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Varietal effects on Greenhouse Gas emissions from rice production systems under different water management in the Vietnamese Mekong Delta

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Abstract

Rice production accounts for 15% of the national Greenhouse Gas (GHG) emissions and Vietnam aims at reducing emissions from rice production by focusing on changing farming practices. However, the potential for mitigation through the selection of different rice varieties is still poorly understood. A two-year field screening of 20 rice varieties under continuous flooding (CF) and alternate wetting and drying (AWD) irrigation was conducted in the Vietnamese Mekong Delta (VMD), Vietnam, employing the closed chamber method for assessing GHG emissions. The results confirmed that varietal variation was the largest for methane (CH_4) emissions under CF. Across the varietal spectrum, CH_4 emissions were more important than nitrous oxide (N_2O) (accounts for less than 2% of the CO_2e) with the lowest emitting variety showing 243 kg CH_4 ha^{-1} and the highest emitting variety showing 398 kg CH_4 ha^{-1} emissions as compared to 0.07 kg N_2O ha^{-1} and 0.76 kg N_2O ha^{-1} emissions, respectively. Under AWD, CH_4 emissions were generally strongly reduced with the varietal effect being of minor importance. Compared with IPCC default values, the data set from the two seasons yielded higher Emission Factors (EFs) under CF (2.92 and 3.00 kg ha^{-1} day^{-1}) as well as lower Scaling Factors (SFs) of AWD (0.41 and 0.38). In the context of future mitigation programs in the VMD, the dry season allows good control of the water table, so varietal selection could maximize the mitigation effect of AWD that is either newly introduced or practised in some locations already. In the wet seasons, AWD may be difficult to implement whereas other mitigation options could be implemented such as selecting low-emitting cultivars.

KEYWORDS
CH_4, drought stress, mitigation, N_2O, seasonal patterns

Key points

- A screening of Greenhouse Gas emissions showed the interaction of variety selection and water management.

- Rice varieties had a modulating effect on the magnitude of Greenhouse Gas levels that were primarily determined by water management.
- Across all field treatments, the overall emission balance was dominated by methane as opposed to a minor role of nitrous oxide.
- Variety selection represents a supplementary or – if others are unfeasible – a stand-alone mitigation option.

1 | INTRODUCTION

Rice production forms the backbone of the food supply in Vietnam and has high economic significance as a source of income for smallholder farmers as well as the trade balance of the country. The area of rice production in Vietnam comprises 7.3 million ha (GSO, 2020) which makes Vietnam the 6th largest rice producer worldwide. Irrigated rice is the predominant environment in the two Vietnamese mega-deltas, namely the Mekong River Delta, which accounts for 55% of all Vietnamese rice production, and the Red River Delta with 18% (GSO, 2020). The tropical monsoon climate encompasses distinct rainy months as well as a relatively dry period from November to April. The delta comprises a complex water infrastructure with over 10,000 km of canals and 20,000 km of dykes which provides irrigation to 90% of the cropland (Nguyen et al., 2020). However, rising sea levels as well as the expansion of highly profitable shrimp farming and subsequent changes in irrigation regimes have led to increasing risk of salinity in coastal rice production systems (Wassmann et al., 2019).

Although population growth is slowing in most Asian countries, the demand for rice is projected to increase globally until at least 2035 (Zeigler & Barclay, 2008). Trends in consumer behaviour with regards to environmentally sustainable production of food are especially important for rice production which is associated with high emissions of CH_4 and – to a lesser extent – N_2O. CH_4 is generated in flooded soils as a result of anaerobic decomposition of organic material. For rice-growing countries such as Vietnam, this is the source of a major share of its national GHG budget. The agriculture sector comprises 27.9% of the total GHG emissions of which almost half (13.8% of the total) is attributed to rice production (MONRE, 2019).

Therefore, the required increase in rice production will rely on adopting technology innovations, site-specific production strategies and improved varieties (Becker & Angulo, 2019). Compared to rice grown under CF, CH_4 emissions can substantially be reduced by allowing the field to dry periodically throughout the season, a practice part of the irrigation technology, AWD. On average, the reduction in emissions is 45% according to the IPCC guidelines (IPCC, 2019). As a trade-off, this practice typically entails increased emissions of another GHG, namely N_2O, but net emissions in terms of CO_2e were shown to be beneficial for mitigation in the vast majority of field measurements (Jiang et al., 2019). As a signatory of the Paris Agreement, Vietnam has reaffirmed “the goal of limiting global temperature increase to well below 2°C, while pursuing efforts to limit the increase to 1.5°C.”

Whereas existing mitigation efforts and plans by the government have focused on adjusted water management such as AWD, the private sector is primarily concerned about marketable rice varieties. To date, the effectiveness of AWD in mitigating GHG emissions from rice production has been well-investigated and described (Arai, 2022; Schneider & Asch, 2020; Uno et al., 2021). However, during the intense southeast Asian rainy seasons, precipitation is often too high for effective and economically viable water-saving irrigation. Therefore, during the rainy season, high GHG emissions from rice production systems appear inevitable. While the different emission levels of rice varieties were documented in the literature (Table 3), these findings appear fragmented over space and time and do not yet translate into a solid database for mitigation projects based on the selection of low-emitting varieties.

The overall objective of this study was to assess the range of GHG emissions of different rice varieties to underpin the concept of selecting low-emission rice varieties in mitigation projects - either in combination with AWD or as a stand-alone strategy. The specific objectives of our study were:

- To quantify the baseline emissions of 20 selected rice varieties under typical growing conditions in the Vietnam Mekong Delta
- To assess the interactive effects of varieties and two different water management practices on GHG emissions to provide the field data for assessing viable mitigation strategies.
- To determine the EFs and SFs as needed in the National Communications (IPCC Tier 2 approach)
- To assess the newly obtained variation in emission potentials in relation to the previously published studies on CH_4 on varietal effect

It should be noted that this study builds on two other publications based on the same field study, namely Asch et al. (2023) on the effects of varieties on methane intensity under CF and AWD, while Johnson et al. (2023) investigates the genotypic responses of rice to AWD water management.

2 | MATERIALS AND METHODS

2.1 | Experimental site and field design

A field experiment was conducted during the Winter–Spring seasons of 2019–2020 (S1) and 2020–2021 (S2) covering the periods from December to March. The experimental site was provided by the Loc Troi Group and was located in Dinh Thanh commune, Thoai

Son district, An Giang province, Vietnam and is characterized by a tropical climate with an annual rainfall of 1415 mm and an average temperature of 27.4°C. Weather data was extracted from a weather station located next to the experimental fields indicating similar temperature ranges in both seasons with averages of 26.5 and 25.8°C in S1 and S2, respectively (Figure 1). Total precipitation was 23 and 89 mm in S1 and S2, respectively. This pronounced inter-annual difference was caused by several high-rainfall events throughout S2 whereas rainfall events were more sporadic and short-lived in the course of S1 (Figure 1).

While the soil properties are given in Tables 1 and 2 shows the sequence of field operations that corresponded to the typical practices in the research area.

Crop management followed the conventional practice of the Loc Troi Group (Table 2) including cropping calendar, fertilizer and pesticide application. Rice straw was burnt in the first season, whereas it was taken out of the field for other purposes in the second season. The stubbles (30–40 cm in height) were partly burnt and incorporated into the soil less than 4 weeks before the season started.

The field experiment comprised 120 plots of 4 × 5 m each separated by bunds and ditches (Figure 2a–c). Plots with different water treatments (see below) were lined with plastic sheets to prevent lateral water seepage between the plots. In the same experimental field, the trials were arranged in a split-plot design, consisting of three replications as randomized blocks. The split was based on water management treatments, namely continuous flooding (CF) and alternate wetting and drying (AWD), and the 20 varieties were used as constituent plots within each split. The varieties are listed and characterized in terms of their agronomic features by Johnson et al. (2023).

2.2 | Water management

Water in the field was controlled by tapping irrigation water from an open canal. In every plot, water level gauges were inserted into the soil at four points and kept for the whole season to ensure measuring at the same positions. The surface water level was manually recorded with a ruler on every regular GHG sampling date at the respective sampling plot plus the level before and after every irrigation event, which was scheduled twice a week according to the regular irrigation plan at the research station. The AWD plots were equipped with PVC tubes to monitor the level of water below the soil surface.

