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Mitigation of greenhouse gas emissions and reduced irrigation water use in rice production through water-saving irrigation scheduling, reduced tillage and fertiliser application strategies

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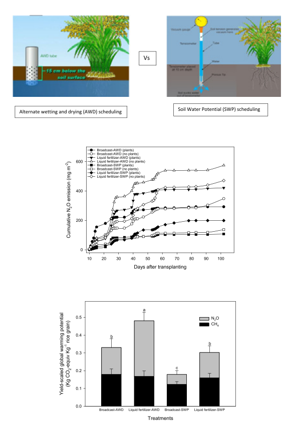
HIGHLIGHTS

- Soil water potential (SWP) scheduling was compared with alternate wetting and drying (AWD)
- AWD and broadcasting fertilisation perform better in terms of maintaining yield
- SWP scheduling reduced N_2O and CH_4 emissions up to 66 and 34% respectively
- Liquid fertilisation/fertigation was only effective in reducing N_2O emission under SWP
- Reduced tillage and SWP irrigation scheduling significantly reduced water use
- Global warming potentials were reduced up to 54% in SWP scheduled reduced tillage treatments.

GRAPHICAL ABSTRACT



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ABSTRACT

Rice production systems are the largest anthropogenic wetlands on earth and feed more than half of the world's population. However, they are also a major source of global anthropogenic greenhouse gas (GHG) emissions. Several agronomic strategies have been proposed to improve water-use efficiency and reduce GHG emissions. The aim of this study was to evaluate the impact of water-saving irrigation (alternate wetting and drying (AWD) vs. soil water potential (SWP)), contrasting land establishment (puddling vs. reduced tillage) and fertiliser application methods (broadcast vs. liquid fertilisation) on water-use efficiency, GHG emissions and rice yield. The experiment was laid out in a randomised complete block design with eight treatments (all combinations of the three factors) and four replicates. AWD combined with broadcasting fertilisation was superior to SWP in terms of maintaining yield. However, seasonal nitrous oxide (N_2O) emissions were significantly reduced by 64% and 66% in the Broadcast-SWP and Liquid fertiliser-SWP treatments, respectively, compared to corresponding treatments in AWD. The SWP also significantly reduced seasonal methane (CH_4) emissions by 34 and 30% in the broadcast and liquid fertilisation treatments, respectively. Area-scaled GWPs were reduced by 48% and 54% in Broadcast-SWP and Liquid fertiliser-SWP treatments respectively compared to the corresponding treatments

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in AWD. Compared to AWD, the broadcast and liquid fertilisation in SWP irrigation treatments reduced yield-scaled GWPs by 46% and 37%, respectively. In terms of suitability, based on yield-scaled GWPs, the treatments can be ordered as follows: Broadcast-SWP < Broadcast-AWD = Liquid fertiliser-SWP < Liquid fertiliser-AWD. Growing-season water use was 15% lower in the SWP treatments compared with the water-saving AWD. Reduced tillage reduced additional water use during land preparation. The conclusions of this study are that improved water management and timely coordination of N fertiliser with crop demand can reduce water use, N loss via N_2O emissions, and CH_4 emissions.

1. Introduction

As the world's population increases, agriculture faces the enormous challenge of providing sufficient healthy food while minimising its environmental consequences in the face of challenges like water scarcity and climate change (Foley et al., 2011; Linquist et al., 2012a, 2012b). Rice is an important staple food, feeding >50% of the global population, is critically important for global food security and sustainable food future (Maclean et al., 2002; Fageria, 2007; Islam et al., 2020). Irrigated rice production in Asia produces approximately 75% of the world's rice supply (Cantrell and Reeves, 2002; Qin et al., 2006). To meet the rising food demand from an ever-increasing population, rice production has to increase by 40% by the end of 2030 (FAO, 2009). Thus, Asian rice farmers must sustainably increase their production to maintain food security since rice is the main staple food in this region. However, the rapidly increasing population and associated water demands for urban and industrial use have put a strain on the freshwater resources affecting rice production (Bouman, 2007; Hussain and Abed, 2019; Solangi et al., 2019). Across Asia, as in many agricultural regions of the world, the effects of climate change are also impacting production, and the frequency of both the physical and economic scarcity of water, labour, land and energy is increasing (Bouman et al., 2005; Alberto et al., 2013). Rice growing areas of South Asia and Southeast Asia will be particularly vulnerable to global climate change impact (Wassmann et al., 2009). In this region rice yields are projected to reduce by 3.2–22% depending on the severity of air temperature increase (1–4 °C) by the end of this century despite farmers' adaptation efforts (Mathauda et al., 2000; IPCC, 2007; Lobell et al., 2011; Ray et al., 2012; Zhao et al., 2017). For some parts of South Asia, yield can be reduced as high as −6.6% per degree Celsius temperature increase (Zhao et al., 2017). The increase in minimum temperature during rice cropping seasons increases the maintenance respiration requirement of the crops and shortens the time to maturity, thus reduces net growth and productivity (Wheeler et al., 2000; Lal, 2011). Studies also reported that an increase in night-time temperatures by 1.1 °C associated with global warming linked to increasing concentrations of greenhouse gases could cause rice yields to fall by 10% (Peng et al., 1995; Peng et al., 2004; FAO, 2005; Hundal, 2007). The characteristic of rice-based Asian agriculture depended on sufficient water all the time since rice is mostly cultivated in a flooded condition. Yet, the spatial and temporal distribution of rainfall has become increasingly uncertain along with a decline in the number of rainy days during the monsoon season (Meehl et al., 2007). A further change of climate projected to trigger 10–15% decrease in both winter and summer rainfall and reduction or more variable water resources for irrigation disrupting rice production (Lal, 2003, Faruque and Ali, 2005; Lal, 2005; Meehl et al., 2007; Lal, 2011). Moreover, the occurrence of weeds, insects and diseases in the continuous cropping of cereals like rice are projected to increase with the rise in surface air temperatures and is a real threat to rice production in the years to come (Aggarwal et al., 2004; Lesk et al., 2016). Thus, in the absence of mitigation and adaptation strategies, rice yield potential in these rice-growing countries are projected to decline by about 50% by 2100 (Sekhar, 2018). To achieve food security for future generations, it will be necessary to develop more sustainable agronomic technologies and methods to increase productivity and the efficiency of resource use in farming systems while mitigating and adapting to the impacts of climate change. Thus, rice production must increase with less irrigation water and labour and the introduction of water and labor-saving technologies in rice farming will be necessary in many parts of Asia to ensure that necessary agricultural productivity gains are realised and sustained.

The majority of rice produced in Asia comes from irrigated production systems, traditionally grown under continuously flooded (CF) conditions that require large amounts of water. Rice places a heavy demand on freshwater resources, consuming >45% of total freshwater resources in Asia and approximately 30% of the world's freshwater irrigation resources (Bouman and Tuong, 2001; Bouman et al., 2007). It is estimated that a shortage of water will have an impact on 15–20 million hectares of Asia's irrigated rice by 2025 (Tuong and Bouman, 2003). A number of water-saving strategies have therefore been developed for rice production systems. The most common of these are alternate wetting and drying (AWD) and irrigation scheduling informed by soil water potential (Mahajan et al., 2012; Siopongco et al., 2013; Sander et al., 2014; Sudhir-Yadav et al., 2012; Yao et al., 2012a, 2012b). The practice of AWD involves intermittent irrigation events with periods of non-flooding, with the water level dropping below the soil surface between each irrigation. Depending on the frequency of wetting-drying cycles and the extent of drying, AWD has been reported to reduce irrigation water use by 7–33% compared with traditional continuously flooded rice systems, with no significant impact on yield (Bouman and Tuong, 2001; Rejesus et al., 2011; Carrijo et al., 2017; Islam et al., 2020), although AWD can negatively affect yield if not carefully managed (Towprayoon et al., 2005; Linquist et al., 2015). The International Rice Research Institute (IRRI) has developed practice guidelines for "safe AWD" (Bouman et al., 2007; Lampayan et al., 2015). Generally, safe AWD maintains a soil water potential between saturation events of around −10 kPa in the topsoil, which is considered non-limiting to the rice crop.

Similar to AWD, irrigation based on soil water potential (SWP) with flush irrigation can effectively maintain soil water potential at −10 kPa in the top 15 cm of the soil profile. Soil water potential irrigation scheduling in rice can achieve greater water savings than AWD (Tuong et al., 2005). Although the high application efficiency of soil water potential irrigation scheduling can further reduce the water requirements of rice production, yield declines are frequently reported in such systems (Bouman et al., 2005). Belder et al. (2004), however, found that there was no impact on rice yield when the soil water potential was maintained at −10 kPa. Irrigated rice production with accurate and timely irrigation scheduling to maintain the soil water potential can thus reduce water requirements.

