https://doi.org/10.17221/402/2025-PSE

Japonica-type *Indica-Japonica* hybrid rice increases yield with reduced CH_4 and N_2O emissions

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Citation: Mo X.R., Xu C.X., Wang Y.R., Fang F.P., Feng J.F., Wang H.H., Li F.B. (2026): *Japonica*-type *Indica-Japonica* hybrid rice increases yield with reduced CH_4 and N_2O emissions. Plant Soil Environ., 72: 138–145.

Abstract: Rice paddy fields serve as an important source of stable food supply and a notable contributor to atmospheric methane (CH_4) and nitrous oxide (N_2O). Rice cultivar selection acts as a pivotal factor in regulating greenhouse gas (GHGs) of CH_4 and N_2O emissions from rice paddy fields. However, little is known about how different types of rice cultivars affect CH_4 and N_2O emissions. In the study, three types of rice cultivars, including *Japonica*-type *Indica-Japonica* hybrid rice (JHR: ZJY1578 and JHY5), *Indica*-type hybrid rice (IHR: ZZY8 and JFY2), and inbred rice (IR: J67 and XS121), were selected to evaluate differences in mitigating GHGs. Results showed that the total CH_4 and N_2O emissions of two *Japonica*-type *Indica-Japonica* hybrid rice cultivars were 49.81–60.01 kg/ha and 0.67–0.83 g/ha, respectively, which were lower than those of the other two rice cultivar types. The total equivalent of carbon dioxide emissions of CH_4 and N_2O (TCO_2-eq) of two *Japonica* hybrid rice significantly reduced by 16.7–46.9%, compared with the other two types of rice cultivars (IHR and IR). CH_4 contributed 85.5–89.9% to the GWP, while 65.6–80.4% in the field of planting inbred rice. The reduction in GHGs emissions is mainly attributed to yield, available carbon and nitrogen contents, root morphological characteristics, and functional genes. Consequently, GHGs emissions in paddy fields could be mitigated by selecting or breeding cultivars with high yield, lower root exudates, and greater root porosity.

Keywords: climate change; high-yielding rice; environmental impact; genotype selection; root morphological traits

Rice is the most crucial grain crop, with over 60% of the Chinese population relying on it as their staple. Improving rice yield is therefore pivotal to ensuring national food security. Meanwhile, rice paddies also serve as a significant source of biogenic CH_4 and N_2O emissions (Qian et al. 2023). They contribute about 22% and 11% of total agricultural CH_4 and N_2O emissions, respectively (IPCC 2021, EPA 2022). Rice paddies are recognised as a net source of greenhouse gas emissions due to their elevated CH_4 emissions compared to other major cereal crops (Jiang et al. 2017). Overall, reducing GHGs emissions from rice paddies is critical to climate change mitigation and ensuring sustainable national food security in China.

Agricultural management strategies and policies have an pivotal role in mitigating GHGs emissions from rice paddies, encompassing measures such as rice cultivar selection (Qian et al. 2023, Chen et al. 2024), modification of flooding regimes, optimisation of nitrogen fertiliser application, adjustment of tillage and cropping practice, soil amendments (Qian et al. 2023), straw management (Cao et al. 2021, Chen et

Supported by the Science and Technology Plan Projects of Quzhou, Project No. 2023K079, 2023; by the Natural Science Foundation of China, Project No. 42177455, 2022; by the "Pioneer" and "Leading Goose" R&D Program of Zhejiang, Project No. 2022C02058, 2022; Central Public-Interest Scientific Institution Basal Research Fund, Project No. CPSIBRF-CNRRI-202408, and by the Agricultural Science and Technology Innovation Program (ASTIP).

https://doi.org/10.17221/402/2025-PSE

al. 2024) and supportive subsidy policy (Maccarone and Santeramo 2026). Among these mitigating approaches, however, one significant challenge persists: without supportive government policies and incentives, farmers face considerable difficulty in altering deeply ingrained cultural practices – ranging from cropping systems and fertilisation methods to residue management and irrigation regimes. Notably, harnessing rice varietal differences in GHGs emissions has emerged as an increasingly recognised cost-effective strategy (Chen et al. 2024). This approach requires minimal adjustments to existing farming practices and incurs no additional costs compared to many other mitigation measures, making it particularly feasible for widespread adoption.

Rice cultivars primarily regulate GHGs emissions through a spectrum of plant traits, including root exudates and rhizosphere microbial community, root system architecture and aerenchyma, plant biomass production and allocation, nitrogen use efficiency, and residue decomposition rates (Qian et al. 2023, Guan et al. 2024, Qi et al. 2024). Disparities in these traits across rice cultivars can alter the availability of carbon (C) and nitrogen (N) substrates, modify rhizospheric oxygen levels, influence plant-mediated CH_4 transport, and ultimately affect CH_4 emissions in paddy fields. Additionally, rice cultivars may modulate N_2O emissions by changing soil nitrogen availability, photosynthate distribution, root exudation, rhizosphere oxygen availability, and microbial communities (Jiang et al. 2016, Chang et al. 2025). Collectively, differences among rice cultivars play a critical role in regulating the GHGs emissions throughout the rice cultivation cycle.