In the CF plots, surface water was maintained at the level of 1–5 cm above the soil surface. In line with the IPCC definitions for baseline management, the plots were kept flooded except for terminal drainage of about 1 week without floodwater in preparation for harvest. In the AWD plots, water levels were monitored using perforated PVC tubes (Lampayan et al., 2015). Irrigation was stopped in given intervals allowing the water level to decline due to evapotranspiration. At the threshold water level of −15 cm below the soil surface, the fields were re-irrigated to a ponded water layer

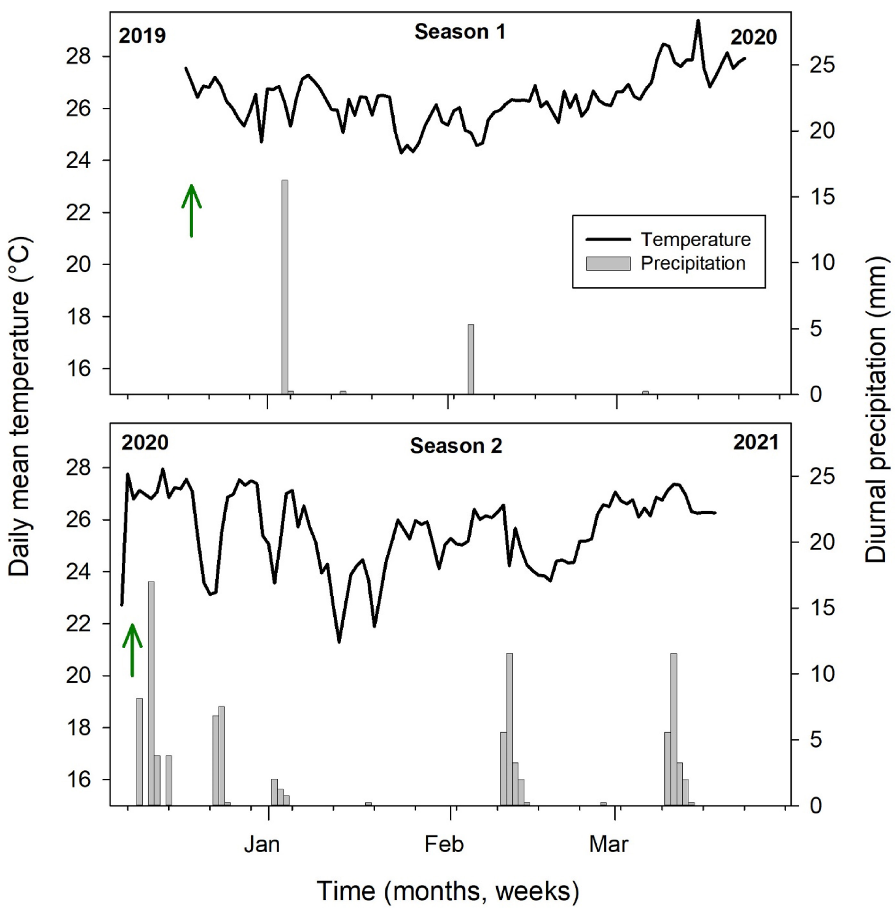

FIGURE 1 Rainfall and temperature at the experimental site during the two observed seasons. The arrows indicate the date of transplanting.

TABLE 1 Soil properties of the experimental site.

Properties	Results	Unit
Coordinates	10°18′44.9 N 105°19′08.3 E	
Soil texture	Clay loam	
pH	5.2	
Electrical conductivity (EC)	0.4	$mS\,cm^{-1}$
Total organic carbon (OC)	3.92	%
Total nitrogen (total N)	0.37	%
Total phosphorus (total P)	93.86	$mg\,kg^{-1}$
Potassium (K)	141.03	$mg\,kg^{-1}$
Calcium oxide (CaO)	232	$mg\,100\,g^{-1}$
Magnesium oxide (MgO)	161	$mg\,100\,g^{-1}$
Potassium oxide (K_2O)	28.2	$mg\,100\,g^{-1}$
Phosphorus pentoxide (P_2O_5)	3.7	$mg\,100\,g^{-1}$
Nitrate-nitrogen (NO_3-N)	0	$mg\,100\,g^{-1}$
Cation exchange capacity (CEC)	13.9	$meq\,100\,g^{-1}$
Silicon dioxide (SiO_2)	15	$mg\,100\,g^{-1}$
Humus	390	%

Note: The soil data analysis procedure follows the Vietnamese standards of soil analytics (see Johnson et al., 2023). The soil data are provided by the Loc Troi Group.

of 5 cm. This practice was incorporated into the concept of 'safe AWD' to prevent eventual drought stress for the plant (IRRI, 2023).

2.3 | GHG field sampling and lab analysis

CH_4 and N_2O fluxes were measured using the closed chamber method as described in Tirol-Padre et al. (2017). In all plots, a square metal base with a diameter of 46 cm was inserted about 10 cm into the soil covering a soil area with four rice hills planted at 20 × 20 cm spacing (Figure 3). Steel bases were placed in each plot before transplanting and remained in the field throughout the season. To minimize physical disturbance and subsequent CH_4 ebullition during the sampling procedure as well as to avoid any border effects, bases were inserted at a one-meter distance from the plot bund. In every plot, a connecting boardwalk (wooden plank) with removable metal bases was temporarily placed on four wooden poles to allow a stable positioning during sampling. The gas collection chambers, constructed of transparent plexiglass with a height of 96 cm and a length and width of 46 cm, were equipped with a sampling port, a thermometer and a battery-operated fan to circulate the air in the headspace of the closed chamber (Figure 3a,b).

At each sampling event, chambers were placed for 30 min on the metal base. The trenches of the bases were filled with water to ensure an airtight enclosure of the soil/water surface and the rice plants (Figure 3c). Gas samples from inside the chamber were retrieved at 0, 15 and 30 min after chamber placement. Gas sampling was implemented in weekly intervals over the whole growing period. While samples were collected from 8:00 to 12:00 in the routine sampling for assessing seasonal emissions, we also conducted sporadic measurements on diurnal patterns of hourly emission rates (data not shown), namely five varieties in S1 (3 measurements) and two varieties in S2 (2 measurements). To optimize labor requirements, these hourly emission rates over one 24-h cycle were aggregated to one value and used as a daily emission rate for the respective variety and given week within the assessment of seasonal emission rates in this study (see calculation procedures below). Since the field experiment included varieties differing in phenology (Table 2), the number of varieties sampled was reduced during the last weeks of both observation periods.

Gas samples from the closed chamber headspace were taken using a 60 mL syringe fitted with a stopcock attached via a valve to the gas sampling port at the chamber headspace. The gas samples were immediately inserted into pre-evacuated vacuum glass vials with a butyl rubber septum and covered by an aluminium cap. Individual steps of sampling, analysis and data evaluation procedure included the following steps: (a) samples were stored in pre-evacuated vials and shipped to the IRRI lab in the Philippines (>9000 samples in total); (b) chemical analysis of CH_4- and N_2O-concentrations through gas chromatography (Model: SRI 8610C); (c) hourly emission rates were derived from the temporal increase (slope) of concentrations (incl. QA/QC procedure of linearity); (d) average of three replicate flux rates were considered as weekly emission record in further data evaluation.

2.4 | Data evaluation and quality control

Hourly emission rates of CH_4 (mg CH_4 $m^{-2}h^{-1}$) and N_2O (µg N_2O $m^{-2}h^{-1}$) were calculated according to Minamikawa et al. (2015). The measurements taken in the morning were assumed to represent daily average flux rates representing a weekly interval. The evaluation of emission rates was done at three levels: (i) hourly emission rates as intermediate data that is not shown in the paper, (ii) daily emission rates derived from the replicate measurements of one variety in a given week and (iii) seasonal emission rates calculated by multiplying the daily emission rates with the number of days of the cultivation period. For the conversion from daily to seasonal emission rates, it was assumed that flux changes between two consecutive sampling days are linear so seasonal emission rates also represent the cumulative emission over one season. The daily emission rates on the day of sowing and harvest were set to "0". The seasonal emission was calculated as the sum of the daily emissions from transplanting to harvest by applying the trapezoidal integration method described by Minamikawa et al. (2015).

Seasonal emission rates are used as the basic metric for the intercomparison of seasons and varieties as well as for references to the national GHG inventory (MONRE, 2019). The individual values of daily emission rates are embedded in the diagrams whereas the mean daily emission rate over a given season is used for the comparison with the default values of the IPCC guidelines (IPCC, 2019).

Calculated fluxes were included when the coefficient of determination (R^2) of the linear regression of gas concentration

TABLE 2 Field management practices in the two seasons 2019–2020 and 2020–2021 (DAT: days after transplanting).

Practice	Season 1–2019–2020		Season 2–2020–2021	
Rice straw management (previous season)	Burnt		Taken out of the field	
Stubble management (previous season)	Burnt and incorporated (<4 weeks)		Burnt and incorporated (<4 weeks)	
Height of incorporated stubbles	30–40 cm		30–40 cm	
Seeding date	05.12.2019		27.11.2020	
Transplanting dates	18–20.12.2019		08–09.12.2020	
Starting gas sampling	6 DAT		8 DAT	
Inorganic fertilizer application (kg ha^{-1})	90 N - 40 P_2O_5 - 40 K_2O		90 N - 40 P_2O_5 - 40 K_2O	
1st application (30% N + 40% P_2O_5 + 20% K_2O)	3 DAT		9 DAT	
2nd application (40% N + 50% P_2O_5 + 30% K_2O)	14 DAT		16 DAT	
3rd application (30% N + 10% P_2O_5 + 50% K_2O)	35 DAT		39 DAT	
Harvest dates	**DAT**	**Variety**	**DAT**	**Variety**
	89	OM18, OM2517, OM4218, OM5451	95	OM18, OM2517, OM4218, OM5451, GKG9, ML202
	92	Dai Thom 8, GKG9, IR64, ML202	98	Dai Thom 8, GKG29, IR64, Loc Troi 1, Loc Troi 5, OM6976
	96	GKG29, GKG35, Loc Troi 1, OM7347, OM6976, OM576	100	GKG35, Jasmine 85, OM4900, OM7347, ST24
	99	BTE1, DS1, Loc Troi 5, Jasmine 85, OM4900, ST24	108	BTE1, DS1, OM576

over time was at least 0.976 and with a $p < .01$ (Minamikawa et al., 2015). In our study, the CH_4 fluxes show a high rate of acceptable values (about 55% met the required R^2 of Minamikawa et al. (2015)), therefore, CH_4 emission data were presented without correction as postulated by Parkin et al. 2012 (cited in Minamikawa et al., 2015). In contrast, only about 10% of the seasonal N_2O emission rates passed the required R^2 value. In this case, data were set to zero for the interpolation and integration. The data were used to determine the EF, SF and area-scaled global warming potential (GWP) of each variety.