Rice production systems are one of the most important sources of anthropogenic methane (CH_4) emission (Le Mer and Roger, 2001). Estimates indicate that these systems are responsible for approximately 15–20% of the annual global anthropogenic efflux of CH_4 (Linquist et al., 2012a, 2012b). The global warming potential (*GWP*) from rice systems is approximately four times that from wheat (*Triticum aestivum*) or maize (*Zea mays*). Linquist et al. (2012a, 2012b) calculated that rice systems emit 100 kg CH_4 ha^{-1} $season^{-1}$ on average, which accounts for 89% of the *GWP* from rice production. The practice of AWD can reduce CH_4 emissions by 40–93% (Qin et al., 2010; Pandey et al., 2014; Linquist et al., 2015; Xu et al., 2015; Sander et al., 2016; Islam et al.,

2020) and soil water potential irrigation scheduling can reduce CH_4 emissions even more due to the higher redox potential resulting from increasingly aerobic soil conditions (Kreye et al., 2007). However, both AWD and soil water potential irrigation scheduling increase the risk of nitrous oxide (N_2O) emission compared to flood-irrigated rice, as the redox potential is often in the optimal range for N_2O production (Kreye et al., 2007).

In addition to increasing the efficiency of water use and adapting to climate change, rice production systems in Asia are also facing constraints in terms of labour and energy resources. The process of puddling (wet tillage) in land preparation accounted for up to 30% of the total irrigation water application in dry season (typically requires 200–250 mm of water (Bouman et al., 2007; Mahajan et al., 2011; Rashid et al., 2018)) and is both labour (>60 h of manual labour per ha (Quilty et al., 2014)) and energy-intensive. Puddling creates a soil environment that increases water retention, achieves effective weed control and enables crop establishment of rice by manual transplanting because the puddled soil is soft. Soil puddling also destroys soil aggregates, breaks capillary pores, disperses clay particles and creates a plough pan that impedes root penetration for following crops like wheat or maize (Haque et al., 2016; Haque and Bell, 2019).With the introduction of mechanical transplanters, it is possible to transplant rice into un-puddled soil. The previous study shows that adoption of non-puddled reduced tillage may be a good alternative to puddling of soil which has the potential to achieve savings in labour, energy, water and time during land establishment and give similar or higher rice yields and lowered total cost of production (Ahmed et al., 2002; Islam et al., 2014; Haque et al., 2016; Rashid et al., 2018). Until now, both conventional continuous flooding practice and water-saving AWD practice typically use puddling practice for land preparation. However, the more water-saving alternative like SWP scheduling is new and can benefit from the additional reduction of water use by reduced tillage land preparation. As SWP scheduling plots use less standing water than other alternatives these fields also suitable for growing other crops (Rice-Wheat systems) which will benefit from non-puddling practice reduced tillage practice. However, the effect of reduced tillage with water-saving SWP on yield still unknown. Moreover, the effects on GHG emissions of omitting puddling have not been thoroughly examined.

Similarly, the process of fertiliser application in irrigated systems across Asia is usually an intensive manual operation (Quilty et al., 2014), and the production of fertilisers requires a large amount of energy, which is still mostly fossil-fuel derived, with a relatively large carbon footprint. Increasing the crop use efficiency of fertiliser nutrients and reducing the labour demands in fertiliser application could potentially be achieved through the use of fertigation, which is the controlled administration of fertiliser nutrients with irrigation water (Li et al., 2003; Scheer et al., 2008) or liquid fertiliser application that is separate from the irrigation events. Although in the past decade greater knowledge and technology have been applied to farming practices worldwide and farmers' capabilities have increased, the use of these techniques is very limited in rice agroecosystems due to greater technical and financial requirements as well as limited knowledge about the benefits of these relatively high-tech solutions. However, in the current climate reality and foreseeable future, these can help to drastically reduce water use and achieve low-emission agriculture. There is also very limited scientific literature available on the efficiency of fertigation or liquid fertiliser application in rice production and its influence on GHG emissions to understand their impact compared with the currently available practice followed by farmers.

Moreover, rice plants strongly affect the methane flux in paddy soils under conventional continuous flooded practice. They supply additional organic matter derived from rhizodeposition (root exudation, sloughed-off cells and decay of roots) to the soil microbial community (Conrad, 2002; Conen et al., 2010). Rice plants also act as vents for gas exchanges between soils and the atmosphere through their aerenchyma (Minami and Neue, 1994). This transport pathway allows for the diffusion of O_2 from the atmosphere to the root zones and also the diffusion of CH_4 from the rhizosphere to the atmosphere (Conrad, 2002). This highlights the importance of rice plants for CH_4 production. Similarly to CH_4 emission, rice plants may affect N_2O emission due to the impact of plants on soil C and N cycling (Pathak, 1999; Baggs and Philippot, 2010; Ly et al., 2013). Plants can directly influence NO_3- availability through uptake and assimilation, making it unavailable to denitrification (Pathak, 1999), reducing N_2O emission. However, how the presence or absence of rice plants affect CH_4 and N_2O emission due to different water-saving irrigation and fertilisation techniques has not been extensively studied.

The aim of this study was to evaluate the impact of contrasting land preparation, irrigation and fertiliser application methods on water-use efficiency, GHG emissions and rice yield. The water-saving irrigation practices assessed in this study were safe AWD and soil water potential irrigation scheduling. These were evaluated along with the land preparation methods of puddling and non-puddled reduced tillage and the broadcast and liquid fertiliser application methods. It was hypothesised that: i) the soil water potential irrigation method results in reduced irrigation water use and CH_4 emissions, and increased N_2O emissions compared with surface irrigation under safe AWD, with no influence on grain yield; ii) liquid fertiliser application reduces CH_4 and N_2O emissions and increases grain yield compared with the broadcast solid fertiliser method under each irrigation regime; iii) no-plant treatments have lower CH_4 emissions and higher N_2O emissions than treatments with plants in both water regimes.

2. Materials and methods

2.1. Site characteristics, treatments and experimental design

The field experiment was conducted during the dry season (January–May) in 2015 at the Zeigler Experimental Station (Block UQ) of the International Rice Research Institute (IRRI) in Los Baños, Laguna, in the Philippines. The site has an elevation of 27 m above mean sea level. The average annual mean air temperature is 27.4 ± 0.4 °C with an average yearly precipitation of 2115 mm (1979–2015). The soil at the experimental site is Lithic Haplustept with a silty loam texture (Soil Survey Staff, 2010). Soil properties include pH of 6.2 (1:1 soil/water suspension), Olsen P of 18–19 mg kg^{-1}, exchangeable K of 0.8–0.9 $cmol_c$ kg^{-1}, organic C of 11 g kg^{-1}, total N of 1.4–1.6 g kg^{-1} and a cation exchange capacity of 27 $cmol_c$ kg^{-1}. The study site has historically been continuously cropped with paddy rice.

The experiment was laid out in a randomised complete block design with eight treatments and four replicates with a main plot size of 96 m^2 each (20 × 4.8 m). All the plots were under surface irrigation. In puddled plots, however, irrigation was scheduled based on AWD principles using a field tube, while in non-puddled reduced-tillage plots irrigation was scheduled with soil water potential (SWP) and these are henceforth referred to as SWP plots. While AWD typically follows puddling land preparation in practice, the SWP scheduling practice is new, and reduced-tillage land preparation was added to boost its water-use efficiency in this study. The experimental treatments were i) Broadcast-AWD (plants) ii) Broadcast-AWD (no plants) (iii) Liquid fertiliser-AWD (plants) iv) Liquid fertiliser-AWD (no plants) v) Broadcast-SWP (plants) vi) Broadcast-SWP (no plants) vii) Liquid fertiliser-SWP (plants) viii) Liquid fertiliser-SWP (no plants).

At the start of the season, puddled plots (AWD) were prepared by dry tillage as the primary cultivation, followed by land soaking + one pass with a primary tillage mouldboard plough (wet) + two passes puddling (wet) + two passes harrowing (wet) + one pass land levelling (wet), and finally maintaining standing water for 48 h prior to transplanting. SWP plots were prepared by one primary tillage with a disc plough (dry) + land soaking + levelling single pass (wet) + manual levelling (wet) + land soaking 48 h prior to transplanting. Fourteenday-old rice seedlings were transplanted manually with a spacing of 20 cm × 20 cm in all plots. The variety used was NSIC Rc18, a high-yielding inbred lowland irrigated variety. In the treatment without plants, any rice hills were uprooted to ensure that no plants were inside the flux chamber. To control golden apple snails, a molluscicide was applied immediately after transplanting in all plots. For weed management, the pre-emergent herbicides Pretilachlor and Butachlor were applied in the puddled and reduced-tillage plots, respectively. Hand weeding was conducted from ~21 days after transplanting (DAT) in all plots to ensure that the results were not influenced by weed competition. In this experiment, weeds effectively controlled in both treatments by using herbicides (pretilachlor/butachlor) and need-based hand weeding.

