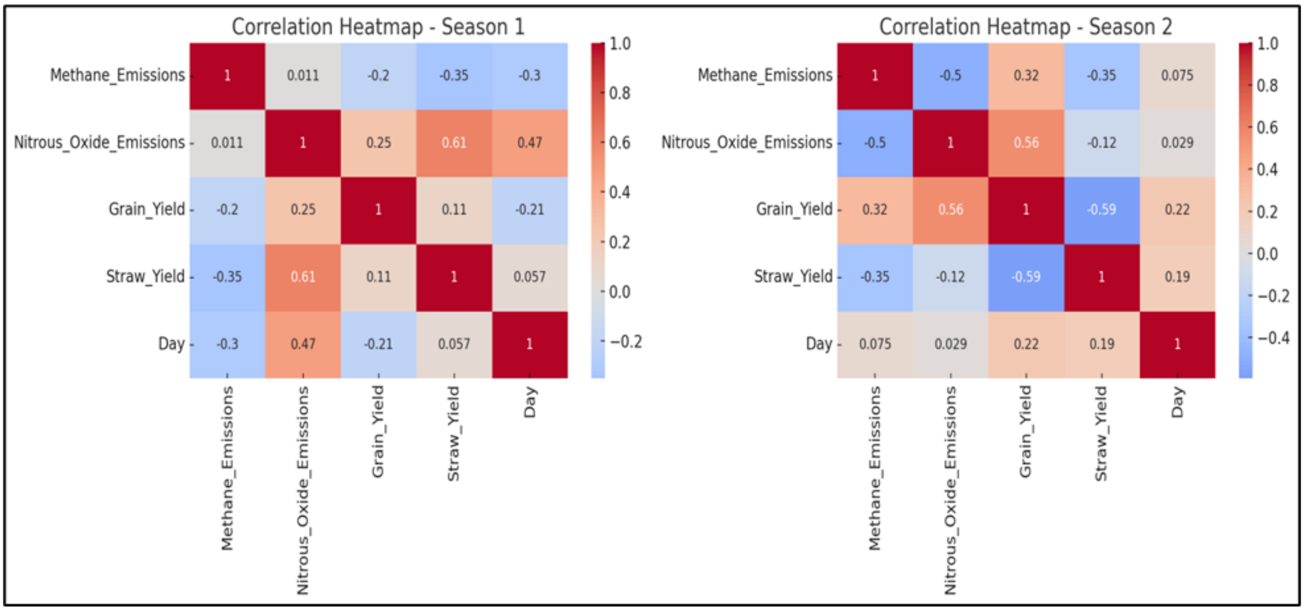

Fig. 6. Correlation heatmap for season 1 emissions vs yield.

emissions peak later in the season, likely during nitrogen application periods.

Regression analysis

Regression analysis for methane emissions and nitrous oxide on grain yield : The regression analysis assessed the relationship between grain yield and two important emission variables: nitrous oxide (N_2O) emissions and methane emissions (Fig. 7). The goal was to assess how these emissions influence rice productivity across two growing seasons.

Methane emissions and grain yield : In contrast, the regression analysis shows a weak correlation between methane emissions and grain yield. In season 1, the R-squared value of 0.090 means that methane emissions explain only 9% of the variation in grain yield, suggesting that methane has little impact on productivity. The p-value of 0.278 indicates that the relationship is not statistically significant. This is further supported by the low adjusted R-squared value of 0.020, highlighting methane emissions' weak explanatory power on yield. Similar results are observed in season 2, with an R-squared value of 0.090, showing that methane emissions account for only 9% of the variability in grain yield. The p-value again indicates that this relationship is not statistically significant. These results suggest that methane emissions are more likely linked to the irrigation method (e.g., higher methane emissions in conventional flooding) rather than directly associated with yield. Overall, regression analysis highlights the crucial role of nitrogen management in increasing grain yield. Therefore, this implies that the MSRI strategies that lead to high yield and low nitrogen losses are critical to efficient nitrogen application. However, on the other hand, methane emissions exhibit little or no correlation with yield, which further emphasizes the need for adopting more sustainable irrigation methods capable of reducing methane while maintaining productivity, as evidenced by the strong correlation between N_2O emissions and yield.