Finally, seasonal emission rates of CH_4 and N_2O per variety were averaged over both seasons and converted to CO_2e with the commonly used GWP-values of CH_4 (28) and N_2O (265) given in the 5th IPCC assessment report (IPCC, 2014) for a time horizon of 100 years. Analysis of variance (ANOVA) was performed to evaluate the effects of water management and variety on CH_4 emission rates and their interactions if the factors differed significantly (by p-value).

3 | RESULTS

3.1 | Water management and rice growth duration

Figure 4 illustrates the seasonal water level dynamics for CF and AWD as measured in the plots during the two cultivation periods. Water levels were efficiently controlled throughout the two seasons with minor differences in seasonal irrigation management. In the first season, water levels in the AWD plots declined to less than −20 cm below the soil surface, whereas in the second season, maximum depletion did not exceed −15 cm. The stronger depletion in the first season may be attributed to the imperfect construction of plot bunds that were initially not yet compacted enough to prevent cracks and holes. This shortcoming was resolved in the second season by making the bunds wider. Moreover, the first season had lower rainfall which probably also contributed to the inter-annual differences in water levels.

Seasons also differed in planting duration, which was in most cases delayed in the second season (Table S1). This may have been due to (a) seedlings being 2 days younger at transplanting in the second season and the season was markedly cooler (Figure 1), which likely extended the growth period in the fields; and (b) surplus water from higher rainfall in the second season.

3.2 | Seasonal emission patterns

The seasonal emission patterns are available for all 20 varieties for both treatments and GHG species. CH_4 emission shows similarity among all varieties and seasons, the differences between CF and AWD were noticeable starting 25 and 35 days after transplanting (DAT) when water levels were periodically below the soil surface in S1 and S2, respectively (Figure 5). In the remaining cultivation periods, daily emission rates of AWD were consistently lower than those of CF. Given the high level of daily emission rates, the graphs of CF showed some fluctuation whereas emission from AWD remained within a very low range. The results of ANOVA showed significant differences in treatment and variety on daily CH_4 emission

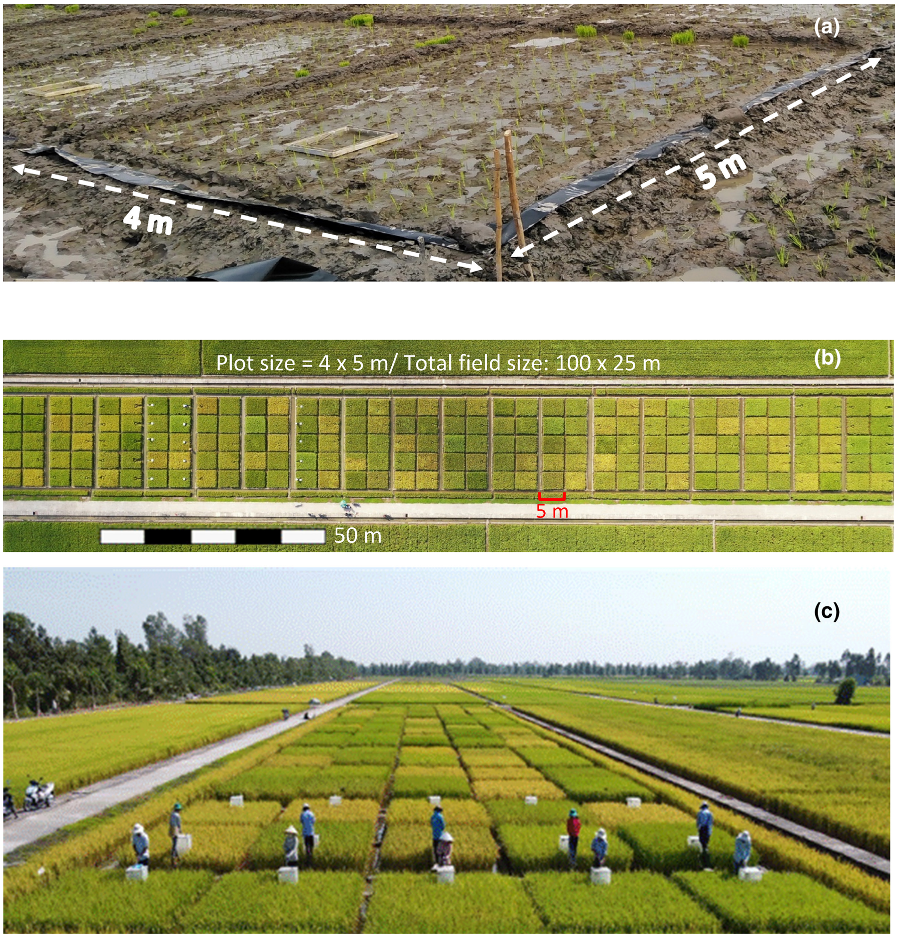

FIGURE 2 (a–c) Photos of field experiment at the farm of Loc Troi Group in An Giang Province, Vietnam; (a) plots before transplanting lined with plastic sheets (along the dotted lines) to prevent lateral water flow; (b) an aerial image of the entire field showing 4 chambers each placed in the 6th, 7th and 11th row and (c) aerial view of the sampling procedure.

rate averaged over the season ($p<.0001$ and $p<.001$ respectively). However, the effect of season on cumulative emission rates was not significant. The variations in N_2O emissions appeared rather irregular during both seasons. Water management does not show any discernable effect based on the seasonal patterns although this observation will not exclude differences in terms of the seasonal emissions. While N fertilizer application did not trigger N_2O peaks, some varieties showed high N_2O emission during the terminal stage of the season when the field was drained for harvest (Figure 6). The average daily N_2O emission rate varied significantly with variety and season ($p<.0001$) but not treatment.

3.3 | Comparison of seasonal emissions

The seasonal emissions show in Figure 7 that CH_4 emissions under CF are at least twice as high as under AWD in both seasons. In the first season, the cumulative CH_4 emission rates had a mean value across all varieties of 315 kg ha^{-1} for CF (ranging from 257 to 416 kg ha^{-1}) and 130 kg ha^{-1} for AWD (ranging from 86 to 182 kg ha^{-1}). In the second season, the mean of the cumulative CH_4 emission rates for CF was 332 kg ha^{-1} (ranging from 222 to 478 kg ha^{-1}and for AWD mean CH_4 emission rate was 120 kg ha^{-1} (ranging from 78 to 158). In comparison to CF, the cumulative CH_4 emission rates under AWD in the two seasons were significantly reduced by 59 and 64%, respectively. Despite large differences between varieties, seasonal emissions were not significantly different between varieties, though treatment effects were significant ($p<.001$). Furthermore, the ranking order of varietal emissions was similar for mean emissions between the two seasons, despite the relatively large variation between the replications.

The seasonal N_2O emissions (Figure 8) reflect the generally low emission levels throughout both seasons. On average, seasonal emissions of N_2O were 0.71 kg ha^{-1} (ranging from 0.2 to 1.35 kg ha^{-1}) in S1 and 0.24 kg ha^{-1} (ranging from 0.04 to 0.58 kg ha^{-1}) in S2, across all varieties. Total N_2O emission in S1 was 3 times greater than that in S2 (Figure 8), due to the lower level of water in AWD plots in the first season. However, the irrigation treatment did not lead to any reduction in N_2O emission rates. Moreover, the N_2O emission rates of certain varieties differed strongly between S1 and S2 (Figure 8) and there were some strong variations among the replications in both seasons. These discrepancies go along with high standard deviations caused by individual extremes of high N_2O emission rates, namely BTE1, Jasmine 85, OM4218, OM4900 and OM576 in S1 as well as Loc Troi 1 and OM6976 in S2. Although treatment effects were significant ($p<.001$), differences in varietal seasonal N_2O emissions were not significantly different.