All the puddled plots closely followed the IRRI's recommendations for "safe AWD" water management, which involves repeatedly flooding the field, typically to a water depth of around 5 cm. The field is then allowed to dry until the water level drops to 15 cm below the soil surface, which is generally equivalent to −10 kPa, before the field is reflooded. AWD tubes made of perforated plastic pipes were installed in each of the research plots to monitor the field water level (FWL). In this study, surface-irrigated AWD started on 14 DAT and the wetting and drying cycles were allowed to continue until flowering to facilitate water saving.

In the reduced-tillage SWP plots, irrigation scheduling was based on the SWP readings of tensiometers placed at a depth of 15 cm in this study. Irrigation was applied when the average SWP readings reached −10 kPa at 15 cm depth. This depth was selected as most of the rice roots are concentrated up to 15 cm soil depth (Kukal and Aggarwal, 2003), and the tensiometers were placed immediately below this depth. A hole was made in the soil up to 16 cm depth having a diameter slightly larger than that of the tensiometer tip. Before lowering the tensiometer into the hole, soil-water slurry was put into the hole so as to ensure soil-tensiometer tip contact for efficient working of the tensiometer. After lowering the tensiometer into the soil, the space around it was thoroughly packed with the excavated soil. The whole instrument was filled with de-aerated water and the silicon cork fitted tightly into the position to ensure leak-proof system. One tensiometer was installed in each treatment and in all replications at a representative site at least 2-m inside the plot to avoid edge effects. Irrigation was applied when the average SWP readings reached −10 kPa at 15 cm depth in the centre of beds. The soil matric potential readings were observed daily between 8:00 a.m. and 9:00 a.m. Irrigation was applied between 8:30 a.m. and 9:30 a.m. A flow meter was used to record the amount of water used for each irrigation of each plot. The water used for irrigation originated from deep wells pumped into a reservoir and contained low levels of bicarbonates and nitrates (pH: 7.98; HCO_3^-: 0.00538 mol L^{-1}; NO_3^--N: <0.1 mg N L^{-1}) (Alberto et al., 2013). Irrigation scheduling for the first 14 days aimed to maintain saturated soil conditions with no standing water to control snails. At 14 DAT, both AWD and SWP irrigation scheduling was implemented.

Fertiliser was applied basally at the rates of 25 kg N ha^{-1}, 45 kg P ha^{-1} and 35 kg K ha^{-1} ten days after transplanting; additional urea fertiliser was applied on three dates (24, 38 and 52 DAT) at rates of 45, 45 and 35 kg N ha^{-1} respectively, totalling 150 kg N ha^{-1}. Plots on which both broadcasted solid (pelletised) fertiliser and liquid fertiliser (aqueous solution of urea) were applied received the same N rate and schedules for fertilisation. Liquid fertiliser was applied using a large handheld boom spray consisting of a tube with evenly spaced holes applying the liquid fertiliser solution across the plots. Some of the liquid fertiliser solutions were therefore applied to rice plant leaves, but the majority reached the soil/paddy water surface.

2.2. Greenhouse gas measurements and flux calculations

Gas fluxes were measured 31 times during the growth period on 10, 11, 12, 13, 14, 15, 21,25, 26, 27, 28, 29, 34, 39, 40, 41, 42, 43,47, 53, 54, 55, 56, 57, 62, 68, 78, 83, 91, 102, 111 DAT, on all occasions between 8:30 am and 11:45 am as the soil temperature during this time was close to the mean daily soil temperature (Zou et al., 2005). Emissions of CH_4 and N_2O were measured using a static chamber method (Minami and Yagi, 1988; Rochette and Eriksen-Hamel, 2008, Fig. 1). Each flux chamber was anchored by a stainless steel base chamber measuring 40 cm × 22 cm × 12 cm (length, width and height respectively) that was inserted into the soil a week before the first gas sampling at about 10 cm depth. The top chambers for gas collection used in this study were made from Plexiglas and were 40 cm long x 22 cm wide with variable heights of 11, 42 and 81 cm in order to accommodate the increasing height of the growing plants in different growth stages inside the flux chamber, following common practices described in Sander et al. (2014). Each flux chamber consisted of a vent to allow pressure equilibration, a thermometer, two fans operated by a 12 V battery to ensure well-mixed air during sampling, and a gas sampling port to collect gas samples. Each chamber included two rice hills inside the chamber for gas sampling. After 0, 10, 20 and 30 min from chamber closure, gas samples were taken by a 60-mL syringe attached with a stopcock. Immediately afterwards, the gas samples were injected into a pre-evacuated vial of 30 mL and the concentration of CH_4 and N_2O emissions were analysed in the laboratory by a gas chromatograph (SRI GC-8610C). Hourly emissions 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) and LaHue et al. (2016). The gas fluxes were calculated using the following equation according to Smith and Conen (2004) and Khalil et al., (2020)

$$F = \frac{\Delta C}{\Delta t} \cdot \frac{v}{A} \cdot \frac{M}{V} \cdot \frac{P}{P_0} \cdot \frac{273}{T}$$

where ΔC is the change in concentration of the gas of interest in time interval Δt, v and A are the chamber volume and soil surface area, respectively, M is the molecular weight of the gas of interest, V is the volume occupied by 1 mol of the gas at standard temperature and pressure (22.4 L), P is the barometric pressure (mbar), P_0 is the standard pressure (1013 mbar), and T is the average temperature inside the chamber during the deployment time (K).

The cumulative emission of CH_4 or N_2O over the rice-growing season was calculated from the integration of the area under the curve of each measurement point according to Adviento-Borbe et al., (2013) and Vu et al. (2015). The area between two adjacent intervals of the measurement days was calculated using the trapezoid formula as follows:

$$A_{t(ab)} = \frac{(t_b - t_a) \cdot (F_{ta} - F_{tb})}{2}$$

where $A_{t(ab)}$ is the area of the two adjacent intervals of the measurement days (between t_a and t_b), t_a and t_b are the dates of the two measurements, respectively, and F_{ta} and F_{tb} are the fluxes of the gas of interest at the two measurement dates, respectively.

Therefore, the cumulative emission of CH_4 or N_2O over the rice growing cycle can be calculated using the following formula: Cumulative emission of CH_4 or $N_2O = \sum A_{t(ab)}$.

2.3. Irrigation water-use efficiency, GWP and yield-scaled GWP

Irrigation water-use efficiency (WUEi, kg grain m^{-3} irrigation water) was calculated as the grain yield per amount of irrigation water applied (Sinclair et al., 1984). The global warming potential (GWP) of N_2O and CH_4 emissions was calculated in CO_2 equivalents over a 100-year time horizon. For N_2O and CH_4, the radiative forcing potential relative to CO_2 with the inclusion of climate-carbon feedbacks was 298 and 34 respectively, therefore seasonal N_2O fluxes were multiplied by a factor of 298 and CH_4 fluxes by a factor of 34 for GWP computation (Myhre et al., 2013; IPCC, 2013). To calculate yield-scaled GHG emissions, CO_2-equivalent emissions (net GWP) were divided by rice