China grows numerous high-yielding rice cultivars. And the new rice cultivars approved each year are showing a trend of rapid growth (Xu et al. 2022). In 2024, there were 1 571 rice cultivars approved at or above the provincial level in China, including 505 conventional *Japonica* rice, 868 *Indica* hybrid rice, and 12 *Indica-Japonica* hybrid rice (CRDC). Among these, *Japonica-Indica* hybrid rice, renowned for its high-yield potential, has garnered substantial research attention in recent years (Xu et al. 2020). Although prior studies have compared CH_4 and N_2O emissions between hybrid and inbred rice, as well as across different management practices (Zheng et al. 2013, Soremi et al. 2023), limited focus has been placed on the impacts and underlying mechanisms of distinct rice cultivar types on greenhouse gas emissions, particularly for *Indica-Japonica* hybrid rice.

This study aims to address this gap by evaluating the effect of three representative cultivars (*Japonica*-type *Indica-Japonica* hybrid rice (JHR), *Indica*-type hybrid rice (IHR), and *Japonica*-type inbred rice (IR)) on: (1) CH_4 and N_2O emissions fluxes in paddy fields; (2) key factors driving these emissions, and (3) TCO_2-eq of CH_4 and N_2O per unit yield and area across these cultivar types.

MATERIAL AND METHODS

Site description. A field-scale experiment was conducted in a rice paddy field (30.03°N, 120.12°E) located in Hangzhou, Zhejiang province, China, from May to September 2023. The experimental site experiences a subtropical monsoon climate, with a mean annual temperature of 17.2 °C and annual precipitation of 1 528.8 mm. The soil exhibited the following properties: total nitrogen (TN) of 1.02 g/kg, ammonia nitrogen (NH_4^+-N) of 3.34 mg/kg, nitrate nitrogen (NO_3^--N) of 310.74 mg/kg, total phosphorus (TP) of 2.49 g/kg, and organic carbon content of 29.21 g/kg.

Experimental design. Six rice cultivars of three types were selected: two JHR cultivars (ZJY1578 and JHY5), two IHR cultivars (ZZY8 and JFY2), and two IR cultivars (J67 and XS121). These three types correspond to distinct categories: the JHR cultivars are super-high-yield inter-subspecific hybrids with *Japonica* traits, the IHR cultivars are high-yield hybrid rice, and the IR cultivars are stable, high-quality pure *Japonica* rice. Each cultivar was replicated three times across 18 experimental plots (3 m × 3 m). The rice was transplanted on 7 June 2023 at a spacing of 16 cm × 25 cm. The N, phosphorus (P) and potassium (K) application rates were 220, 34.93 and 124.47 kg/ha, respectively. Of these, P and K were applied as basal fertiliser before transplanting. For N fertiliser applications were split into three stages – pre-transplanting (110 kg/ha), early tillering (66 kg/ha), and panicle initiation (44 kg/ha). Alternate wetting and drying irrigation was implemented during the experiment.

Sampling and measurement. The gas samples were collected using static-chamber methods, with detailed procedures described in Yang et al. (2023). Samples were collected weekly. Intensive sampling was performed on days 1, 3, 5, and 7 following field drying and fertilisation events, after which regular weekly sampling resumed. Concentrations of CH_4 and N_2O were determined by gas chromatography (GC2010, Shimadzu, Kyoto, Japan). CH_4 and N_2O

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fluxes calculations followed the methodology outlined by Yang et al. (2023).

Soil samples were collected monthly after rice planting from each plot at a 0–10 cm depth, with five points per plot. The collected soil was divided into two portions. One portion was immediately stored at 4 °C for the determination of NH_4^+-N, NO_3^--N, and nitrite N (NO_2^--N), dissolved organic matter (DOC), microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN). The other portion was frozen at –80 °C to analyse the abundance of functional genes involved in GHG emissions (*mcrA*, *pmoA*, *AOA*, *AOB*, *nirS*, *nirK*, and *nosZ*). The contents of available N and C were determined by standard methods (SSSC 1999). For microbial functional gene abundance, quantitative real-time PCR (qPCR) was performed using a Bio-Rad CFX96 system (Bio-Rad Laboratories, Hercules, USA).