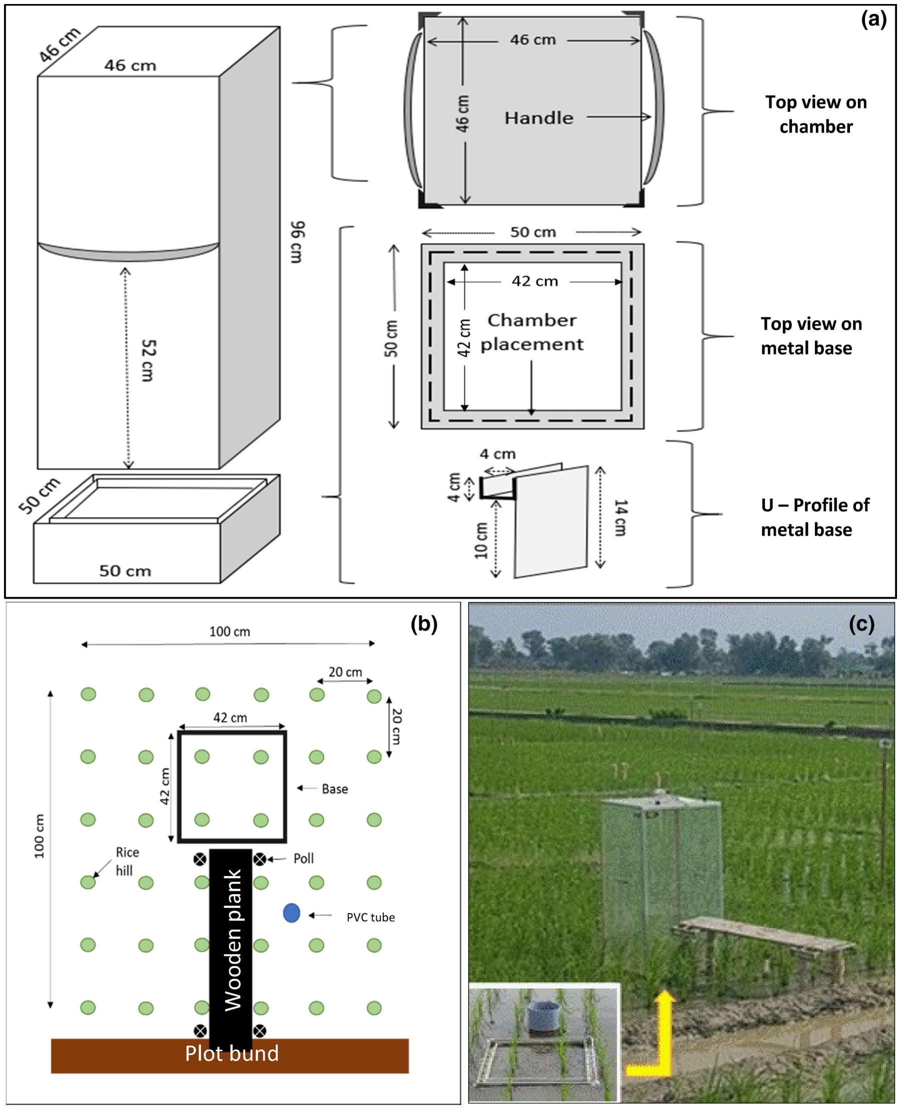

FIGURE 3 (a–c) Design and placements of closed chambers (a) design of chamber and base. (b) schematic drawing of field placement, (c) photo of actual sampling point setup.

3.4 | Variety-dependent emissions under given and changing water management

Strong varietal effects on GHG emissions were found in the CF treatment where emissions of the highest emitting variety were factor 1.6 and 2.1 higher than those of the lowest emitters in S1 and S2, respectively. Referenced to the average of all varieties, the seasonal emission rates range from a reduction of 59 kg CH_4 ha^{-1} (19%) for the lowest emitting variety to an increment of 100 kg CH_4 ha^{-1} (32%) for the highest emitting variety in S1. These figures were similar in S2, namely 110 kg CH_4 ha^{-1} (33%) and 150 kg CH_4 ha^{-1} (44%; Table S1). Despite all the variations inherent in this data set, the results for CF indicate a sizable mitigation potential by variety selection in the range of 19% and 44%. As for AWD, however, the CH_4 seasonal emission rates show a converging trend across different varieties. In part, this can be attributed to generally low emission levels that translate into small differences in absolute terms ranging from 130 and 120 kg CH_4 ha^{-1} for S1 and S2, respectively. Even in relative terms, the variations of 59 and 64% were lower than for CF. Likewise, for the N_2O emissions, the results do not allow recommending a specific variety. Daily N_2O emission rates were generally low under both CF and AWD which was superimposed by large variations from season to season.

In order to assess the magnitude of the individual varietal mitigation potential under the two irrigation management methods, we calculated the difference (delta) between the individual, seasonal varietal emissions and the mean seasonal emissions across all varieties and plotted these for the two irrigation methods. Figure 9 comprises the 4 charts with the delta CF values plotted against the x-axis and delta AWD values against the y-axis for CH_4 and N_2O in both seasons. The delta values reflect the different magnitudes of absolute emissions under CF and AWD, i.e. Figure 9a shows data of CH_4 for season 1, delta CF varied from −59 (±20) to 100 (±22) kg ha^{-1} while the delta AWD values varied from −45 (±16) to 51 (±45) kg ha^{-1} whereas that of delta value from season 2 (Figure 9b) ranged from −111 (±16) to 145 (±89) and−42 (±3) to 38 (±37) for CF and AWD, respectively. The CH_4 data clearly shows the seasonal effect on varietal emissions but for CF the range is similar in both seasons, even though, probably due to temperature differences, the varietal range was larger and thus also the mitigation potential in the second

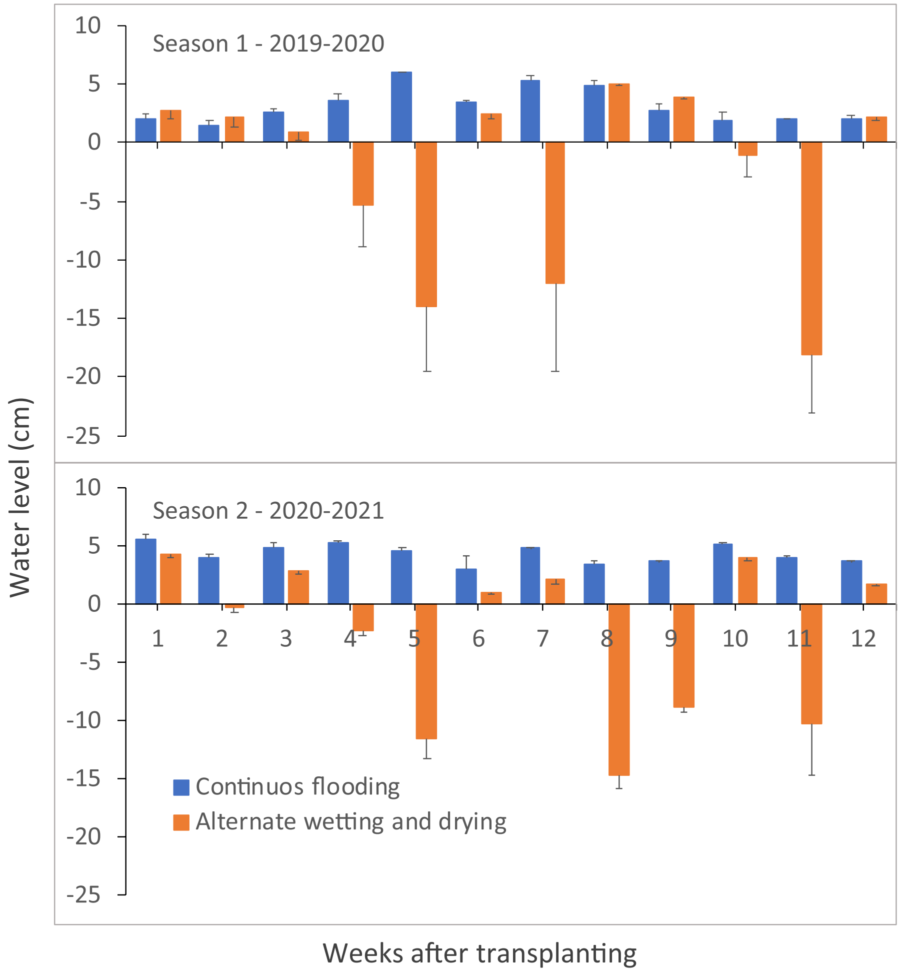

FIGURE 4 Patterns of plot water levels summarized across varieties measured by water level gauges and PVC tubes in the season 2019–2020 (upper graph) and the 2020–2021 (lower graph), respectively; Error bars = standard error.

season where AWD is almost evenly scattered around zero and the distribution of the delta CF values is skewed, i.e. the positive values stretch over a larger range than the negative values. For N_2O, Figure 9c,d shows a large range of emissions between the two seasons, particularly, varietal differences are more apparent in the first than in the second season but deltas are very small and irrigation treatment has only a minor effect on the emissions.

The two zero dotted lines in each graph create four clusters in the chart corresponding to different priorities in variety selection. The varieties in the lower left cluster (III) can be assigned the highest priority for future mitigation projects due to their above-average mitigation effect for both CF and AWD. The varieties in the upper left quarter (I) could be considered as a second priority because they reduce emissions as long as the CF water management is maintained. The varieties in the lower right quarter (IV) would in principle qualify for mitigation projects that switch from CF to AWD, but varietal emissions vary in a smaller range than GHG emissions reductions achieved by AWD. Finally, the cluster of varieties in the upper right quarter (II) should not be considered in future mitigation efforts.

However, the database allows conclusions on the interactive nature of variety selection and water management. The chart in Figure 10 depicts the baseline emissions as the x-axis with the respective net mitigation as the y-axis to allow easy identification of the most promising varieties for mitigation. The net mitigation potential in the season ranged between 135 (OM576) and 270 (OM7347) kg ha^{-1}. The largest reductions through AWD in those varieties with high baseline emissions are shown in the orange circles, whereas, low-emitting varieties AWD had smaller effects than those with green arrows. To maximize net mitigation potential, varieties should be selected according to season.