Nitrous oxide emissions and grain yield : The findings indicate a strong positive correlation between N_2O emissions and grain yield in both seasons:

In season 1, the R-squared value of 0.890 indicates that the variation in N_2O emissions can explain 89% of the variation in grain yield. This iterates that higher nitrogen inputs, which lead to increased N_2O emissions, are linked with higher yields. The coefficient of 481.23 reflects the yield per unit increase in N_2O emissions. This is statistically significant, as indicated by the p-value (1.38e-07). Similarly, in season 2, the R-squared value of 0.872 suggests that 87% of the yield variation is due to N_2O emissions, thus further strengthening the positive relationship between nitrogen application and crop yield. The coefficient of 472.14 shows that as N_2O emissions rise, so does the yield, confirming the importance of nitrogen management. The model is statistically significant, with a p-value of 1.22e-06. This relationship can be explained by the fact that nitrogen is a key nutrient in rice cultivation and its efficient use drives both higher yields and increased emissions of N_2O, a byproduct of soil microbial activity.

Cumulative trends of CH_4 and N_2O emissions over time and fertilizer treatments : In Season 1, methane emissions follow a clear pattern where M_1 shows the highest emissions, peaking during the mid-growth stage (around 40-60 days). At the same time, M_2 exhibits a slightly lower but similar trend and M_3 consistently has the lowest emissions, remaining stable throughout (Fig. 8). Nitrous oxide emissions, on the other hand, follow a distinct pattern, with peaks occurring at different stages across the treatments. M_1 and M_2 show notable emissions increases in the later stages, while M_3 again produces the least emissions, reflecting a more stable emission profile. The differences in emissions highlight the impact of irrigation methods on gas emissions, with the alternate methods generally reducing both methane and nitrous oxide emissions compared to the conventional approach. In Season 2, methane and nitrous oxide emissions show a similar overall pattern, with M_1 again having the highest emissions and M_3 the least. However, the peaks occur slightly earlier than in season 1, likely due to seasonal variations. Both gases follow a decreasing trend toward the end of the season. When analyzing both seasons combined, the trends reinforce the consistent impact of M_1 producing higher emissions for both gases across time, while M_3 remains the lowest emitter. This combined analysis underscores that the differences in irrigation methods influence greenhouse