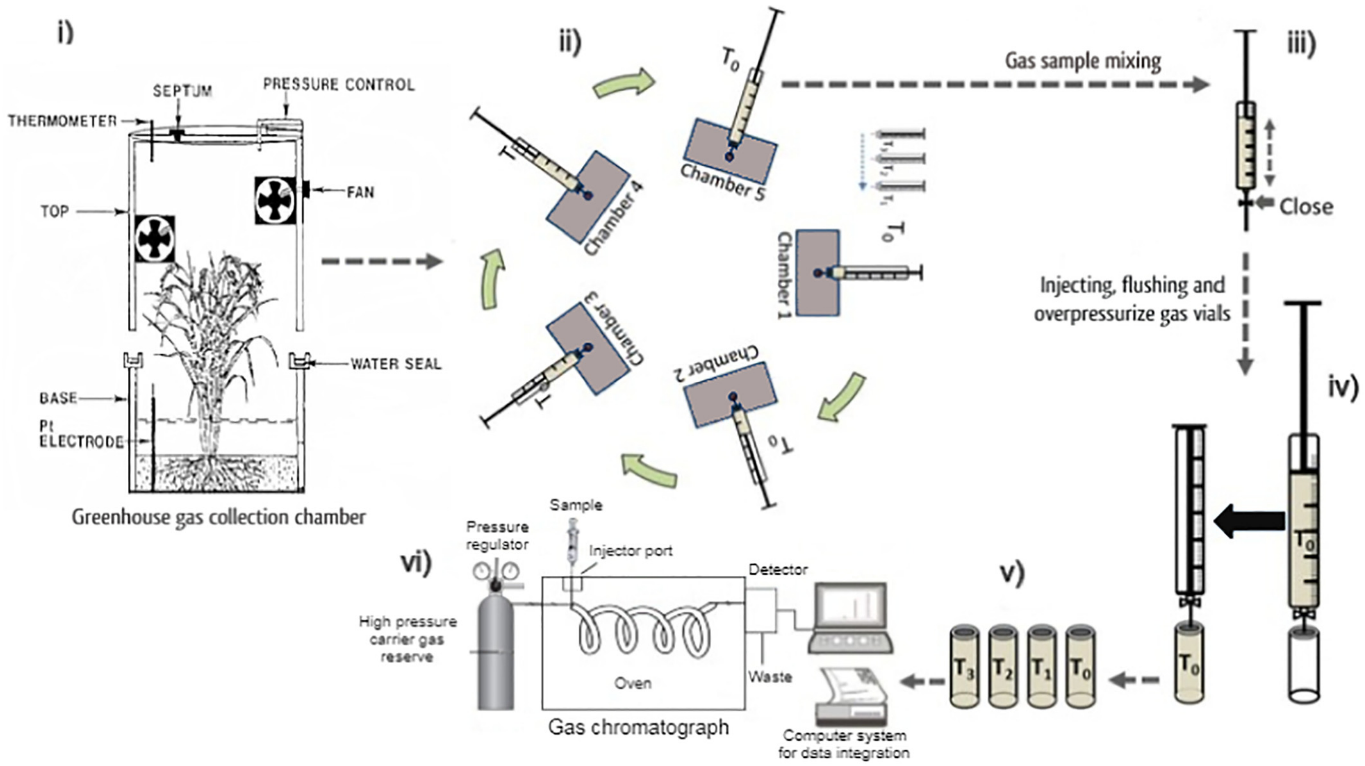

Fig. 1. Schematic presentation of various steps and instrumentation of greenhouse gas sampling and analysing: i) chamber for collecting greenhouse gas, ii) gas pooling across chambers for a given sampling time, iii) gas sample mixing within the syringe, iv) transfer of the gas sample to a vial, v) four vials for four sampling times and five chambers, vi) gas sample analysis using gas chromatography and data analysis by the computer system.
(Adapted from Lindau et al., 1991; Islam et al., 2018; Butterbach-Bahl et al., 2016).

grain yield expressed in kg CO_2-equivalents per kg of grain yield (Van Groenigen et al., 2010).

2.4. Statistical analysis

For statistical analysis, Statistical Analysis System (SAS) software version 9.4 (SAS Institute Inc., USA) was used in this study. The independence, normality and homogeneity of variance of the dataset were examined, and all the data met the assumptions without transformation. PROC MIXED in SAS software was used to perform analysis of variance (ANOVA) with the general linear model (GLM) procedure, with repeated separate measures of CH_4 and N_2O fluxes. The dependent variables of grain yield, seasonal CH_4 and N_2O emissions, GWP and yield-scaled GWP were analysed using the GLM Procedure in SAS. Where differences between treatments were identified, Tukey's HSD test was used to determine the significance of the differences at the 95% level ($P < 0.05$).

3. Results

3.1. Grain yield, water use and irrigation water-use efficiency

The highest rice grain yield was found in the Broadcast-AWD treatment (5.1 Mg^{-1} ha^{-1}), which was 20% higher than that of the Liquid fertiliser-AWD treatment (4.1 Mg^{-1} ha^{-1}, Table 1). In the Broadcast-SWP treatment, the yields were similar to Broadcast-AWD, but again were significantly higher (4.9 Mg ha^{-1}) than the Liquid fertiliser-SWP treatment (3.0 Mg ha^{-1}).

The average daily water use in AWD was significantly higher than in the SWP irrigation treatments, i.e. 1.94 and 1.64 m^3 $plot^{-1}$ for the AWD and SWP irrigation treatments, respectively. The seasonal irrigation water uses in the AWD treatments averaged 12,321 m^3 ha^{-1}. On average, 15% less water was used with the SWP treatments than with the water-saving AWD treatments. Irrigation water-use efficiency was highest in the Broadcast-SWP treatment (0.49 kg grain m^{-3}), which was significantly higher than in the Liquid fertiliser-SWP treatment, but no different from the Broadcast-AWD treatment. However, due to a lower yield, the lowest irrigation water-use efficiency was found in the Liquid fertiliser-SWP treatment with 0.27 kg grain m^{-3}.

3.2. Methane emissions

The temporal variations in net CH_4 fluxes were strongly influenced by water management regimes in this study. Methane emissions in the various water treatments were generally low and varied during the season. In general, CH_4 fluxes decreased with time and returned to background levels when rice fields were drained prior to harvesting (end of April). In the Broadcast-AWD water regime, CH_4 emissions were recorded a few days after the initial field flooding and they peaked at 14, 34 and 47 DAT, whereas in the Liquid fertiliser-AWD treatment, CH_4 emissions started to increase slowly at the start and then showed the highest individual measurements at 10, 34 and 57 DAT (Fig. 2). Mean CH_4 fluxes during the growing season were 28.7 and 20.4 mg CH_4 m^{-2} day^{-1} respectively in the Broadcast-AWD and Liquid fertiliser-AWD treatments with plants. Similar to the AWD water regime, the CH_4 fluxes in the SWP irrigation treatments fluctuated, but emissions were generally low. Growing season mean CH_4 emissions of Broadcast-SWP and Liquid fertiliser-SWP treatments with plants were 22.6 and 15.7 mg CH_4 m^{-2} day^{-1} respectively. Relative to broadcast fertilisation, liquid fertilisation (with plants) significantly decreased CH_4 emission by 25% in the AWD water regime and by 21% for SWP regime (Table 2). Seasonal CH_4 emissions varied between 14 and 27 kg CH_4 ha^{-1} $season^{-1}$ for treatments with plants and between 10 and 16 kg CH_4 ha^{-1} $season^{-1}$ for treatments without plants. In general,

Table 1
Irrigation water use, both daily average and seasonal (m^3 ha^{-1}), and irrigation water-use efficiency $IWUE_y$ (kg m^{-3}) in the rice-growing season.*

Treatments	Irrigation water use		Grain yield ($Mg\ ha^{-1}$)	Irrigation water-use efficiency, $IWUE_y$ ($kg\ m^{-3}$)
	Daily average water use (m^3 $plot^{-1}$)	Seasonal water use (m^3 ha^{-1})		
Broadcast-AWD	1.91 ± 0.05^a	$12,145 \pm 363^a$	5.15 ± 0.25^a	0.42 ± 0.02^b
Liquid fertiliser-AWD	1.96 ± 0.07^a	$12,498 \pm 377^a$	4.11 ± 0.33^b	0.33 ± 0.03^c
Broadcast-SWP	1.60 ± 0.03^b	$10,179 \pm 246^b$	4.94 ± 0.24^a	0.49 ± 0.02^a
Liquid fertiliser-SWP	1.69 ± 0.03^b	$10,763 \pm 247^b$	3.02 ± 0.31^c	0.27 ± 0.02^d

* Data shown are means ± standard deviation of four replicates. Within the column, values with different letters are significantly different at the $p < 0.05$ level.

cumulative CH_4 emissions were higher in the AWD treatments than in the SWP treatments (Fig. 3). The highest cumulative CH_4 emissions were recorded from the Broadcast-AWD (plant) treatment and the lowest from the Liquid fertiliser-SWP (no plants) treatment.

The SWP (with plants) regime significantly reduced growing season CH_4 emissions by 34 and 30% for broadcast and liquid fertilisation treatments, respectively, compared to their corresponding treatments in AWD. Generally, all the treatments without plants resulted in lower CH_4 emissions compared with the corresponding planted treatment, which averaged a seasonal emission of just 13.5 kg CH_4 ha^{-1} (Table 2). The average seasonal emission of treatments with plants was 19.9 kg CH_4 ha^{-1} $season^{-1}$. On average, the presence of plants significantly increased seasonal CH_4 fluxes by 32% in these two water-saving regimes compared to no-plant treatments.

3.3. Nitrous oxide emissions

Nitrous oxide fluxes showed consistently low daily average emissions, with the exception of peaks (Fig. 2) following fertilisation events. This effect of fertilisation method on daily N_2O flux was observed in all treatments within a week of fertiliser application. Four peaks were recorded in all treatments at approximately 10–14, 25–26, 40–42 and 55–56 DAT, corresponding to the period following N fertiliser application. Growing season average N_2O fluxes were 6.72, 9.84, 1.44 and 3.60 mg N_2O m^{-2} day^{-1} in the Broadcast-AWD, Liquid fertiliser-AWD, Broadcast-SWP and Liquid fertiliser-SWP treatments respectively. In general, cumulative N_2O emissions were significantly higher in the liquid fertilisation treatments and lower in the broadcast treatments (Fig. 4). The highest cumulative N_2O emissions were recorded from the Liquid fertiliser-AWD (no plant) treatment and the lowest from Broadcast-SWP (plants) treatments.

In terms of water treatment, the cumulative seasonal N_2O fluxes were significantly lower in the SWP irrigation treatments than in the AWD treatments (Table 2). Within the AWD water regime, liquid fertilisation significantly increased N_2O emission by 66% compared with broadcasting. Broadcast and liquid fertilisation with plants resulted in similar N_2O emissions in SWP irrigation, while seasonal N_2O emissions were significantly reduced by 64% and 66% in the Broadcast-SWP and Liquid fertiliser-SWP treatments, respectively, compared with the corresponding treatments in the AWD water regime. Treatments without plants showed significantly higher seasonal N_2O emissions in both water regimes except for Broadcast-SWP, where seasonal N_2O emissions were numerically higher in the no-plants counterpart. However, the difference was not significant.