Scaling factors varied between 0.29 and 0.55. Small AWD effects in low-emitting varieties resulted in the highest SFs. Given the underlying equation of calculating SFs, however, the resulting data points project an inverse image as in Figure 10 that the most promising varieties are plotted in the lower right corner. This clearly indicates that SFs alone are not sufficient to describe the varietal effect on seasonal emissions, but have to be seen against the backdrop of high versus low baseline emissions and that varieties should be annually low emitting with a small SF.

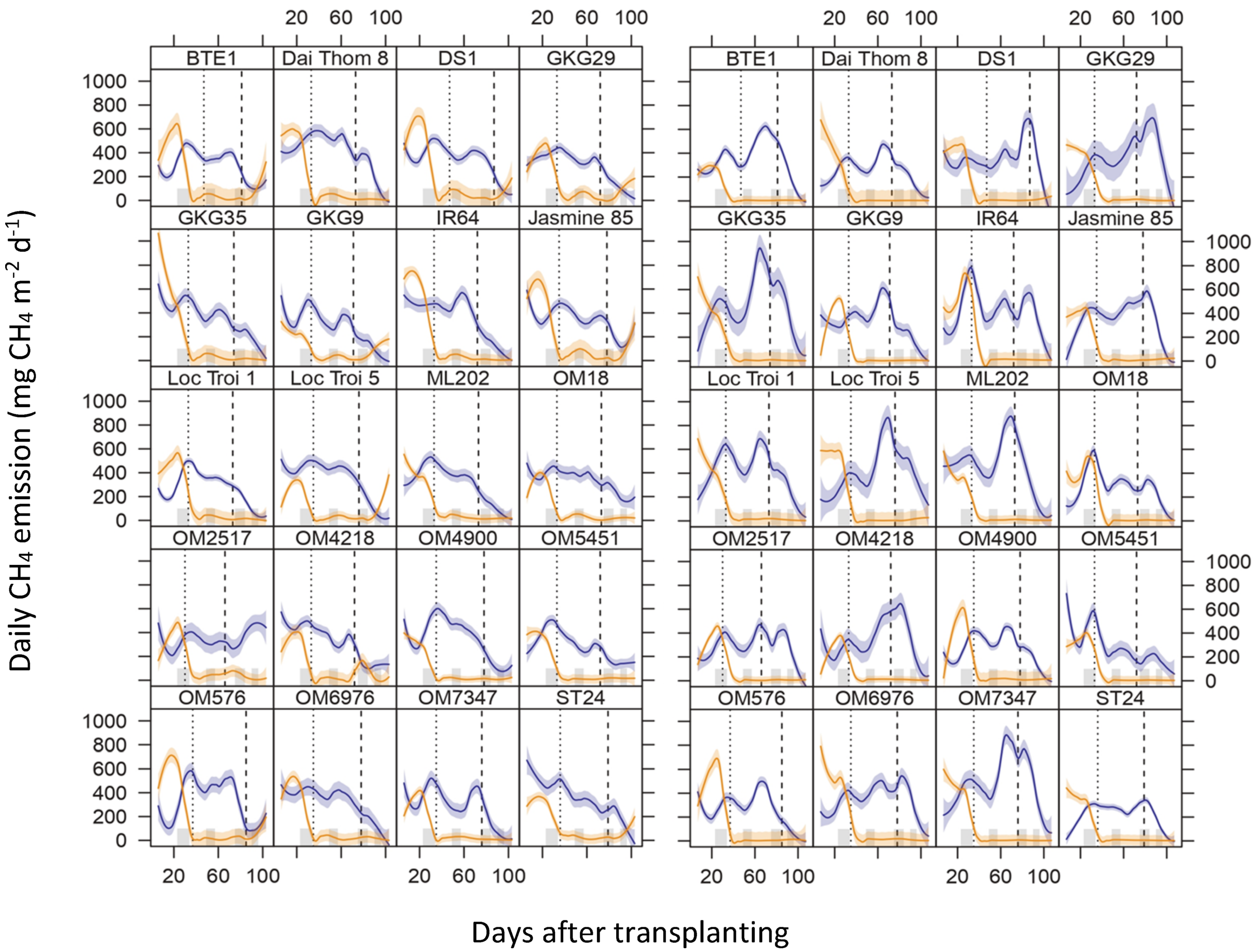

FIGURE 5 (a, b) Daily CH_4 emission rates from 20 rice varieties; (a) the first season (2019–2020) and (b) the second season (2020–2021). The lines are loess regressions (locally estimated scatterplot smoothing) for all replicates by variety with an alpha of 0.3. The shaded band around each line represents standard error. Line colour indicates irrigation treatment: blue, alternate wetting and drying (AWD) and orange, continuous flooding (CF). The grey blocks on the x-axis represent the duration of a drying event related to the implementation of AWD. The dotted vertical line represents panicle initiation, and the dashed vertical lines, flowering.

3.5 | Global warming potentials

Figure 11 shows the CH_4 and N_2O emissions per variety averaged over both seasons and converted to CO_2e with the GWP-values of 28 and 265, respectively, that were adopted from the 5th IPCC Assessment Report (IPCC, 2014). It should be noted that these values vary from the GWP used in Vietnam's National Communication (i.e. 25 for CH_4 and 298 for N_2O) adopted from the 4th Assessment Report (MONRE, 2019). The varieties were plotted in ascending order of the GWP which highlights the predominant role of CH_4 versus N_2O—even for those varieties with high GWP. Particularly, 98% and 99% contributed by CH_4 in S1 and S2, respectively. Across all varieties, the reduction potential of AWD was above the IPCC default (40%) ranging from 57% and 63% in seasons 1 and 2, respectively. In terms of CH_4 contribution, the relative share was 75.3% CH_4 from CF and 24.7% from AWD treatment in the 1st season. Similarly, the share was 69.9% and 30.1% in the 2nd season and that results in a significant variation in an overall GWP observed between water management in each season.

4 | DISCUSSION

4.1 | Literature data on rice varieties

In the current study, 19 lowland rice varieties from Vietnam and one international check variety (IR64 from the Philippines) were investigated for their GHG emissions during two consecutive dry seasons under two irrigation managements in the MRD, Vietnam. The aim was to elucidate the mitigation potential for GHG emissions via (a) irrigation management and (b) selection of low-emitting varieties. Whereas the body of literature describing the mitigation potential of AWD for CH_4 emissions is comprehensive, the mitigation potential originating from selecting suited

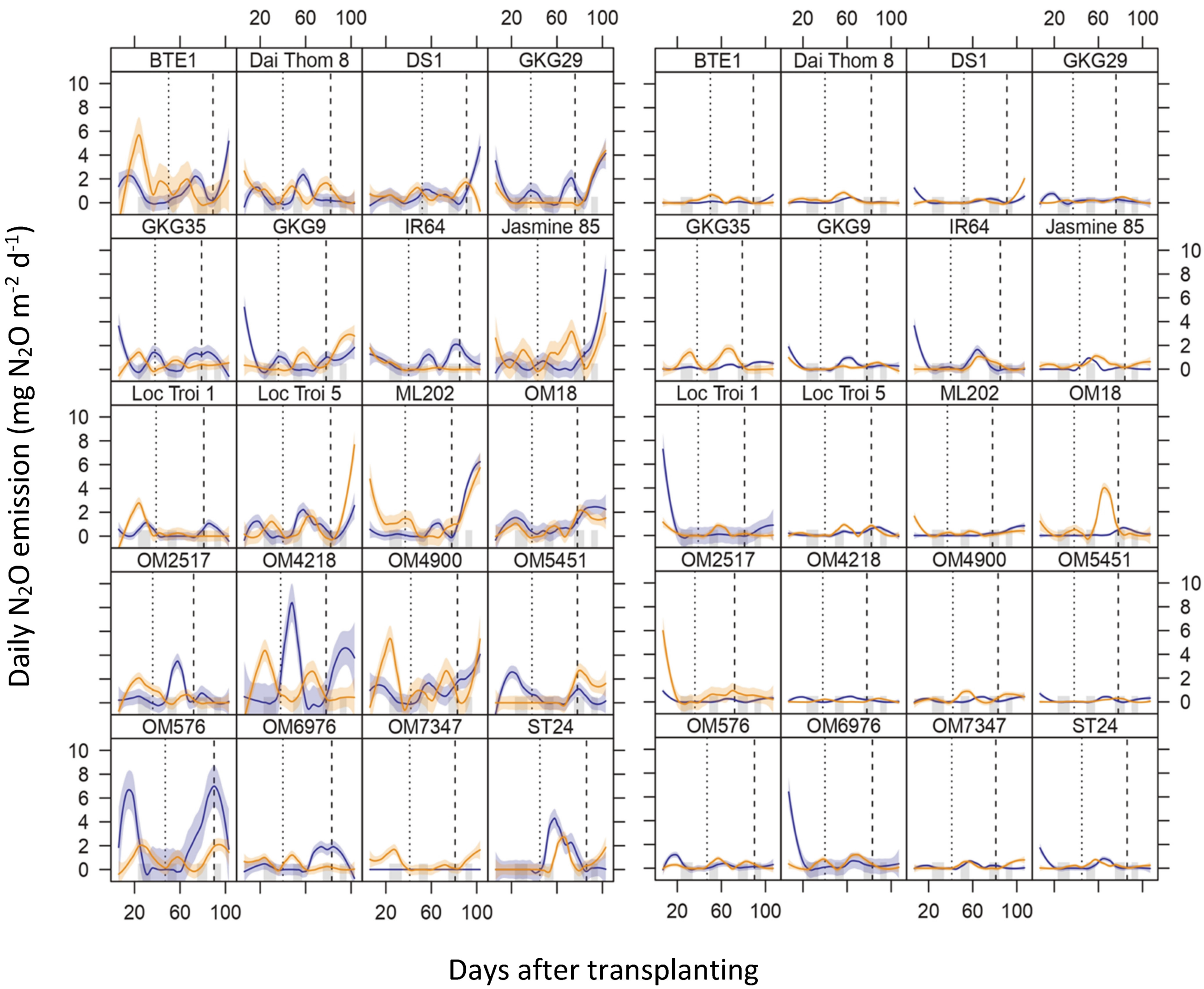

FIGURE 6 (a, b) Daily N_2O emission rates from 20 rice varieties; (a) the first season (2019–2020) and (b) the second season (2020–2021). The lines are loess regressions (locally estimated scatterplot smoothing) for all replicates by variety with an alpha of 0.3. The shaded band around each line represents standard error. Line colour indicates irrigation treatment: blue, alternate wetting and drying (AWD) and orange, continuous flooding (CF). The grey blocks on the x-axis represent the duration of a drying event related to the implementation of AWD. The dotted vertical line represents panicle initiation, and the dashed vertical lines, flowering.