Root segments, excised 15–20 mm proximal to the root tip using a razor blade, were sampled at the middle growth stage and visualised under a scanning electron microscope (S-3400 N, Hitachi, Japan). Aerenchymatic pore area was quantified using ImageJ software (Bethesda, USA), and the proportion of aerenchyma was determined as the ratio of pore space area to the total cross-sectional area of the root.

Data analysis. The total equivalent of carbon dioxide emissions of CH_4 and N_2O (TCO_2-eq, kg CO_2-eq/ha) and GHGs intensity (GHGI, kg CO_2-eq/kg) were calculated by the formulas:

$$TCO_2\text{-eq} = CH_4\ (\text{kg } CH_4/\text{ha}) \times 27 + N_2O\ (\text{kg } N_2O/\text{ha}) \times 273 \quad (1)$$

$$GHGI = TCO_2\text{-eq/yield (kg/ha)} \quad (2)$$

The numbers 27 and 273 (IPCC 2021) are the conversion factors for CH_4 and N_2O to CO_2 in Eq. (1), respectively.

A one-way analysis of variance was employed to analyse the effect of rice cultivars. The Tukey's *HSD* (honestly significant difference) test was used to compare the mean differences among treatments. All analyses were conducted using R (Auckland, New Zealand).

RESULTS

CH_4 and N_2O emissions. The seasonal dynamics of CH_4 and N_2O emissions across different cultivar types showed two and one peaks, respectively (Figure 1).