3.4. GWP and yield-scaled GWP

The *GWP* from the liquid fertiliser-AWD treatment was highest (1978 kg CO_2 equivalent $season^{-1}$), while the lowest *GWP* was recorded from the Broadcast-SWP (886 kg CO_2 equivalent $season^{-1}$) treatment (Table 2). In contrast to the typical flooded rice systems, N_2O played a major role in the seasonal global warming potential (*GWP*) for all treatments in this study (Table 2). Seasonal *GWPs* were significantly reduced by 48% and 54% in Broadcast-SWP and Liquid fertiliser-SWP treatments respectively than in the corresponding treatments in the AWD water regime, mainly due to the reduction in N_2O emissions.

Yield-scaled *GWP* was highest in the Liquid fertiliser-AWD treatment, averaging 0.48 kg CO_2 eq kg^{-1} rice grain (Fig. 5). The lowest yield-scaled GWP (0.17 kg CO_2 eq kg^{-1} rice grain) was recorded from the Broadcast-SWP treatment. In the SWP irrigation treatments, yield-scaled GWP was 46% and 37% lower with broadcast and liquid fertilisation respectively than in the AWD treatments (Fig. 5).

4. Discussion

4.1. Grain yield and water use

Grain yield in this study was affected by both the irrigation and the fertilisation methods applied. The highest rice grain yield was found in the Broadcast-AWD treatment (5.1 Mg ha^{-1}), which was 20% higher than that of the Liquid fertiliser-AWD treatment (Table 1). Previous studies in the same location/upland farm of IRRI's experimental station in dry-season under conventional practice reported rice yield varied between 3.8 and 4.4 Mg ha^{-1} (Opena et al., 2014; Romasanta et al., 2017). Our results are in agreement with previous studies by Zhang et al. (2009), Qin et al. (2010), Ye et al. (2013), Chu et al. (2015), and Islam et al. (2020) who observed an increase of rice yields for intermittent water regimes. In contrast, other studies observed decrease of rice yields (Minamikawa and Sakai, 2005; Towprayoon et al., 2005; Kudo et al., 2014; Linquist et al., 2015) by water suppression in determined periods of rice cycle, and this apparent divergence is related to differences of drainage frequency, degree and duration of the water stress for rice plants, rice variety, among others (Feng et al., 2013). In general, in our study AWD resulted in a higher yield than the SWP water regime, which may be linked to the differences in their drainage frequency and the degree and duration of water stress for the rice plants. Although no significant difference was found between the Broadcast-AWD treatment and the Broadcast-SWP treatment, AWD resulted in a significantly higher yield in the liquid-fertilised plots than SWP. However, both the liquid fertiliser-AWD and liquid fertiliser-SWP irrigation scheduling plots in the current study resulted in a significantly lower yield than their broadcast counterparts, which may be a result of the method of liquid fertilisation used in the current experiment. In both the broadcast and liquid fertilisation, urea was applied in four equal doses, mostly concentrated during the vegetative stage of the crop cycle. In liquid-fertilised plots compared with the broadcast-fertilised plots, a higher amount of N may have been available within a short timeframe, exceeding the plant-uptake capacity/requirement and thus resulting in higher losses, which can be confirmed by the higher N_2O emissions from these plots (Table 1). The percolation rate in the reduced-tillage plots was observed to be higher than in the puddled plots (based on recorded observations in the field experimental log), and therefore it is possible that the applied N in solution may have leached below the soil's active rootzone more quickly in the liquid-fertilised plots due to no puddling, i.e. no hard pan, thus taking the fertiliser with it, whereas with the broadcast application method, the fertiliser may have stayed on the soil surface for longer and only been leached slowly. Losses may also be due to some parts of the liquid fertiliser not reaching the soil but

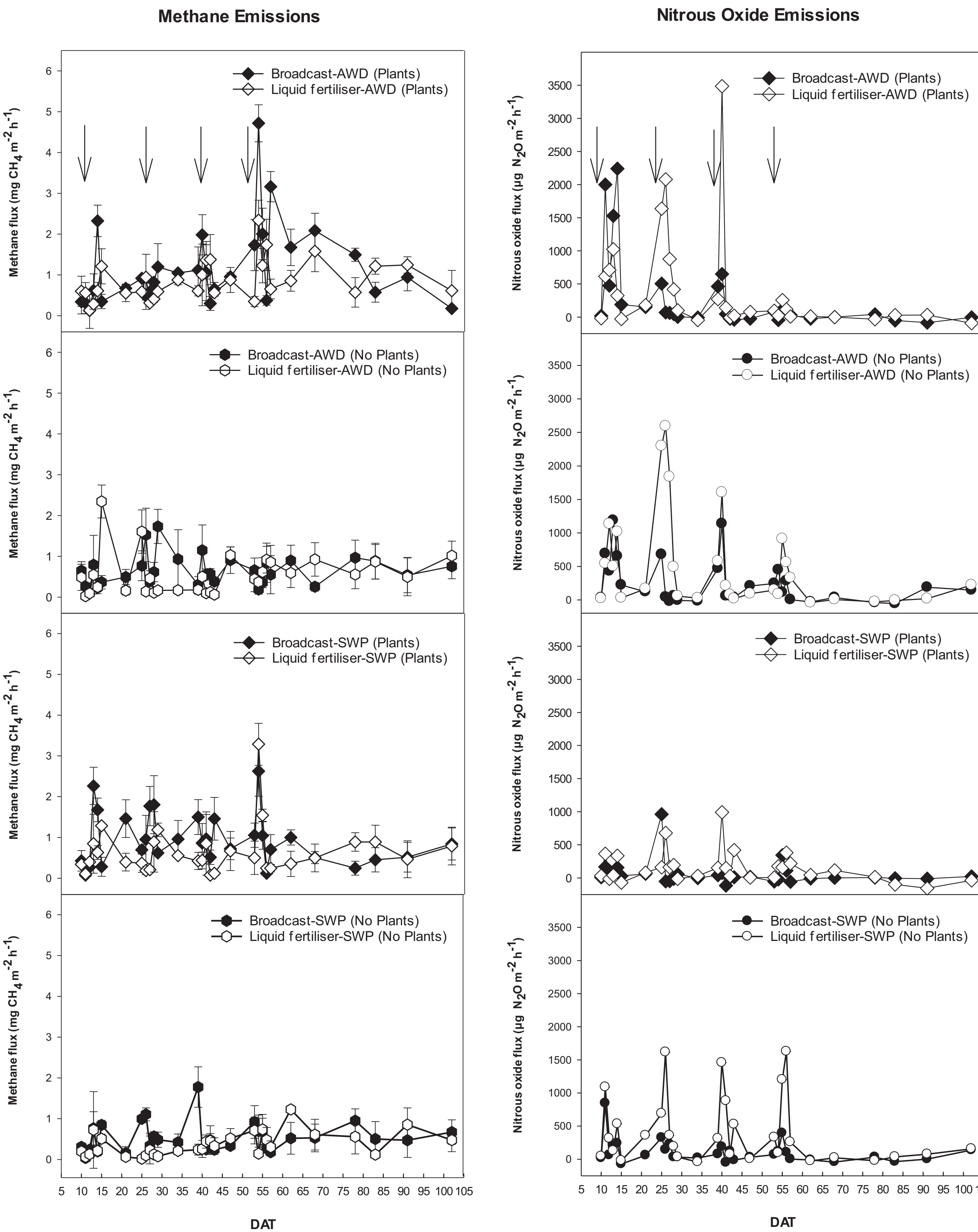

Fig. 2. Temporal patterns of methane and nitrous oxide flux rates as affected by the two water-saving irrigation regimes and two methods of fertilisation. Error bars indicate 1 SEM ($n = 4$). In the case of nitrous oxide, error bars are omitted for improved clarity. Arrows indicate top dressing of N fertiliser. AWD represents surface irrigation scheduled with alternate wetting and drying, whereas SWP represents surface irrigation scheduled with soil water potential. DAT = days after transplanting.