low-emitting varieties for the rainy season has hardly been investigated. Two meta-analyses addressed this issue: Zheng et al (2014) compared the GWP measured in 27 publications from field studies in China that included 120 data points while the meta-analysis by Jiang et al. (2017) comprised 17 field studies from 6 Asian countries covering 79 varieties in total. However, these meta-analyses only marginally dealt with field studies from southeast Asia. We compiled a list of field studies that were not included in these two meta-analyses.

As shown in Table 3, several field studies have reported substantial effects of rice varieties on GHG emissions, especially CH_4. We also reported the principal findings of each study in the respective line of each study, so that the content of Table 3 collectively reflects the current state of knowledge on varietal effects on GHG emissions from rice. Based on the present mechanistic understanding, the main impact of rice plants on emissions seems to be through the duration to maturity resulting in different lengths of periods of ponded water layers. In a field experiment in Indonesia, Wassmann et al. (2000) showed that seasonal emissions of an early maturing (110 days) variety were proportionally lower than the traditional variety with a duration of 140 days. This is also reflected in the IPCC methodology for GHG inventories (IPCC, 2019) that multiplies daily emission rates with the days from planting to harvest. In this respect, the prevailing breeding of new, early-maturing rice varieties – has contributed to reducing emissions from rice production systems at the global scale. However, when looking closer into a set of varieties less contrasting than landraces versus improved varieties or short duration (<90 days) versus long

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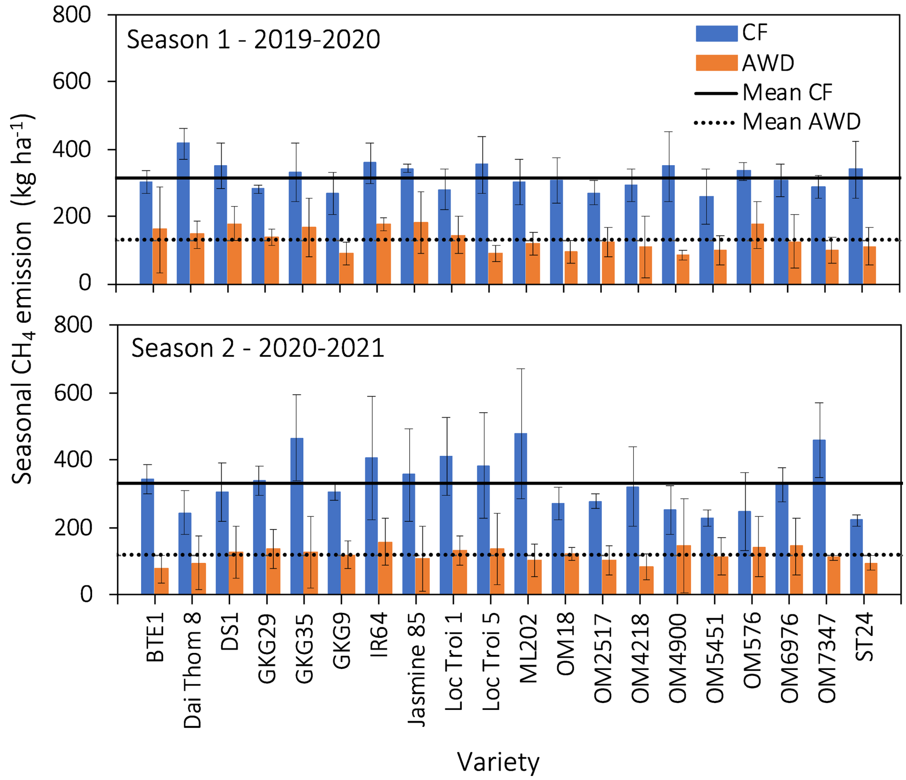

FIGURE 7 Seasonal CH_4 of 20 rice varieties in 2019–2020 (upper graph) and 2020-2021(lower graph), respectively. CF, continuous flooding; AWD, alternate wetting and drying; Error bars = standard deviation.

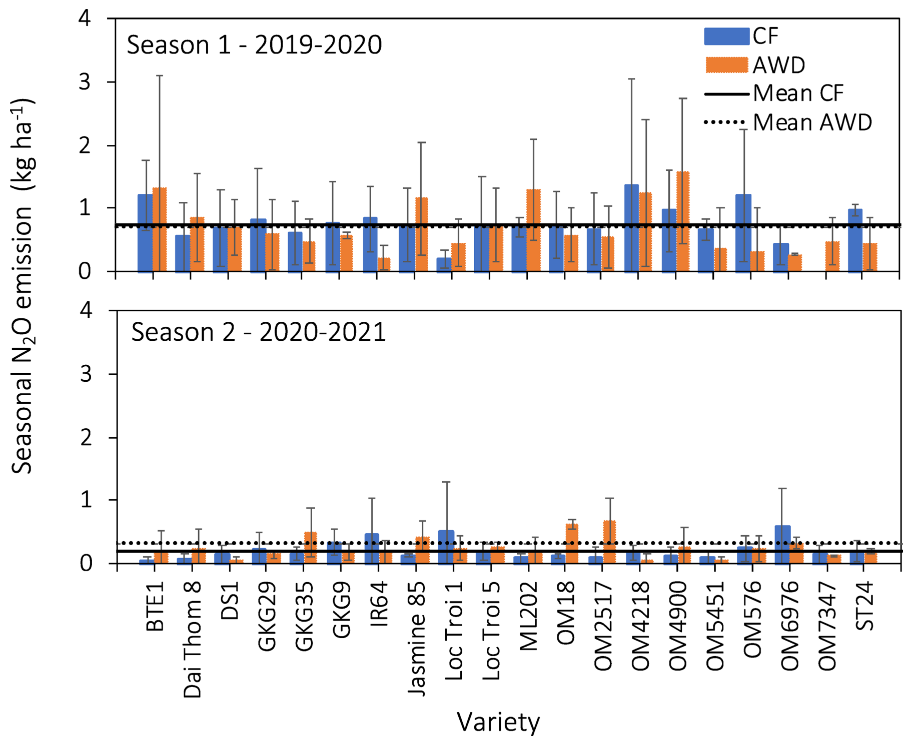

FIGURE 8 Seasonal N_2O of 20 rice varieties in the season 2019–2020 (upper graph) and 2020–2021(lower graph), respectively. CF, continuous flooding; AWD, alternate wetting and drying; Error bars = standard deviation.

duration (>130 days), as in the current study, where the duration to maturity varied among the varieties at maximum by 18–21 days in the respective seasons (data shown in Johnson et al., 2023), these patterns do not hold. We showed that under CF the emissions of the highest emitting variety are factor 1.6 and 2.15 higher than those of the lowest emitters in season 1 and season 2, respectively. The varieties emitting consistently lower than average, OM18, OM5451, OM2517 and GKG 9, were with on average 83.5 (S1) and 87.5 (S2) days to maturity indeed among the varieties with the shortest duration. However, the varieties that showed strongly