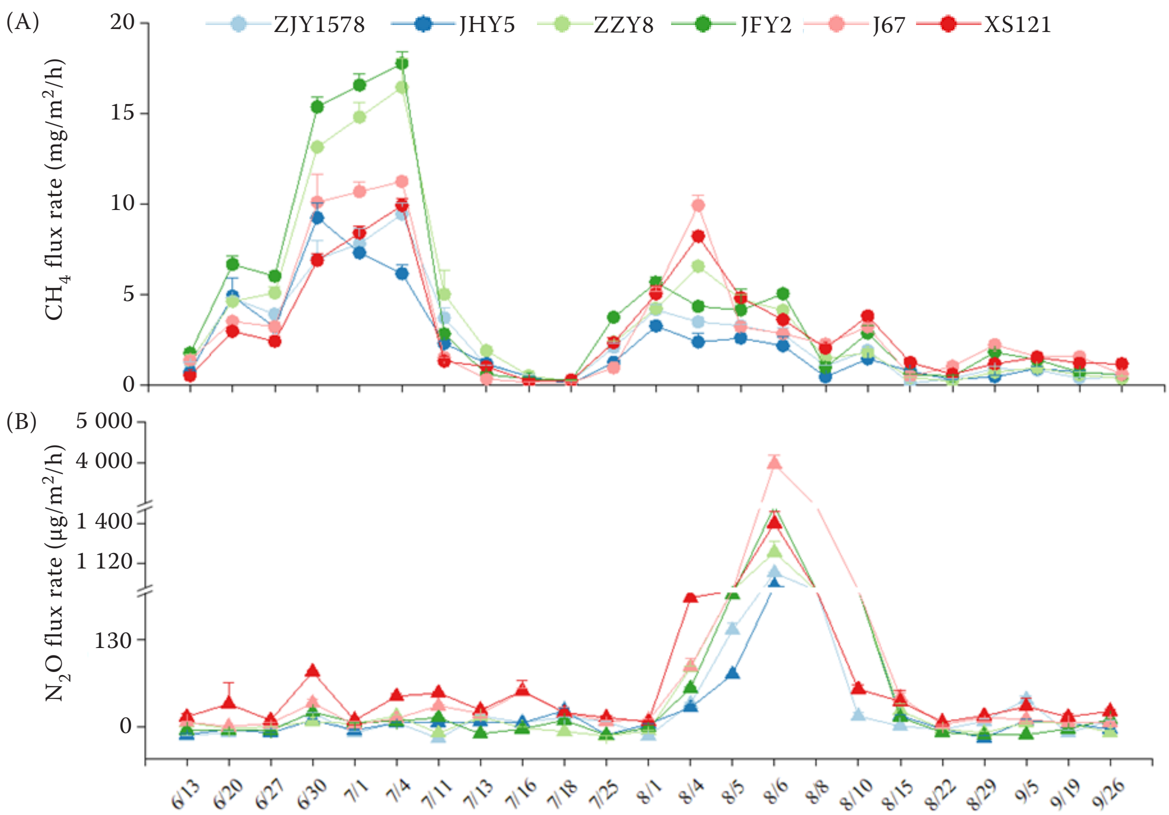

Figure 1. CH_4 and N_2O fluxes of different rice cultivars

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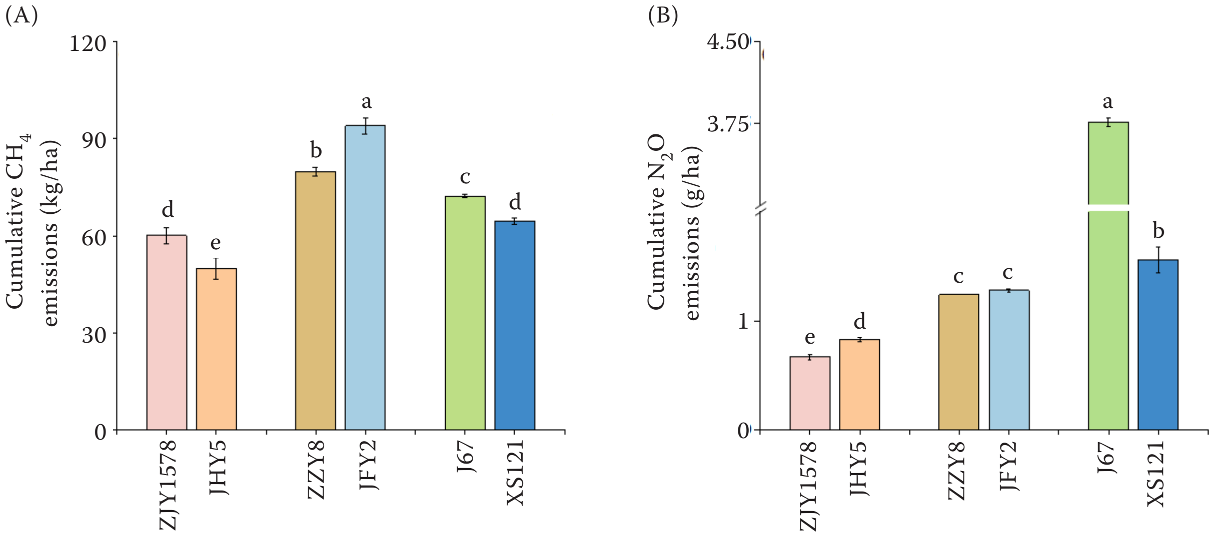

Figure 2. (A) Cumulative CH_4 and (B) N_2O emissions of different rice cultivars. Different lowercase letters denote differences between rice cultivars (P < 0.05)

