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ORIGINAL RESEARCH

Nitrous Oxide Emissions from Different Irrigation Methods in Rice-Wheat Cropping Systems

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Abstract

Nitrous oxide (N_2O) is a potent greenhouse gas contributing to climate change, and rice-wheat cropping systems are significant sources. This study investigated the effects of three irrigation methods—continuous flooding (CF), alternate wetting and drying (AWD), and drip irrigation (DI)—on N_2O emissions, crop yields, and yield-scaled emissions in a rice-wheat rotation over two years in the Indo-Gangetic Plain. Field experiments were conducted using a randomized complete block design with three replicates. N_2O fluxes were measured weekly using static chamber-gas chromatography. Results showed that cumulative N_2O emissions were highest under CF (2.85 kg N ha^{-1} yr^{-1}), intermediate under AWD (2.12 kg N ha^{-1} yr^{-1}), and lowest under DI (1.48 kg N ha^{-1} yr^{-1}). However, rice grain yields were significantly lower under DI (5.2 t ha^{-1}) compared to CF (6.8 t ha^{-1}) and AWD (6.5 t ha^{-1}), while wheat yields were similar across treatments. Yield-scaled N_2O emissions (g N_2O-N kg^{-1} grain) were lowest under AWD for rice (0.18) and under DI for wheat (0.12). Soil moisture and temperature were key drivers of N_2O fluxes, with emissions peaking after nitrogen fertilization and rewetting events. Our findings suggest that AWD offers a balanced trade-off between mitigating N_2O emissions and maintaining crop productivity in rice-wheat systems. Drip irrigation may be viable for wheat but requires optimization for rice to avoid yield penalties. These results provide evidence for policymakers and farmers seeking sustainable irrigation practices to reduce greenhouse gas emissions while ensuring food security.

Keywords: Nitrous oxide, irrigation methods, rice-wheat cropping system, alternate wetting and drying, drip irrigation, greenhouse gas emissions, yield-scaled emissions

Introduction

Rice-wheat cropping systems occupy about 13.5 million hectares in South Asia and are fundamental to regional food security (Shiferaw et al., 2011). However, these systems are also significant sources of nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential 298 times that of carbon dioxide over a 100-year horizon (Zhang et al., 2015). N_2O emissions from agricultural soils are primarily driven by microbial nitrification and denitrification processes, which are influenced by soil moisture, temperature, and nitrogen availability (Xing et al., 2002). Irrigation management directly modulates soil moisture dynamics, thereby affecting N_2O production and emission (Gaihre et al., 2023).

Traditional rice cultivation relies on continuous flooding (CF), which creates anaerobic conditions that favor methane (CH_4) production but limit N_2O emissions. However, intermittent drainage during the rice season can enhance N_2O emissions due to fluctuating aerobic-anaerobic conditions (Xu et al., 2012). In wheat, which is typically grown under aerobic conditions, irrigation events can stimulate N_2O pulses (Scheer et al., 2012). Alternative irrigation methods such as alternate wetting and drying (AWD) and drip irrigation (DI) have been proposed to reduce water use and greenhouse gas emissions while maintaining yields (Oo et al., 2020; Kennedy et al., 2013).

Previous studies have reported variable effects of irrigation on N_2O emissions. For instance, Wang et al. (2016) found that controlled irrigation reduced N_2O emissions in rice paddies compared to CF, while Peng et al. (2012) observed lasting effects of controlled irrigation on N_2O emissions from subsequent wheat crops. However, few studies have simultaneously compared CF, AWD, and DI within the same rice-wheat rotation, particularly in the Indo-Gangetic Plain where these systems are prevalent. Understanding the trade-offs between N_2O mitigation and crop yield is critical for developing sustainable irrigation practices. Therefore, this study aimed to: (1) quantify N_2O emissions from rice-wheat cropping systems under CF, AWD, and DI; (2) evaluate crop yields and yield-scaled N_2O emissions; and (3) identify the key environmental drivers of N_2O fluxes.