Table 2
Cumulative emissions of CH_4 and N_2O during the entire rice-growing season, and total CO_2 equivalent area-scaled GWPs over the 100-year time horizon as affected by the two water-saving irrigation systems and two methods of fertilisation.*

Treatments	CH_4 emissions (kg ha^{-1} season^{-1})	N_2O emissions (kg ha^{-1} season^{1})	Global warming potential (GWP) (kg CO_2 eq. season^{-1})
Broadcast-AWD (plants)	27.26 ± 2.4^{a}	2.60 ± 0.3^{d}	1702 ± 66.2^{c}
Broadcast-AWD (no plants)	15.94 ± 1.1^{c}	3.38 ± 0.2^{c}	1550 ± 44.6^{d}
Liquid fertiliser-AWD (plants)	20.42 ± 1.9^{b}	4.31 ± 0.3^{b}	1978 ± 76.2^{b}
Liquid fertiliser-AWD (no plants)	14.90 ± 1.6^{c}	5.78 ± 0.5^{a}	2230 ± 84.8^{a}
Broadcast-SWP (plants)	18.00 ± 0.9^{b}	0.92 ± 0.2^{e}	886 ± 46.7^{e}
Broadcast-SWP (no plants)	13.06 ± 0.7^{c}	1.19 ± 0.3^{e}	799 ± 62.9^{e}
Liquid fertiliser-SWP (plants)	14.20 ± 1.8^{c}	1.45 ± 0.3^{e}	915 ± 76.2^{e}
Liquid fertiliser-SWP (no plants)	10.41 ± 1.1^{d}	4.54 ± 0.4^{b}	1707 ± 78.7^{c}

* Data shown are means ± standard deviation of four replicates. Within the column, values with different letters are significantly different at the $p < 0.05$ level. AWD represents surface irrigation scheduled with alternate wetting and drying principle, while SWP irrigation is scheduled with soil water potential using the tensiometer.

adhering to leaves instead, promoting ammonia volatilisation and reducing plant uptake and yield. Moreover, as the fertiliser application was mostly confined to the rice plants' vegetative phase, the plants might show excessive vegetative growth during their juvenile phase, whereas in the reproductive phase, limited growth may be due to insufficient N availability, which could lead to premature plant senescence and reduced grain yields (Qu et al., 2012). Farneselli et al. (2015) found that lower frequency fertigation events were not able to supply the critical N concentration necessary for plant growth, causing lower LAI, biomass accumulation and yield than from more frequent fertigation.

In the current study, broadcast fertilisation combined with SWP irrigation maintained yields at a similar level to AWD irrigation, demonstrating that it is possible to achieve the same or a better yield with less water. However, the smallest yield found in liquid-fertilised plots under SWP irrigation (3.0 Mg ha^{-1}) may be an indication of the combined negative effect of higher water stress and lower N availability for plant uptake and yield formation at different critical stages of crop growth. In terms of water use, crop yield water productivity is a vital parameter to assess the performance of agricultural crops (Tuong and Bouman, 2003). A study by Bouman et al. (2007) found that the water productivity of rice varies between 0.2 and 1.2 kg grain m^{-3} water. While the water productivity of all treatments in the current study (Table 1) was found to be within this range, the highest mean water productivity, observed in Broadcast-SWP, was 0.49 kg grain m^{-3} water. The soil of the study site had a higher percolation rate might be due to the absence of hardpan, which may have resulted in higher water use.

The reduced tillage overtime may weaken the plough pan and in turn, alter water balance in the rice-based systems. Future long-term studies, therefore, should measure crop evapotranspiration rate, soil infiltration rates and the surface runoff, which will enable to do a water balance (Hoogeveen et al., 2015). Such water balance will enable accounting of all water volumes that enter and leave in the system thus will improve the efficiency of irrigation scheduling like SWP. In a global meta-analysis, Carrijo et al. (2017) found that the water use in AWD practice was 25.7% lower on average than that of conventional continuous flooding (CF). Compared with AWD, the SWP irrigation treatments in the current study showed that growing season water use could be reduced by a further 15% with no significant yield reduction without accounting the reduction of water use by reduced tillage. Similar to our findings an overall reduction in water use of due to intermittent irrigation regimes has been reported elsewhere (Belder et al., 2004; de Vries et al., 2010; Yao et al., 2012a, 2012b; Liu et al., 2013; Pandey et al., 2014; Linquist et al., 2015). The water savings in the rice-growing season in SWP were a result of the limited period of flooding in the field compared with the AWD treatments. Additionally, the adoption of reduced tillage decreased water use on average by 200 mm water in SWP scheduling treatments during the land preparation stage compared with the puddling practice. Parthasarathi et al. (2012) described water savings of

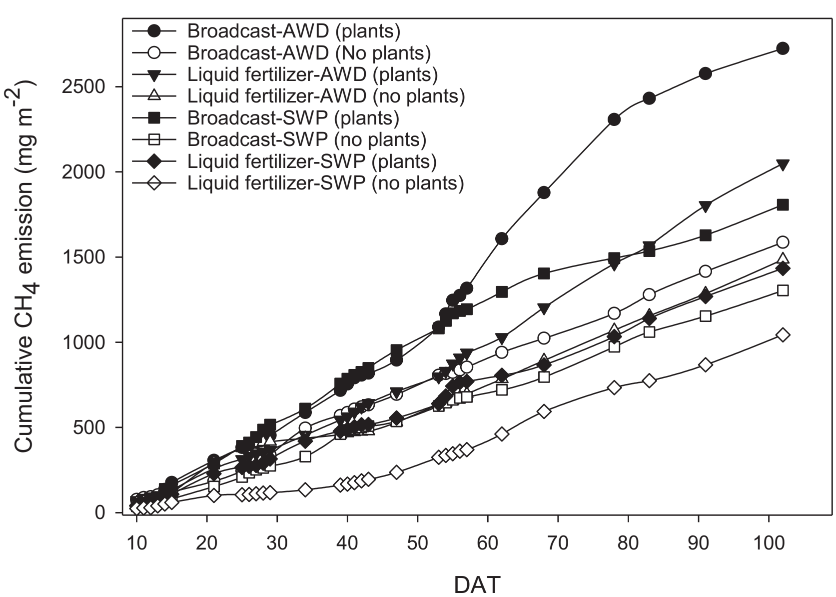

Fig. 3. Cumulative CH_4 emissions during the rice-growing season. AWD = alternate wetting and drying, SWP = soil water potential scheduling and DAT = days after transplanting.

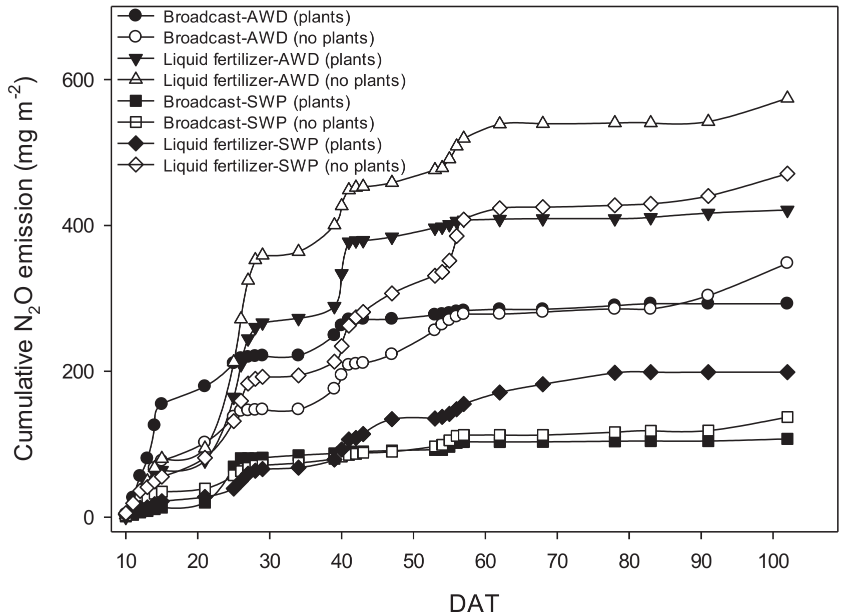

Fig. 4. Cumulative N_2O emissions during the entire rice-growing season. AWD = alternate wetting and drying, SWP = soil water potential scheduling and DAT = days after transplanting.