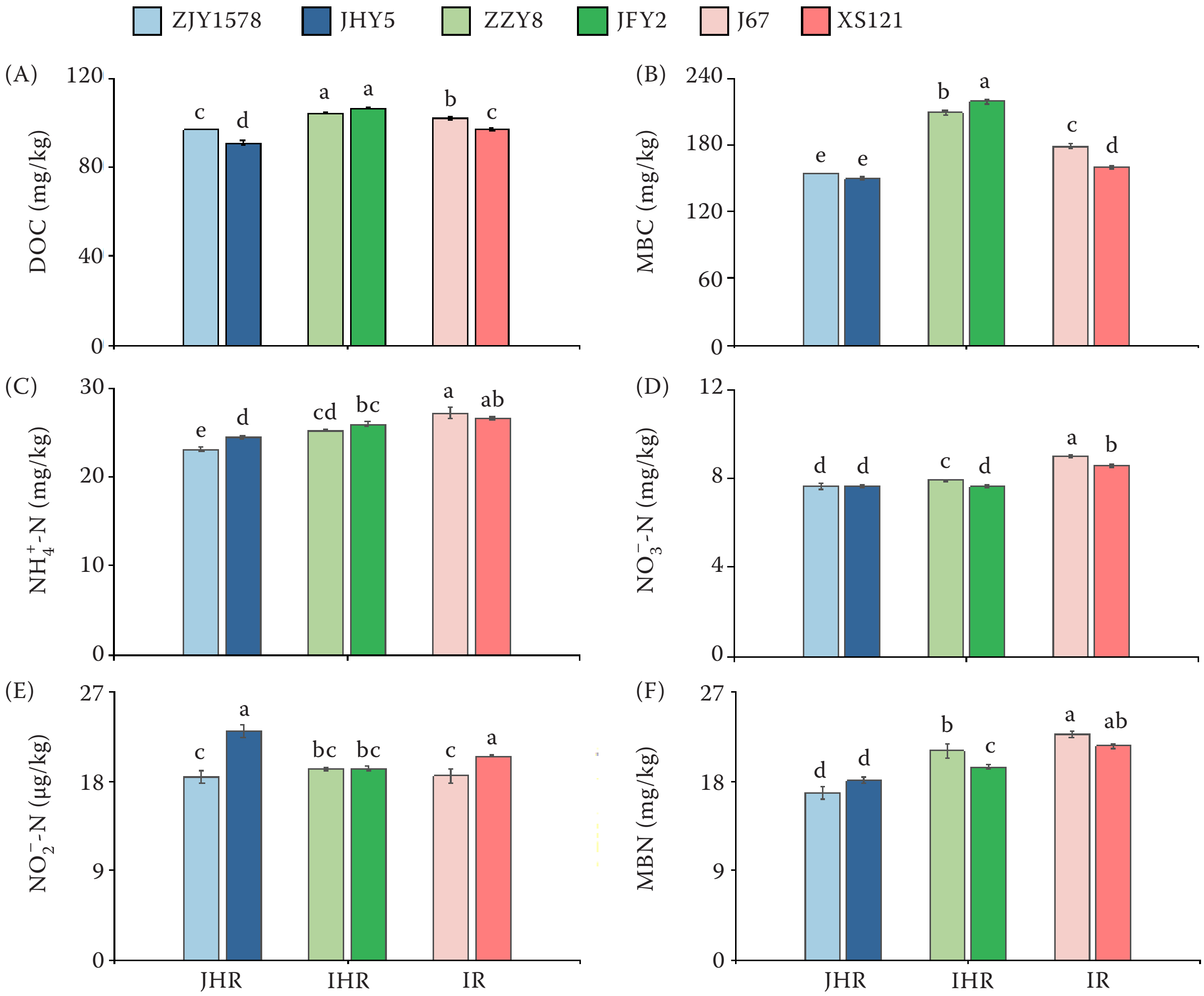

Figure 3. Chemical parameters in the soil of different rice cultivars. This is the mean value calculated from eight samplings and measurements. DOC – dissolved organic matter; MBC – microbial biomass carbon; MBN – microbial biomass nitrogen. Different lowercase letters denote differences between rice cultivars (P < 0.05)

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Cumulative CH_4 emissions across the three cultivar types showed a significant decreasing order of IHR (79.80–93.99 kg/ha) > IR (64.42–72.22 kg/ha) > JHR (49.81–60.01 kg/ha), with significant intra-type variations (Figure 2A). Cumulative N_2O emissions also followed a significant decreasing trend, with the order of IR (1.56–3.76 g/ha) > IHR (1.24–1.28 g/ha) > JHR (0.67–0.83 g/ha) (Figure 2B). Significant differences were observed between the two varieties within the JHR and IR group.

Available carbon and nitrogen contents in soil. Soil DOC content under IHR was significantly higher than that under other cultivar types. Significant intra-type variations in DOC content were also observed within both IR and JHR groups between the two varieties (Figure 3A). For MBC content, significant differences were detected across cultivar types, following the order: IHR > IR > JHR (Figure 3B). Rice cultivars also influenced soil available N content (Figure 3C–F). Under IR, soil NH_4^+-N, NO_3^--N, and MBN contents were significantly higher than those under other cultivar types, except for NH_4^+-N in JFY2 and MBN in ZZY8, which showed no significant differences. For NO_2^--N contents, JHY5 exhibited 12.1–25.1% higher than other evaluated rice cultivars.

Functional genes involved in CH_4 and N_2O emissions in soil. Rice cultivars significantly affected soil functional gene abundances (*mcrA*, *pmoA*, *mcrA*/*pmoA* ratio) and nitrification-denitrification genes (Figure 4A–C). *mcrA* was higher under XS121, ZZY8, JFY2; *pmoA* was elevated under XS121. *mcrA*/*pmoA* ratios were lower in ZJY1578, JHY5, and XS121. For nitrification-denitrification, IR cultivars showed higher *nirS* but lower *nosZ* than other types, with (*nirS* + *nirK*)/*nosZ* ratios significantly elevated in IR. No significant differences were observed in *AOA*/*AOB* abundances across cultivars (Figure 4C–I).

Morphological traits of rice roots. The area of transverse section of the six rice cultivars followed the order: JHY5 > JFY2 > ZZY8 > XS121 > ZJY1578 > J67 (Figure 5A). A comparable trend was observed for aerenchyma areas in their transverse sections, with minor deviations noted for JHY5 and JFY2 (Figure 5B). Notably, the two IHR exhibited a significantly higher ratio of aerenchym area to total transverse area compared to both the two JHR cultivars and XS121 (Figure 5C).