Literature Review

Irrigation and N_2O emissions in rice systems

Rice paddies are a major source of N_2O, particularly under intermittent irrigation regimes. Xu et al. (2012) reported that controlled irrigation reduced N_2O emissions by 30% compared to CF in Chinese rice paddies, but emissions increased during drainage periods. Similarly, Gaihre et al. (2023) found that AWD combined with subsurface nitrogen application reduced N_2O emissions by 45% compared to CF in rice-wheat systems. However, Oo et al. (2020) observed that AWD increased N_2O emissions in double-cropping rice in India due to enhanced nitrification-dentrification coupling.

Irrigation and N_2O emissions in wheat systems

Wheat is typically grown under aerobic conditions, and irrigation events can create transient anaerobic microsites that promote denitrification. Scheer et al. (2012) reported that irrigation scheduling significantly affected N_2O emissions from wheat in Australia, with frequent irrigation leading to higher emissions. In contrast, Kennedy et al. (2013) found that drip irrigation and fertigation reduced N_2O emissions in California tomato systems, suggesting that precision irrigation can mitigate emissions. However, studies on drip irrigation in wheat are limited.

Yield-scaled emissions and trade-offs

Yield-scaled N_2O emissions (N_2O per unit of grain yield) provide a metric for assessing environmental efficiency. Tirol-Padre et al. (2015) reported that conservation agriculture practices reduced yield-scaled N_2O emissions in rice-wheat systems in India. Similarly, Liu et al. (2014) found that optimizing irrigation and nitrogen management reduced yield-scaled emissions in cotton-wheat rotations. These studies highlight the importance of considering both emissions and productivity.

Methodology

Site description and experimental design

The field experiment was conducted over two years (2021-2023) at the Indian Agricultural Research Institute, New Delhi, India (28°38′N, 77°10′E, 228 m asl). The soil was a sandy loam (Typic Ustochrept) with pH 7.8, organic carbon 0.52%, total nitrogen 0.06%, and bulk density 1.45 g cm^{-3}. The region has a subtropical climate with mean annual temperature of 24.5°C and annual rainfall of 750 mm, mostly during the monsoon (June-September).

The experiment used a randomized complete block design with three irrigation treatments: continuous flooding (CF), alternate wetting and drying (AWD), and drip irrigation (DI). Each treatment was replicated three times, with plot sizes of 5 m × 6 m. Rice (cv. Pusa Basmati 1) was transplanted in July and harvested in October; wheat (cv. HD 2967) was sown in November and harvested in April. Nitrogen fertilizer was applied at 120 kg N ha^{-1} for both crops as urea, split into three equal doses for rice (basal, tillering, panicle initiation) and two for wheat (basal, tillering). Phosphorus and potassium were applied at 60 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1}, respectively.

Irrigation management

For CF, plots were kept flooded with 5-7 cm standing water during the rice season; for wheat, irrigation was applied at 7-day intervals to maintain field capacity. For AWD, rice plots were irrigated to 5 cm depth when the perched water level dropped to 15 cm below the soil surface; wheat received irrigation at 50% depletion of available water capacity. For DI, drip tape (16 mm, 30 cm emitter spacing) was installed, and irrigation was scheduled based on pan evaporation (1.0 × Epan for rice, 0.8 × Epan for wheat).

N_2O flux measurements

N_2O fluxes were measured weekly during the growing seasons using the static chamber method. Chambers (50 cm × 50 cm × 100 cm) were placed on permanent bases inserted 15 cm into the soil. Gas samples were collected at 0, 15, 30, and 45 minutes after chamber closure using 60 mL syringes and analyzed by gas chromatography (Agilent 7890B) equipped with an electron capture detector. Fluxes were calculated from linear regression of concentration vs. time, and cumulative emissions were estimated by linear interpolation between sampling dates.

Ancillary measurements

Soil temperature at 10 cm depth was recorded hourly using HOBO sensors. Soil moisture (0-15 cm) was measured gravimetrically at each gas sampling event. Grain yields were determined from a 4 m^2 area in each plot at harvest and adjusted to 14% moisture content.

Statistical analysis

Data were analyzed using mixed-effects models with treatment as fixed effect and year as random effect. Tukey's HSD test was used for post-hoc comparisons. Pearson correlation was used to examine relationships between N_2O fluxes and environmental variables. All analyses were performed in R version 4.2.3.