250 mm in irrigated rice by reducing puddling intensity and water use in land preparation, which might be the case in the SWP treatments with reduced tillage. Thus, if water saving is believed to be due to adoption of the reduced-tillage practice during the land preparation stage in the SWP scheduling, the total water saving will be much higher. The high water saving without a significant yield reduction in the SWP irrigated plots with broadcasting compared with AWD is an encouraging finding for water-limited areas. Moreover, the use of an irrigation system with a smaller water requirement (i.e. SWP irrigation scheduling with a sprinkler) can where applicable mitigate CO_2 emissions associated with energy used for pumping (Lal, 2004). However, the initial investment required for SWP irrigation scheduling (tensiometer) and irrigation systems could be the main barrier to wider adoption of these products by farmers (Sanz-Cobena et al., 2017). For most rice-growing countries in Asia, rice contributes around 50% of their agricultural emissions, further exacerbating climate change will increase the risk of smaller rice yields, water shortage and higher GHG emissions (Sekhar, 2018). SWP scheduling with micro-irrigation techniques, e.g. sprinkler irrigation, can be one such measure for the future that could dramatically decrease GHG emissions and water use without affecting yield. Therefore, water-efficient practices should combine wider environmental benefits with economic advantages for farmers. In a future climatic scenario where the scarcity of water will be greater and its costs higher, further investment of this kind can be justified. However, there are currently few incentives for smallholder farmers to invest in such technologies. Despite farming practices being improved by knowledge and technology transfers and farmer's economic and technical capabilities continuing to increase worldwide, in this study AWD is assumed to represent a low-tech, low-cost and easily adaptable water-saving technique for smallholder farmers, while the

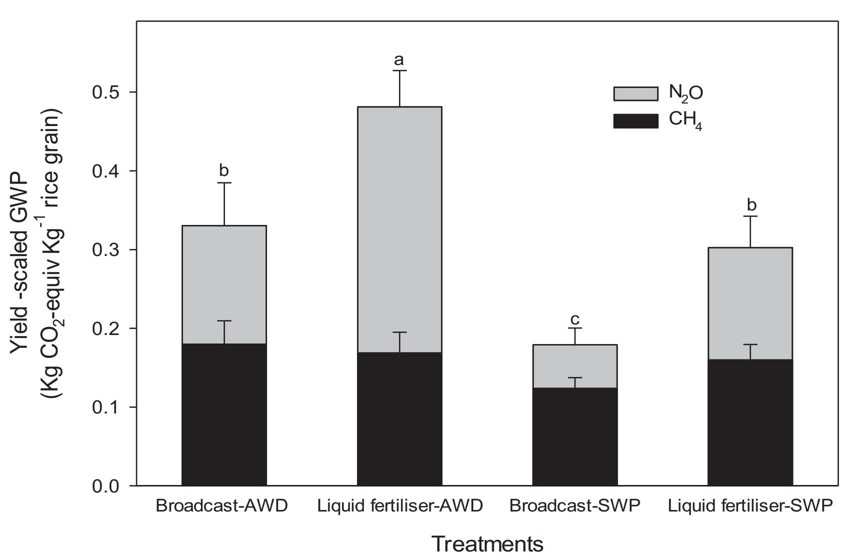

Fig. 5. Yield-scaled *GWPs* as affected by two water-saving alternate water management regimes and fertilisation methods. Error bars indicate 1 SEM (n = 4). Different letters indicate significance ($p < 0.05$) of treatments of rice production (small letters). AWD represents surface irrigation scheduled with alternate wetting and drying, whereas SWP represents surface irrigation scheduled with soil water potential.

SWP scheduled fertigation may be a more suitable option for large-scale farmers. In addition to the AWD irrigation technique, smallholder farmers can also easily adopt non-puddling reduced-tillage land establishment to save water and reduce labour requirements.

4.2. Methane emissions

Net soil CH_4 emissions are the result of a delicate balance between methanogenic and methanotrophic activities (Goulding et al., 1995). The results of the present study indicated that the seasonal CH_4 emissions from water-saving irrigation like AWD and SWP irrigation scheduling were low, varying between 14 and 27 kg CH_4 ha^{-1}. When compared with the global average of 100 kg CH_4 ha^{-1} for conventional CF irrigation reported in the meta-analysis by Linquist et al. (2012a, 2012b), this is between 73% and 86% lower. A separate experiment with the same rice variety under conventional continuous flooding carried out in the same season in a neighbouring field site of the experimental station of IRRI by Romasanta et al. (2017) resulted in seasonal methane emissions of 130 kg ha^{-1}. The very low seasonal CH_4 emissions in the present study are well in line with findings from other studies on GHG emissions from non-continuously flooded rice fields (Towprayoon et al., 2005; Ly et al., 2013; Singh and Dubey, 2012; Pandey et al., 2014; Linquist et al., 2015; Tariq et al., 2017; Islam et al., 2020). It is reported that lower methane emissions from water-saving irrigation where frequent drainage is practised are due to: i) lower average daily CH_4 fluxes that do not reach the levels observed for the continuously flooded treatment, ii) lower peak or spike CH_4 fluxes because drainage stabilises the readily available carbon supplied from soil, litter and root exudates, thus reducing substrates for methanogens, and iii) the absence of a spike in CH_4 emissions at the end of the season commonly found in CF systems (Islam et al., 2018; Islam et al., 2020). The present study showed the absence of this end-of-season peak, possibly because there was not a sufficiently long period of time when the soil was flooded for methanogenesis to occur prior to drainage. Moreover, the higher water percolation rate of the soil observed under SWP plots (recorded in the field experimental log) may have resulted in many dry phases throughout the season, all of which aid the very large reduction of CH_4 emissions in this SWP water-saving irrigation regime.

Differences in emission also depended on the fertilisation technique in AWD and the general difference between the two water-saving irrigations in question. Relative to broadcast fertilisation, liquid fertilisation significantly decreased CH_4 emission by 25% and 21% in AWD and SWP water regime respectively. In rice fields, three processes determine the amount of CH_4 that will be emitted: CH_4 production, oxidation and transport from the soil to the atmosphere (Linquist et al., 2012a, 2012b). The observed difference in emission between broadcast and liquid fertilisation may be explained in terms of the N fertiliser. Numerous previous studies have demonstrated the influence of N supply on CH_4 production, oxidation, transport and emission (Cai et al., 2007). Application of urea either as broadcast or liquid fertilisation supplies NH_4^+ to the soil, which in liquid fertilisation is more immediately available than in the broadcast treatment (Tian et al., 2017). In general, N fertiliser boosts plant growth, which both increases the carbon supply for methanogens and gives a larger aerenchyma cell pathway for CH_4 transportation from the soil to the atmosphere (Linquist et al., 2012a, 2012b). At the biochemical level, CH_4 consumption is inhibited by NH_4^+, which is believed to occur because of the similarity in the size and structure of NH_4^+ and CH_4. As a consequence, CH_4 monooxygenase enzyme (which oxidises CH_4) binds and reacts with NH_4^+ instead of CH_4 (Dunfield and Knowles, 1995; Gulledge and Schimel, 1998). However, at the microbial community level, the growth and activity of methanotrophs (CH_4 oxidising bacteria) are stimulated by N fertilisation, which leads to a decrease in emissions (Bodelier and Laanbroek, 2004). Furthermore, as a large part of the CH_4 is emitted through the plant (Wassmann and Aulakh, 2000), larger plants with more tillers provide a greater transport pathway for CH_4 to be emitted to the atmosphere as well as more root exudates for methane production. The liquid fertilisation in the present study may have resulted in a larger amount of immediately available N, which may have exceeded the plant uptake capacity, resulting in a higher loss of N than from the broadcast treatment. Plants in the broadcast treatment were larger and more vigorous (recorded in the field experimental log), which also translated into their better yield performances. The larger plants in broadcasted plots might have favoured better plant-mediated transport of CH_4 with a well-developed aerenchymatous system (Wang et al., 2015), resulting in higher methane emissions compared with liquid fertilisation.

In terms of the type of irrigation, SWP irrigation resulted in 33% less methane emission on average than from AWD irrigation. Soil aeration is typically a key factor controlling processes involving methanotrophic and methanogenic activity, therefore CH_4 fluxes could depend greatly on the irrigation management. The AWD water regime had flooded phases during which CH_4 is produced, while SWP was never really waterlogged. The lower soil moisture in SWP may also have increased CH_4 oxidation through enhanced diffusion of CH_4 from the atmosphere into the soil pore spaces and through improvement in gas diffusivity, which allowed enhanced microbial CH_4 oxidation that varied inversely with soil moisture (Ball et al., 1997; Brumme and Borken, 1999; Smith et al., 2003; Wu et al., 2014; Tate, 2015; Maris et al., 2015). Moreover, reduced tillage in SWP might have delayed the onset of methanogenesis, thus also contributing to the reduction in CH_4 fluxes.

4.3. Nitrous oxide emissions

Water regime management and N fertiliser have a crucial impact on N_2O emissions in irrigated rice-based cropping systems. The present results showed higher N_2O emissions in the AWD water regime than the previously reported N_2O emissions from conventional continuously flooded irrigated plots, which vary between 0.88 and 1.5 kg N_2O ha^{-1} season globally (Linquist et al., 2012a, 2012b; Romasanta et al., 2017). Similar findings of higher N_2O emissions in AWD have also been observed in previous studies (Cai et al., 1997; Xu et al., 2013, 2015; Pandey et al., 2014; Lagomarsino et al., 2016; Miniotti et al., 2016; Tariq et al., 2017; Islam et al., 2020). It is commonly believed that the anaerobic conditions found in conventional rice production practices largely impede the production of NO_3^- from nitrification as well as promote complete denitrification of any NO_3^- to N_2, together resulting in low N_2O emissions. However, the AWD practice, which is a shift towards more aerobic conditions, may enhance nitrification and NO_3^- production and elevate enhanced but less complete denitrification, increasing N_2O production overall (Yu et al., 2007; Devkota et al., 2013; Verhoeven et al., 2019). The elevated N_2O emissions in the AWD water regime started in the early part of the season and ended in around the middle of the season (56 DAT), which might be associated with the N cycling in the first month of seedling establishment and was probably produced by mineralisation of native soil N during this period (Fig. 2).