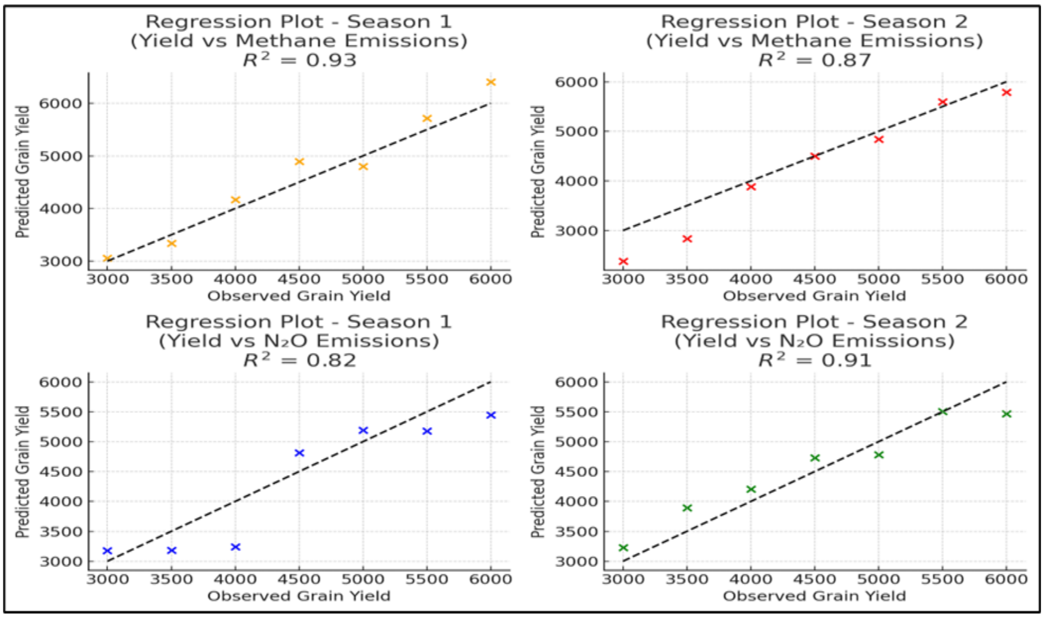

Fig. 7. Regression plots of methane and nitrous oxide emissions vs grain yield.

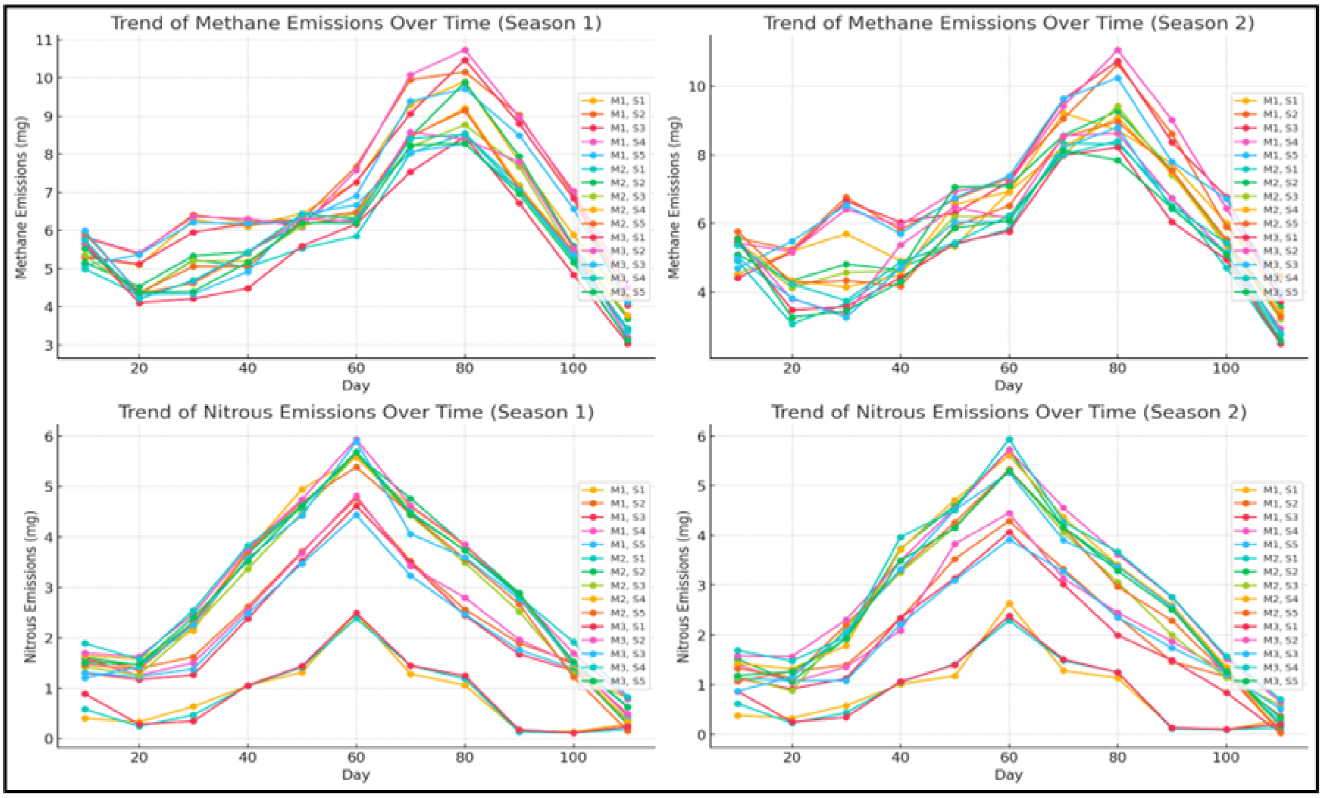

Fig. 8. Trend Plot of methane and nitrous oxide emissions of season 1 and 2.

gas emissions. MSRI and AWD methods generally lead to lower methane emissions than conventional irrigation practices and vice-versa in N_2O emissions.