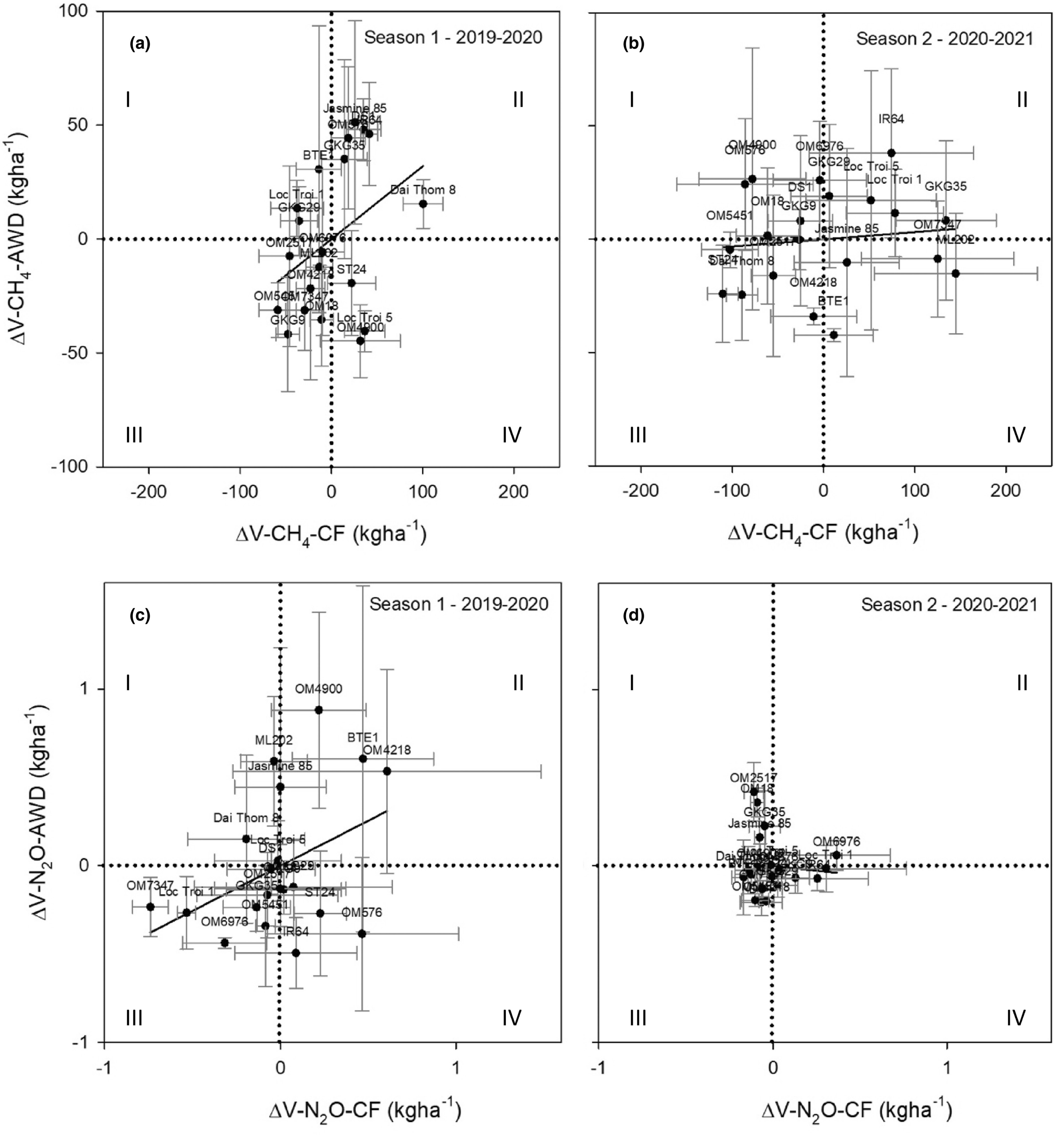

FIGURE 9 (a–d) Delta variety (ΔV) of continuous flooding (CF) and alternate wetting and drying (AWD) of CH_4 and N_2O ($kg\,ha^{-1}$) values of 20 varieties from two seasons. Roman numbers indicate the chart quarters.

above-average emissions in both seasons, Loc Troi 5, Jasmine 85 and IR64, had on average 88.5 (S1) and 94 (S2) days to maturity which were 11.3% (S1) and 6.3% (S2) shorter durations than the respective longest durations observed. The varieties with the longest durations in both seasons, BTE 1 and DS1, had seasonal emissions at the genotypic average level. The remaining varieties showed no consistent emission pattern across seasons.

An earlier study in India (Das & Baruah, 2008) found lower CH_4 emissions from improved varieties than from traditional varieties. In another study, Baruah et al. (2010) examined ten popularly grown rice varieties in India and confirmed that CH_4 emissions were higher in the traditional varieties than in improved high-yielding varieties. This was attributed to the profuse vegetative growth in the traditional variety since CH_4 emissions showed significant positive

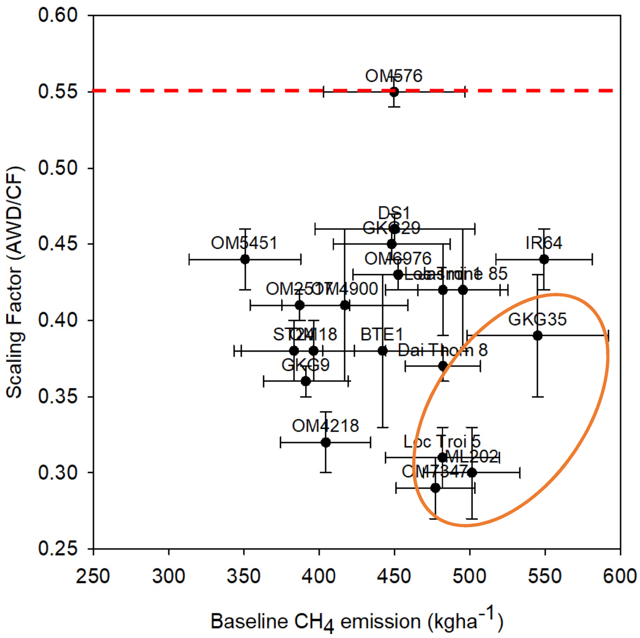

FIGURE 10 Varietal scaling factor for 20 rice varieties. The orange circle includes high emitters with strong AWD reduction potential; the dashed line indicates the scaling factor (AWD/CF) according to IPCC. Data show the means over two seasons. Error bars = standard error.

correlations with leaf area, leaf number, tiller number and root dry weight. The current study underlines the large variation among genotypes. Here, only improved, high-yielding varieties were included and with few exceptions seasonal emissions were lower than the improved, semi-dwarf international check IR64.

4.2 | Comparison with IPCC default values

4.2.1 | CH_4 emission factor

In the context of the IPCC guidelines on CH_4 emissions from rice, the term Emission Factor refers to the baseline management as done in our experiment, that is, CF alongside a short period of fallow water cover and no organic amendments. Figure 12 shows the results of the comparison of EFs of CH_4 across all varieties averaged for both seasons. The values for given varieties ranged from 2.52 (OM5451) to 3.96 kg ha^{-1} season^{-1} (ML202). The IPCC (2019) Refinement specifies a default Tier 1 EF for sub-continental regions, i.e., the default EF of CH_4 for southeast Asia is given as 1.22 kg ha^{-1} day^{-1} with a range of 0.83 to 1.81 kg ha^{-1} day^{-1}. The EFs of this study were also higher in comparison to previously published data for baseline emissions of continuously flooded rice fields in the

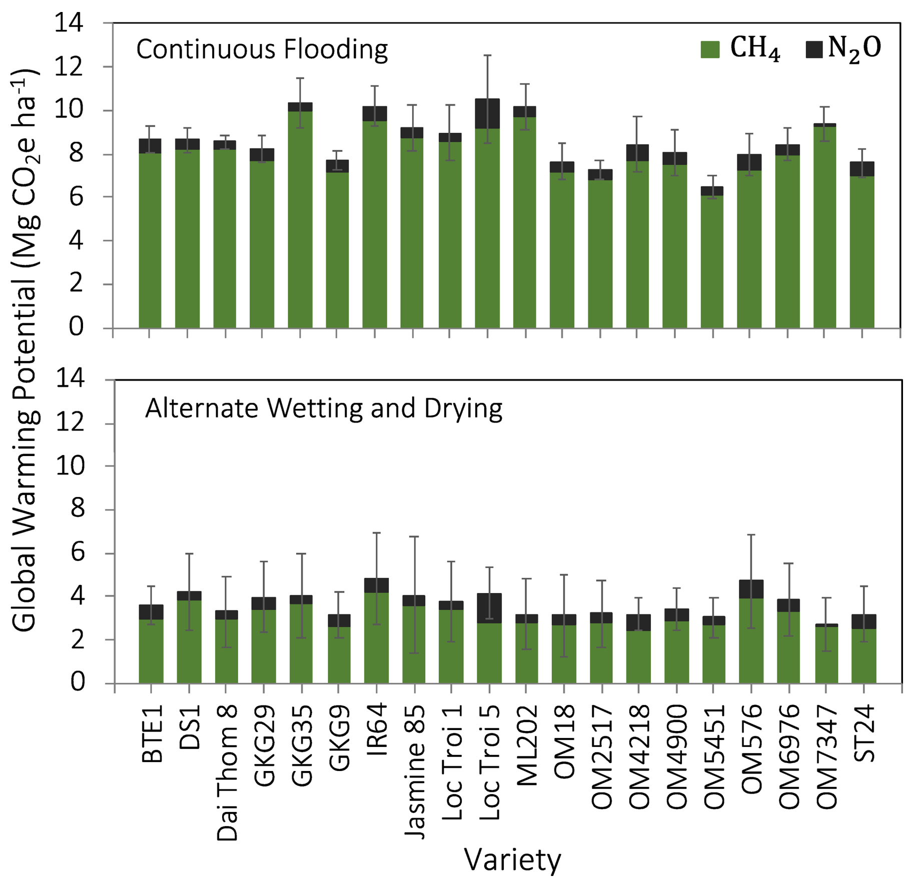

FIGURE 11 Seasonal global warming potential (GWP) of 20 rice varieties under continuous flooding (upper graph) and alternate wetting and drying (lower graph) based on aggregated emissions of CH_4 (GWP_{CH4} = 28) and N_2O (GWP_{N2O} = 265). The bars show the means over two seasons and the error bars show the standard deviations of the aggregated emissions.