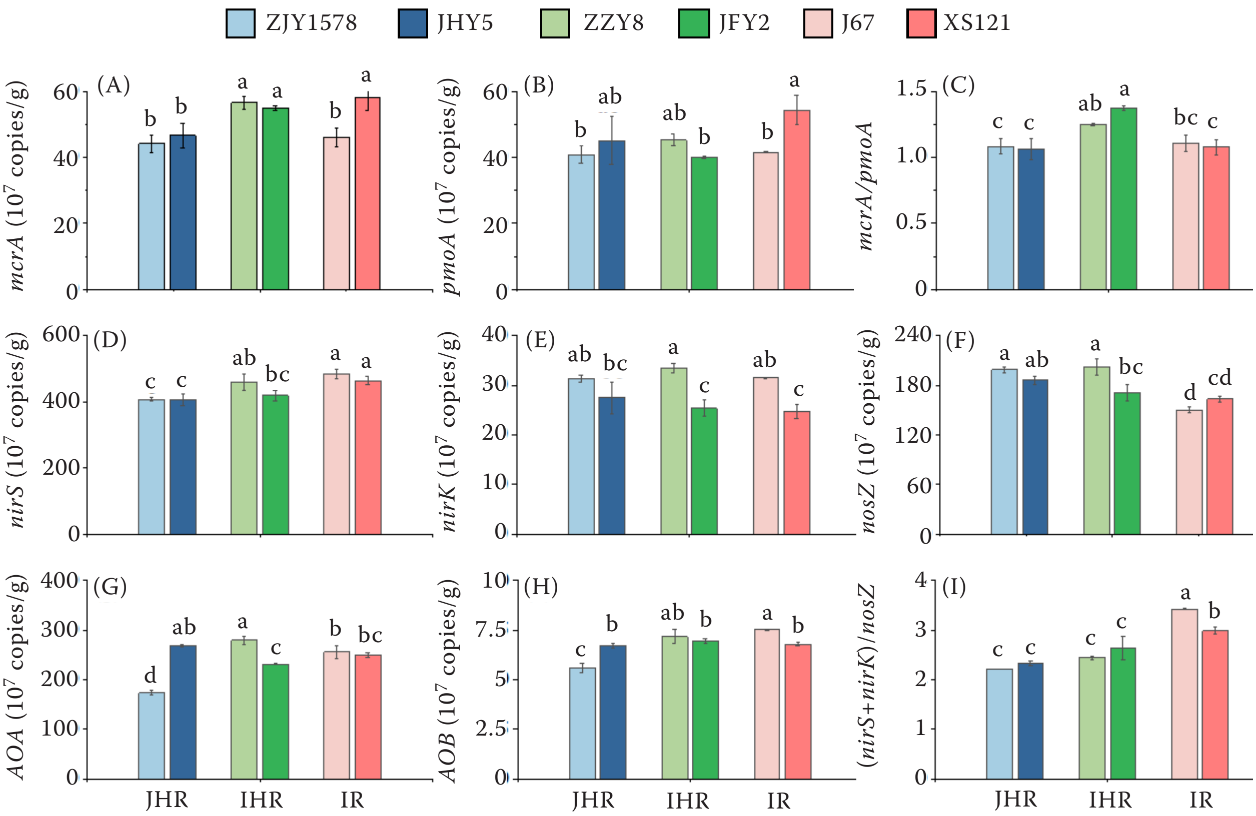

Figure 4. Function genes abundance in the soil of different rice cultivars. Different lowercase letters denote differences between rice cultivars ($P < 0.05$)