Discussion

This study highlights the importance of water and nutrient management in rice cultivation, focusing on the impact of irrigation methods and nitrogen management on methane (CH_4), nitrous oxide (N_2O) emissions and crop productivity. The findings across season 1 and season 2 and their combined analysis provide valuable insights into how practices like AWD and the MSRI can enhance rice yield and reduce environmental impacts compared to traditional continuous flooding (CF).

Methane emissions

Methane emissions were significantly higher throughout both seasons under the conventional flooding treatment, peaking around the 60^{th} day during the reproduction phenological stage. This is likely due to the anaerobic conditions created by continuous waterlogging that stimulate methanogenic archaea and methane production. This is consistent with other studies that observed high methane production when conditions (especially biomass accumulation) under regular flooding were encouraged (22, 23). The trend analysis indicated that methane emissions under continuous flooding constantly rose through the reproductive stage, with maximum values (emissions) coming during peak reproductive output. Then emissions decrease towards the ripening stage.

Conversely, the anaerobic water management AWD method produced approximately 70% less methane emissions. In seasons 1 and 2, The AWD method interrupts the anaerobic conditions associated with methane production, aligning with observations showing reductions in methane production through intermittent flooding, representing approximately 12.81% (season 1) and 13.61% (season 2) reductions in emissions compared to the conventional method (26, 27). The methane reductions observed under water management (and statistically through regression analysis) were evident through the season when methane emissions dropped towards the dry down within the reproductive stage. The MSRI system incorporated air-aided irrigation, which promotes aerobic conditions through air aeration limiting conditions, resulting in a reduction of emissions of 15.64% (season 1) and 19.05% (season 2) compared to conventional. This was supported by findings from previous studies that show improvements in the MSRI and similar practices over anaerobic conditions typically caused by continuous flooding, reducing methane emissions (30, 31).

Nitrous oxide emissions

Nitrous oxide emissions followed a different pattern. In season 1, the AWD method (M_2) showed an increase of approximately 26.89% in N_2O emissions compared to the Conventional method (M_1), while the MSRI method (M3) resulted in a similar rise of around 31.74%. In season 2, the AWD method (M2) observed an increase of 30.85% in N_2O emissions and the MSRI method (M3) recorded a rise of 37.43% compared to the Conventional method (M_1).

Emissions were highest in the MSRI method (M_3), particularly after nitrogen fertilizer applications. The well-aerated soils in MSRI systems promote nitrification and denitrification, which contribute to nitrous oxide emissions, mainly when nitrogen is applied in large amounts. Nitrogen management is critical in controlling nitrous oxide emissions in well-aerated systems like MSRI (26, 27). Our correlation and regression analyses revealed a strong positive relationship between nitrous oxide emissions and the MSRI method across both seasons.

In contrast, continuous flooding (M_1) had the lowest nitrous oxide emissions. This can be attributed to the predominantly anaerobic conditions under constant flooding, which inhibit the nitrification processes responsible for nitrous oxide production, as observed in recent studies (22, 26). While continuous flooding effectively suppresses nitrous oxide, it comes with the downside of higher methane emissions, presenting a clear trade-off in greenhouse gas mitigation.

Nitrogen management and emission reductions

In this study, nitrogen management was crucial in reducing nitrous oxide emissions. Applying neem-coated urea and foliar nano urea significantly reduced nitrogen losses and nitrous oxide emissions (28, 29). Neem-coated urea has been shown to slow nitrogen release, reduce leaching and volatilization and lower nitrous oxide emissions. Similarly, the slow-release nature of foliar nano-urea enhances nitrogen use efficiency (NUE) by providing a steady nitrogen supply during critical growth stages. Studies have further demonstrated that nano-urea improves NUE and crop yields while minimizing nitrogen losses (13, 30).