TABLE 3 Comparison with literature data on rice varieties.

Study	Number of varieties	Country	Observed differences
Wang et al. (2021)	4	China	Rice variety was among the most important factors affecting CH_4 emission and GWP whereas N_2O emission was mainly related to N-fertilizer
Gogoi et al. (2008)	10	India	Traditional varieties showed higher seasonal CH_4 emission rate Positive correlation between CH_4 and leaf numbers, tiller numbers, leaf area index
Baruah et al. (2010)	10	India	CH_4 emissions were higher in the traditional varieties than in improved high-yielding varieties CH_4, N_2O had a significant positive correlation with leaf area, leaf numbers, tiller numbers, root dry weight
Khosa et al. (2010)	3	India	Significant variation in CH_4 emission among varieties
Bharali et al. (2017)	6	India	Significant differences in photosynthetic rate among varieties, which were found to influence CH_4 emission
Bhattacharyya et al. (2019)	7	India	Significant variation in CH_4 emission among varieties; low emission found in short-growth-duration varieties
Subadiyasa et al. (1997)	3	Indonesia	No distinction in emissions between improved varieties
Setyanto et al. (2004)	3	Indonesia	Rice varieties showed different ability in emitting CH_4 in flooded soil
Arianti et al. (2022)	3	Indonesia	Significant variations in CH4 emission
Butterbach-Bahl et al. (1997)	2	Italy	Difference between 2 varieties in CH_4 emissions; the variety with high emissions had a significantly higher gas transport capacity
Shin and Yun (2000)	8	Korea	Rice varieties did not influence the CH_4 seasonal patterns but the total amount of CH_4 emitted
Aulakh et al. (2002)	22	Philippines	Rice varieties widely differ in CH_4 transport capacity
Wassmann et al. (2002)	19	Philippines	Varietal effect is not a major determinant factor for CH_4 emissions
Kerdchoechuen, 2005	4	Thailand	Seasonal CH_4 emission rate significantly differed with varieties
Liou et al. (2003)	2	Taiwan	GHG emission depends on the type of N fertilizer and rice varieties
Lindau et al. (1995)	6	USA	Rice variety had a significant effect on the emission in Louisiana flooded plots

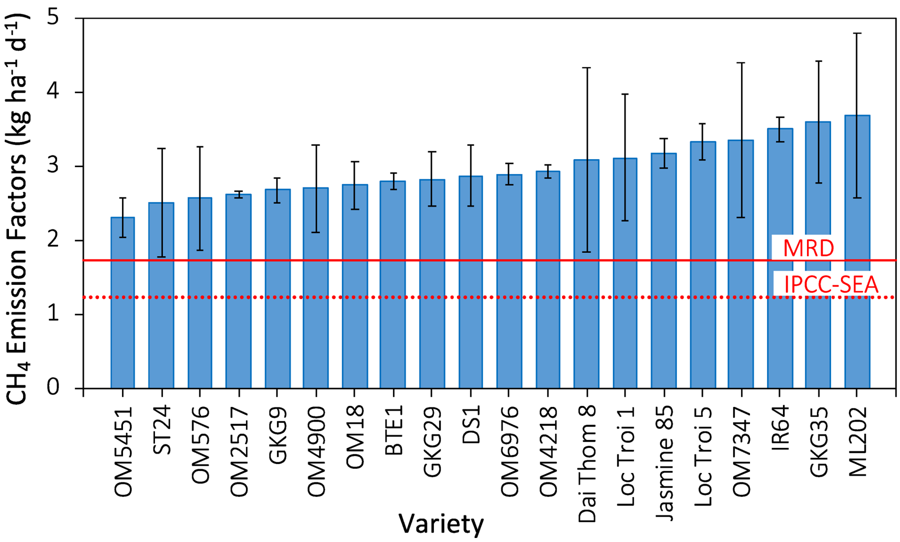

FIGURE 12 Emission factors of 20 varieties plotted against the IPCC value for southeast Asia (IPCC-SEA) and a literature value for the Mekong River Delta; The bars show the means over two seasons and the error bars show the standard deviations of the aggregated emissions.

Mekong River Delta (Vo et al., 2018, 2020). Regarding the possible impact of the cultivation period, OM5451 was in the earliest harvest group of both seasons whereas ML202 did not belong to the latest harvest group. The new guidelines also contain default values for the cultivation period at a sub-continental scale that is shorter in southeast Asia (102 days with a range of 78–150 days) whereas the average cultivation period of the selected 20 cultivars was 95–100 days depending on the growing condition. Nevertheless, when looking closer into the groups of low and high-emission varieties, the early-maturing varieties such as OM5451, OM2517 tend to have low EF whereas GKG35 and OM7347 were late-maturing and had high emission in both seasons.

4.2.2 | CH_4 scaling factor for AWD

While CH_4 emissions of AWD ranged from 0.76 to 1.68 and 0.65 to 1.41 $kg\,ha^{-1}\,day^{-1}$ in the first and second seasons, Figure 10 reveals the AWD Scaling Factors (corresponding to the ratio between CF and AWD) had average values of 0.41 and 0.38 in S1 and S2, respectively, which are considerably lower than the default value (0.55) given by IPCC (2019). This indicates that the shift from CF to AWD entailed higher emission savings in our field experiments as predicted through the IPCC defaults (Figure 10a). As compared to the mitigation assessment following the IPCC defaults, the net emission impact derived from this study will considerably be higher because the lower AWD/CF ratio will further be amplified by higher background levels under CF as compared to the IPCC values (see above).

4.2.3 | N_2O emission factor

According to the data provided in Table S1, the average seasonal N_2O emissions was 0.47 kg N_2O ha^{-1} for CF. To allow comparison with the IPCC default value, these rates have to be converted to the amount of N emitted (44% of the amount of N_2O) and be set in relation to a synthetic fertilizer application rate of 90 kg N ha^{-1}. In turn, the relative amount of applied N that was emitted as N_2O was 0.14%. The percentage is in a lower range than the IPCC default (0.3%) given for flooded rice fields (IPCC, 2019).

As for AWD, however, the refined IPCC guidelines of 2019 introduced a separate value, namely 0.5% of the applied N fertilizer, to account for the empirical findings of slightly enhanced N_2O emissions under frequent drainage. Our data also showed a similar level of N_2O emissions in AWD across the seasons by 0.49 kg N_2O ha^{-1}. In terms of EFs, our data indicate 0.24% which is again lower than the given IPCC value. However, the standard deviation is too high (Figure 8) for giving a solid confirmation of the magnitude of the IPCC Emission Factor for AWD versus CF.

5 | CONCLUSION

To the best of our knowledge, this study represents the first systematic screening of the interaction of rice variety selection and water management on GHG emissions. Since rice varieties often have been selected to perform best in a specific production environment, special adaptations, such as varietal GHG emissions are best tested within the target environment in the genetic diversity that is present in the system. The 20 varieties that have been screened in this study represent a section through the genetic diversity of rice in the Vietnamese MRD and although not transferable to rice in general, this study offers several generic take-home messages on the role of varietal emissions within mitigation efforts in rice production.

The data generated in this study demonstrated that variety-dependent GHG emissions cannot be expressed through a monocausal potential for a given variety, but is determined by a complex interaction of genetic and environmental factors alongside crop management. This $G \times E \times M$ relationship as found in our field study is further elucidated by Asch et al. (2023). In line with the objectives shown above, the principal purpose of this publication was to document the field measurements and the resulting database. The latter included the overall range of variety-dependent emission rates whereas the possible exploitation of the results in future mitigation projects is only addressed generically and has to be referred to Asch et al. (2023). As a general take-home message, the varietal effects are much smaller than water management effects, so it will be crucial to define a specific 'niche' for this approach within the available mitigation strategies over space and time.

Varietal variation was largest for CH_4 emissions under CF. Under AWD CH_4 emissions were generally strongly reduced with the varietal effect being of minor importance. For both irrigation methods, N_2O emissions played a minor role and varietal effects were small. Therefore, if AWD can be implemented, the choice of variety is of minor importance since for all varieties, the SFs. On the contrary, the choice of variety can have a decisive influence on CH_4 emissions if drainage capacities are insufficient or the field remains flooded for most of the season during periods of heavy rainfall.

In addition, shifting from CF to AWD often does not agree with the farmers' preferences in the adoption of technological changes. The relative ease of interventions in seed distribution to farmers, either supplied by local governments or accessed from the private sector, is a well-established fact derived from numerous development projects whereas rice farmers are generally more reluctant to change water management. Thus, the proper selection of varieties should be factored into mitigation efforts, either as an additional measure to maximize the AWD effect during the dry season or as a stand-alone mitigation option in locations or seasons where mitigation through AWD is not possible.

AUTHOR CONTRIBUTIONS

Thi Bach Thuong Vo: Writing – original draft; writing – review and editing; conceptualization; investigation; formal analysis; methodology; data curation; validation. **Kristian Johnson:** Writing – original draft; formal analysis; software. **Reiner Wassmann:** Writing – original draft; writing – review and editing; conceptualization; investigation; formal analysis; methodology; validation; supervision. **Bjoern Ole Sander:** Funding acquisition; methodology. **Folkard Asch:** Supervision; project administration; funding acquisition; conceptualization; investigation; methodology; writing – original draft; writing – review and editing; formal analysis.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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