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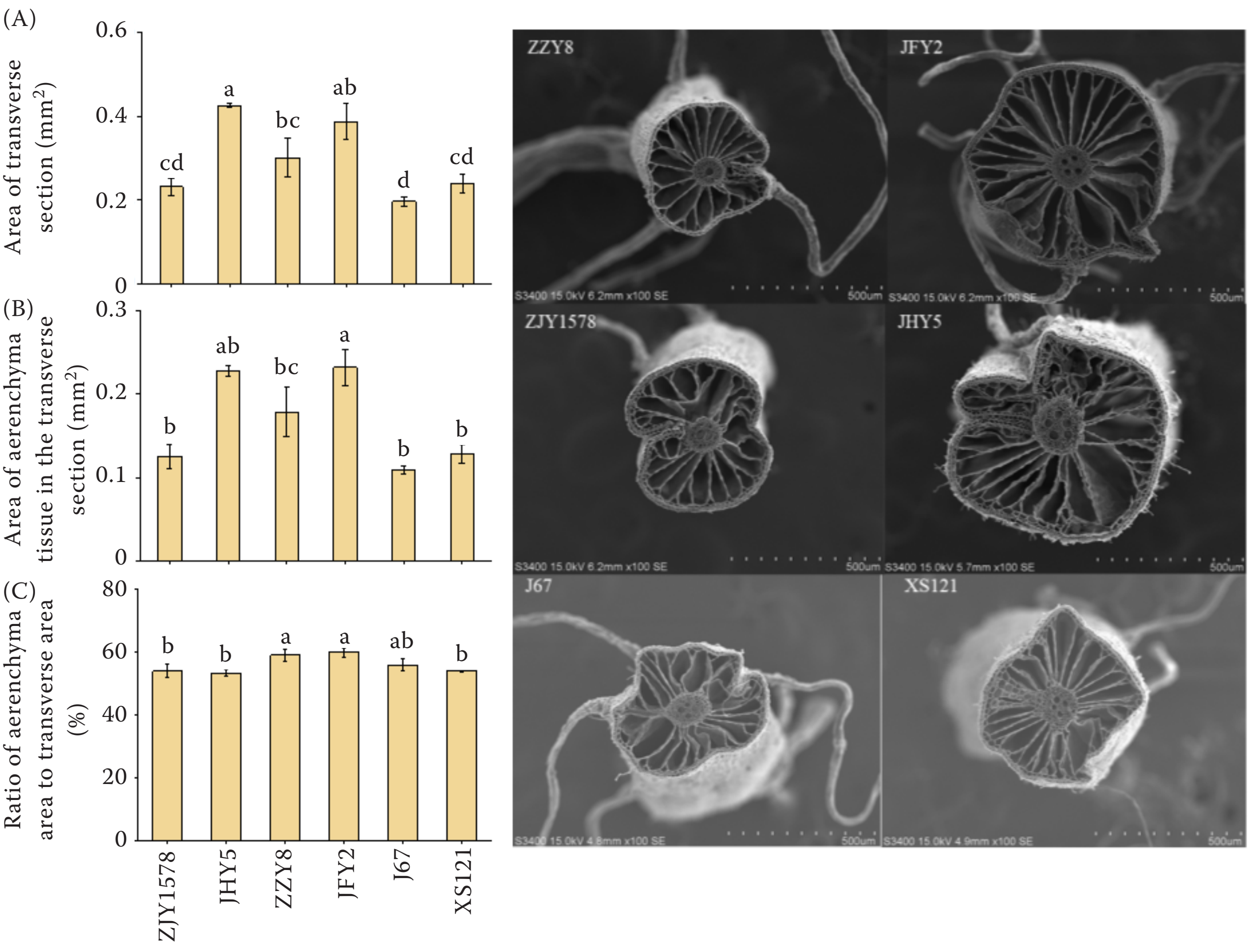

Figure 5. Root morphological traits of different rice cultivars. Different lowercase letters denote differences between rice cultivars (P < 0.05)

Rice yield, TCO_2-eq, and GHGI. The yields of the six rice cultivars varied significantly: the yields of two JHR were higher than those of the one IHR (JFY2) and two IR cultivars (Table 1). The TCO_2-eq of CH_4 and N_2O was significantly lower for the two JHR compared to the other cultivar types. CH_4 contributes 85.5–89.9% of total TCO_2-eq in hybrid fields, whereas 65.6–80.4% in inbred rice fields. Furthermore, the GHGI of two JHR cultivars was significantly lower than that of other cultivars.

DISCUSSION

Different rice cultivars showed significant variability, which, in turn, influenced CH_4 emissions and grain yields. In this study, we observed that cumu-

Table1. Yields and TCO_2-eq of different rice cultivars

Type	Cultivar	Rice yields (kg/ha)	TCO_2-eq (kg CO_2-eq/ha)	Contribution of CH_4 to the TCO_2-eq (%)	Contribution of N_2O to the TCO_2-eq (%)	GHGI (kg/kg)
Japonica hybrid rice	ZJY1578	14 889.83^{a}	1 802.54^{d}	89.87^{a}	10.13^{e}	0.12^{d}
	JHY5	14 640.81^{ab}	1 571.77^{e}	85.46^{c}	14.54^{c}	0.11^{d}
Indica hybrid rice	ZZY8	13 896.04^{b}	2 493.90^{b}	86.39^{bc}	13.61^{cd}	0.18^{c}
	JFY2	11 596.41^{c}	2 886.68^{a}	87.89^{ab}	12.11^{de}	0.25^{b}
Inbred rice	J67	9 347.31^{d}	2 959.94^{a}	65.56^{d}	34.44^{a}	0.32^{a}
	XS121	6 660.33^{e}	2 164.57^{c}	80.38^{c}	19.62^{b}	0.33^{a}

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lative CH_4 emissions from JHR were notably lower than those from IHR and IR. This difference likely resulted from several factors. First, JHR achieved yields 7.2–123.6% higher than others (Table 1). The greater grain yield led to a larger allocation of photosynthate to grain development, thereby reducing root exudate release into the rhizosphere and diminishing substrate availability for methanogens (Qian et al. 2023). Additionally, the DOC and MBC contents in soil under JHR cultivation were 0.3–14.7% and 3.3–31.7% lower than those under other rice cultivars, respectively (Figure 3A, B), further restricting carbon supply to methanogenic communities. Furthermore, CH_4 are influenced by rhizospheric oxidation and rice-mediated transport to the atmosphere (Jia et al. 2001). The lower ratio of aerenchym area to transverse area from JHR (53.47–54.14%) may lead to shorter rice plant-mediated transport from soil to atmosphere (Figure 5C). Moreover, the *mcrA*-to-*pmoA* ratio in soil under JHR was 1.6–22.8% lower than in other rice cultivars, suggesting enhanced CH_4 oxidation capacity in *Japonica* hybrid systems, which may partially explain their reduced CH_4 emissions.