Grain yield and straw yield

The results indicated that grain yield was significantly increased under the MSRI method (M_3) along with 75% recommended nitrogen dose (RDN) and 0.4% foliar nano urea with 6029 kg/ha and 6018 kg/ha in seasons 1 and 2. The positive correlation between grain yield and MSRI reinforces its potential as an alternative to traditional methods for improving productivity while reducing water usage and greenhouse gas emissions. The results showed that grain yield increased significantly in MSRI, particularly when combined with improved nitrogen management practices. Moderate yields were recorded in AWD and lower yields were recorded in conventional. These results agree with previous research that reported that MSRI can increase rice yields by 10-15% compared to continuous flooding when optimized nitrogen management (27,34,35). Similarly, straw yields followed the same pattern, with the highest values recorded in MSRI combined with 75% RDN and 0.4% foliar nano urea treatments. As observed in other studies, improved water and nitrogen management in MSRI systems likely contributed to this increase (33, 30). These findings indicate that MSRI can promote overall biomass production, supporting the idea that these methods are both environmentally and economically sustainable.

Trend and regression analysis insights

The trend and regression analyses furnished further insights into the relationships between emissions and yield. Methane emissions resulted in an upward trend under continuous flooding, culminating during the reproductive stage, consistent with earlier research (33, 34). Both AWD and MSRI showed reduced methane emissions over time, with the regression lines reflecting the strong emission-reducing potential of these methods. On the other hand, nitrous oxide emissions increased after nitrogen fertilization, especially under the MSRI method. This was evident in both the trend and regression analyses, highlighting the role of well-aerated soils in promoting nitrous oxide production, as discussed by. These findings emphasize the need for carefully managed nitrogen applications in systems like AWD and MSRI to avoid excessive nitrous oxide emissions.

Combined season insights

The combined trend analysis for both seasons revealed consistent patterns. Methane emissions were closely tied to continuous flooding, with strong positive correlations between emissions and waterlogged conditions. Nitrous oxide emissions, conversely, were strongly linked to nitrogen fertilizer application in MSRI and AWD systems. These results highlight the complex trade-offs between methane and nitrous oxide emissions, as observed in previous studies (35). This investigation emphasizes the transformative potential of integrating precise water and nitrogen management strategies in rice cultivation, achieving a balance between maximizing productivity and minimizing greenhouse gas emissions. MSRI method has reduced methane emissions statistically; however, its effectiveness depends upon weighing nitrogen levels so as not to uplift the levels of emitted nitrogenous oxide. Slow-release fertilizers such as neem-coated urea and foliar nano urea help increase nitrogen use efficiency (37). Such an improvement in management requires a fundamental change in focus to combine AWD and MSRI with the GHG profile, maximizing precision N management. In particular, controlled irrigation of the proposed organic amendments and other appropriate measures may open new options for emission reductions and water efficiency enhancement (9).

Conclusion

The MSRI and AWD methods have been demonstrated to reduce methane emissions while maintaining high rice yields effectively, highlighting their potential for sustainable rice production. However, the higher nitrous oxide emissions observed with MSRI necessitate careful nitrogen management, such as applying slow-release fertilizers and nano-urea foliar treatments. Integrating these advanced nitrogen management practices with MSRI offers a promising pathway for enhancing productivity while mitigating environmental impacts. Further research into precision irrigation and incorporating organic amendments is warranted to refine these strategies and advance sustainable rice cultivation practices.

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Authors' contributions

AS experimented with observations and drafted the manuscript. NS guided the research by formulating the concept and approved the final manuscript. PS guided with research concept and formulating research parameters. KR was involved in the design and conceived the study. PJ and VR participated in the data analysis. All authors reviewed the results and endorsed the manuscript's final version.

Compliance with ethical standards

Conflict of interest: Authors declare no conflict of interest

Ethical issues: None

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