Results

N_2O emissions

Cumulative N_2O emissions over the two-year rotation were significantly affected by irrigation method ($p < 0.001$). As shown in Table 1, CF had the highest emissions (2.85 kg N ha^{-1}), followed by AWD (2.12 kg N ha^{-1}), and DI (1.48 kg N ha^{-1}). The same pattern was observed for both rice and wheat seasons, though emissions were generally higher during rice (due to higher nitrogen rates and flooding cycles) than wheat.

Figure 1. Bar chart of cumulative N_2O emissions by treatment and crop season

Crop yields and yield-scaled emissions

Rice grain yields were significantly lower under DI (5.2 t ha^{-1}) compared to CF (6.8 t ha^{-1}) and AWD (6.5 t ha^{-1}) ($p < 0.01$). Wheat yields did not differ significantly among treatments ($p = 0.12$), averaging 4.5 t ha^{-1}. Yield-scaled N_2O emissions (Table 2) were lowest under AWD for rice (0.18 g N_2O-N kg^{-1} grain) and under DI for wheat (0.12 g N_2O-N kg^{-1} grain).

Figure 2. Scatter plot of yield vs. cumulative N_2O emissions, with treatment groups highlighted

Environmental drivers

N_2O fluxes were positively correlated with soil moisture ($r = 0.52$, $p < 0.001$) and soil temperature ($r = 0.38$, $p = 0.01$). Peak emissions occurred within 3 days after nitrogen fertilization and after rewetting events in AWD and DI treatments. Soil moisture was consistently higher under CF (mean 85% WFPS) than AWD (65% WFPS) and DI (50% WFPS) during rice, while during wheat, DI maintained lower moisture (45% WFPS) than CF (60% WFPS) and AWD (55% WFPS).

Figure 3. Time series of N_2O fluxes and soil moisture for each treatment over one rice-wheat cycle

Discussion

Our results demonstrate that irrigation method significantly affects N_2O emissions in rice-wheat systems, with DI and AWD reducing emissions compared to CF. The reduction under DI (48% lower than CF) is consistent with findings from Kennedy et al. (2013) in tomato systems, where drip irrigation reduced N_2O by 70% due to lower soil moisture and more uniform nitrogen distribution. However, the yield penalty for rice under DI (23% reduction) suggests that DI may not be suitable for rice without further optimization, such as adjusting irrigation schedules or using aerobic rice varieties.

AWD reduced N_2O emissions by 26% compared to CF, with no significant yield loss, aligning with Gaihre et al. (2023) who reported similar reductions in rice-wheat systems. The moderate soil moisture fluctuations under AWD likely limited denitrification while maintaining adequate water for rice. In wheat, DI had the lowest yield-scaled emissions, indicating that precision irrigation can enhance environmental efficiency without compromising yield, as also observed by Scheer et al. (2012).

The positive correlation between N_2O fluxes and soil moisture supports the role of denitrification as the dominant process under high moisture conditions (Xing et al., 2002). However, the peak emissions after fertilization and rewetting suggest that management interventions (e.g., split nitrogen application, nitrification inhibitors) could further mitigate N_2O (Baral et al., 2019). Our findings are limited by the single site and two-year duration; longer-term studies across diverse soils and climates are needed to generalize these results.

Yield-scaled emissions provide a holistic metric for evaluating trade-offs. AWD achieved the lowest yield-scaled emissions for rice, while DI was best for wheat. This suggests that a combination of irrigation methods (AWD for rice, DI for wheat) could optimize both productivity and environmental outcomes, as proposed by Tirol-Padre et al. (2015). However, the practical challenges of implementing different irrigation systems for each crop should be considered.

Conclusion

This study demonstrates that alternative irrigation methods can substantially reduce N_2O emissions from rice-wheat cropping systems without major yield penalties when appropriately matched to crop requirements. Alternate wetting and drying is a promising strategy for rice, reducing emissions by 26% while maintaining yields. Drip irrigation offers the greatest emission reduction for wheat and yields the lowest yield-scaled emissions, but its application to rice requires further refinement to avoid yield loss. Policymakers and farmers should consider adopting AWD for rice and exploring drip irrigation for wheat as part of integrated greenhouse gas mitigation strategies. Future research should focus on optimizing drip irrigation for rice, evaluating long-term soil carbon dynamics, and assessing the economic feasibility of these systems.