Rice cultivars may influence N_2O emissions by changes in N cycling, rhizosphere, root exudation, and soil microbes (Baruah et al. 2010, Jiang et al. 2016). In this study, cumulative N_2O emissions in hybrid rice fields were consistently lower than those in IR fields during the growing period (Figure 2b). This aligns with the findings of Sun et al. (2015), who reported that hybrid rice cultivars emitted less N_2O than conventional rice cultivars. Several mechanisms may account for this decrease in N_2O emissions for hybrid rice. Firstly, rice cultivars with higher yields may enhance N use efficiency, thereby reducing soil plant-available N (NH_4^+-N and NO_3^--N). Lower available N limits the substrate pool for N_2O-producing microbial processes. In our study, the superior yield performance (11 596.41–14 889.83 kg/ha) and reduced available N contents (7.62–7.92 mg/kg for NO_3^--N and 23.06–25.93 mg/kg for NH_4^+-N) in hybrid rice likely contributed to their lower N_2O emissions (Table 1, Figure 3C, D). Secondly, rice plants modulate denitrification through root exudates and aerenchyma-mediated gas transport, thereby shaping the rhizospheric environment (Abalos et al. 2014, Jiang et al. 2016). Under hypoxic conditions, rice supplies C substrate (e.g., sugars, organic acids) that serve as energy sources for denitrifying bacteria. High-yielding cultivars, however, may allocate more photosynthates to grain development rather than root exudation, reducing rhizospheric microbial activity and subsequent N_2O production (Jiang et al. 2016). In this study, hybrid rice yields were 19.39–55.27% higher than those of IR. Thirdly, rice plants influence soil microbial communities, thereby regulating N_2O dynamics. Varieties harbouring microbial communities with lower abundances of denitrification genes may exhibit higher N_2O emissions due to reduced microbial capacity for N_2O reduction (Chang et al. 2025). In our study, the abundance of *nosZ* genes in the two IR soils was 4.42–25.48% lower than that in hybrid rice soils (Figure 4F), providing a microbial mechanism for the elevated N_2O emissions observed in IR systems.

The TCO_2-eq of two JHR cultivars (ZJY1578 and JHY5) was 1 802.5 and 1 571.8 kg CO_2-eq/ha, respectively, and was significantly lower than that of the JHR and IR cultivars. This difference was likely attributed to their lower CH_4 and N_2O emissions per unit area (Figures 1 and 2). Notably, among the two IHR treatments, ZZY8 and JFY2 exhibited lower TCO_2-eq than J67 but higher than XS121. This pattern could be explained by the notably higher N_2O emissions from J67, whose N_2O contribution to TCO_2-eq reached 34.4%-significantly exceeding that of other cultivars (Table 1). In contrast, the GHGI of hybrid rice was significantly lower than that of inbred rice (Table 1). This result was consistent with Simmonds et al. (2015), who reported that hybrid at Arkansas sites achieved the highest yield and lower TCO_2-eq and GHGI than inbred cultivars. Consistently, our study observed that the GHGI of two JHR cultivars was reduced by 33.3–56.0% to IHR cultivars. Similar results were reported by Zheng et al. (2013), who noted that GHGI in *Indica* rice varieties was significantly higher than in *Japonica* rice varieties. It should be noted that this study assessed CH_4 and N_2O dynamics in only two cultivars per type. Genotypic variability and interactions with management practices may also influence CH_4 and N_2O emissions (Zhang et al. 2024, Chang et al. 2025). Further research should focus on identifying high-yielding rice cultivars with low GHG emissions and on elucidating the mechanisms underlying GHG mitigation.

In conclusion, this research demonstrated that different rice cultivars exert significant impacts on soil CH_4 and N_2O emissions and grain yields. Notably, the two JHR (ZJY1578 and JHY5) outperformed the other evaluated cultivar types by achieving higher grain yields while concurrently reducing both the TCO_2-eq and GHGI associated with CH_4 and N_2O

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emissions. The mitigation of GHGs emissions was primarily regulated by higher yields, lower available C and N contents, and functional genes. Collectively, these findings suggest that GHGs emissions from paddy fields could be effectively mitigated by selecting or breeding cultivars with high yield potential, favourable root morphological traits (e.g., enhanced oxygen release capacity), and reduced root exudation rates.

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Received: September 16, 2025
Accepted: February 9, 2026
Published online: February 22, 2026