Peak N_2O emissions observed following top dressings of N fertiliser (Fig. 2) corroborated the finding that N_2O emissions are primarily controlled by irrigation and fertilisation practices (Sander et al., 2014). Irrespective of the treatments, each of the topdressings of mineral N was followed by a significant increase in N_2O emissions. Similar observations have been made in previous studies (Pathak et al., 2002; Zou et al., 2005). Within the AWD water regime, the application of liquid fertilisation significantly increased N_2O emissions by 65% more than the broadcasting method of fertilisation. Application of liquid fertilisers may lead to a high concentration of NH_4^+ reaching the soil, which in turn can increase the rate of nitrification (Meijide et al., 2007; Sanchez-Martín et al., 2010; Vallejo et al., 2006), as was evident from the liquid fertilised treatment in the present study. Dissolved urea was applied in the liquid fertilisation treatment by water solution, whereas it was broadcast as solid pelletised urea fertiliser on the soil surface in the broadcast treatment. In liquid fertilisation, the urea was mixed well with the water solution, causing relatively rapid high substrate availability for nitrification-denitrification in the liquid-fertilised treatments compared with the broadcast treatment under the AWD regime. The higher N_2O fluxes in the liquid-fertilised treatments compared with the broadcast treatments found in the present study are in agreement with previous studies of a fertigated olive orchard by Maris et al. (2015) and of fertigated watermelon and melon crops by Abalos et al. (2016) and Vallejo et al. (2014) respectively. In non-planted treatments, there were no N uptake by the plants, which increased the available nitrate substrate for denitrification, resulting in a greater loss of N as N_2O fluxes compared with the plant treatments. This information will help with planning field management to include fallow periods in view of the effect of N residues and water levels on emissions.

In the present study, SWP irrigation scheduling produced significantly lower N_2O emissions than the AWD water regime. The average N_2O emissions from SWP irrigation scheduling were within the range of that produced by conventional continuously flooded irrigated plots (0.88–1.5 kg N_2O ha^{-1} season) reported globally, which is an encouraging finding for water-saving irrigation regimes. Within the SWP water regime, no significant difference in N_2O emissions was found between the broadcast and liquid-fertilisation technique. Along with increased water-use efficiency and lower N_2O emissions, SWP irrigation scheduling can be a potential climate-smart strategy in rice agroecosystems. These results demonstrated that the Broadcast-SWP and Liquid fertiliser-SWP treatments mitigated seasonal N_2O emissions 64% and 66% more respectively than their AWD counterparts ($P < 0.05$). The lower N_2O emissions in SWP can be explained by two main factors. Firstly, and most significantly, the amount of water applied in SWP plots was generally lower compared with AWD plots, resulting in higher soil aeration in the SWP plots. In addition, the soil moisture level in SWP was maintained at a similar level throughout the season using a tensiometer, thus avoiding a large shift between aerobic and anaerobic conditions, which may have resulted in lower N_2O emissions in the SWP treatments than in the AWD treatments. Secondly, the factor of NH_4^+ availability in the topsoil can also contribute to the greater reduction in N_2O emissions in both fertilisation techniques in SWP compared with AWD. Previous studies have indicated that N_2O emissions are driven by NH_4^+ availability in the topsoil as these N_2O emissions are mostly produced at shallow depths (5 cm and 12.5 cm) and subsequently emitted (Yano et al., 2014; Verhoeven et al., 2019). In the present study, the SWP plots were drier than the AWD plots, and the percolation rate in the reduced-tillage SWP plots was observed (recorded in the field experimental log) to be higher than in the puddled AWD plots due to the absence of hardpan. It is therefore possible that the applied fertiliser may have gone below the topsoil more quickly, which reduced the amount of NH_4+ available for nitrification in the shallower depth, thus reducing N_2O production. However, care should be taken to reduce higher leaching because the yield was found to be lower in the Liquid fertiliser-SWP treatment. Thus, these results indicate that soil moisture plays a more central role in emissions than fertilisation technique. In well-aerated soils such as those in SWP plots, the oxidation process dominates, i.e. nitrification of available N, and the most common gas released from such a system is NO instead of N_2O (Davidson et al., 2000).

4.4. Global warming potential and yield-scaled global warming potential

Global warming potential as expressed on a CO_2-equivalent basis incorporates GHGs to exhibit the overall global warming impact of a production system and each GHG's contribution to the global warming process. The average GWP of CH_4 and N_2O emissions from the present AWD and SWP irrigation scheduling treatments were 51% and 76% lower respectively than the global average estimate of GWP (3757 kg CO_2 eq ha^{-1} season) in rice systems reported by Linquist et al. (2012a, 2012b). Furthermore, these AWD and SWP water-saving irrigation strategies showed similar large differences in GWP compared with conventionally irrigated rice with continuous flooding (3936 kg CO_2 eq ha^{-1} season) reported from an experiment carried out in the same location, with the same variety and in the same season by Romasanta et al. (2016). These large differences were probably due to the very low methane emissions in the present study's water-saving irrigation treatments and the relatively moderate increases in N_2O emissions. Within water-saving irrigations, the SWP irrigation treatment reduced GWP on average by 51% relative to AWD applied in surface irrigation (Table 2). Greater reductions in GWP were observed in broadcast-SWP (886 kg CO_2 ha^{-1}), with the decrease in GWP mainly achieved by having the lowest N_2O emission among all the treatments as well as low CH_4 emissions. In contrast to most previous rice system studies, in the present study N_2O was the major determinant of the GWP of various treatments and the contribution of N_2O to GWP varied at between 31% and 65% for treatments with plants and between 44% and 79% for treatments without plants.

This GWP metric has been central to gas comparison discussion by the Intergovernmental Panel on Climate Change (IPCC) and has been adopted by the United Nation (UN) systems as the universal metric for reporting GHG emissions, and for evaluating the success of mitigation. While this metric is widely used by most countries to compare emissions from different sectors, set overall targets, and inform emissions trading, GWP is not without criticism (O'neill, 2000; Fuglestvedt et al., 2003; Shine, 2009; Cain et al., 2019). There is no single universally accepted methodology for combining all the relevant factors into a single metric (O'neill, 2000; Shine, 2009; Tanaka et al., 2013). While some alternatives are proposed, the scientific community had a wider realisation that it's next to impossible to find a “best” metric, regardless of its envisioned usage (Shine et al., 2005; Shine, 2009). While GWP might be imperfect, it still accomplishes a vital role in allowing the implementation of the Kyoto Protocol and other climate policy tools. Moreover, as we learn more about methane and feedbacks in the climate system, methane's GWP has continually increased. For example, the IPCC's second assessment report (1995) suggested methane's 100-year GWP value of 21. Between the IPCC's fourth (AR4) and fifth assessment report (AR5), the GWP value of methane increased by about 20%, which included multiple climate-carbon feedbacks in the atmosphere. The change in GWP reflects our increased understanding of the warming potential of Carbon dioxide in last 20 years, as well as our understanding of how long methane typically stays in the atmosphere before being converted into CO_2. On the other hand, the GWP value for nitrous oxide for 100 years period remained the same between IPCC's AR4 and AR5 report. Emissions reporting under UNFCCC now necessitate the use of Global Warming Potential of 100 years to account for all greenhouse gases. The most recent IPCC report (AR5) indicate methane's 20-year GWP value at 86 and 100-year GWP at 34, and there is fierce debate over whether it is best to look at the impact of methane over a 20-year time frame or over a 100-year time frame. The choice of time frame has a big impact in policy dimensions, and some argue 100-year time frame is more appropriate as it allows policy tools like the Kyoto Protocol to take place (Shine, 2009). The debate over the meaning of the metric or 20-year versus 100-year effects can sometimes distract from the essential fact that underlies that we need to act fast to minimise the negative effect from these dangerous gases as well as we need to follow UN guidelines to be able to compare data from various sources and countries coherently.

In the face of challenges such as climate change and water scarcity, global agriculture needs to double its production of food to meet the demand of an increasing population while minimising its environmental footprint (Foley et al., 2011). Given this reality, GWP should be measured as a function of crop yield in an effort to make a trade-off between increasing the yield of crops and reducing GHG emissions through innovative cropping systems (Van Groenigen et al., 2010). Assessment of GHG emissions from crop production should therefore be quantified at yield scale rather than area scale (Pathak et al., 2010; Linquist et al., 2012a; Venterea et al., 2011). For water-saving purposes, irrigation strategies should be identified that allow for the lowest yield-scaled GWP. The

Broadcast-SWP scheduling treatment in the current study produced statistically identical yields to AWD, but had the lowest GHG emissions and thus achieved the lowest yield-scaled GWP (0.17 kg CO_2 eq kg^{-1} rice grain). As a result, this study recommends broadcast urea application with SWP irrigation scheduling as the most effective climate-smart option (Fig. 5). In terms of suitability based on yield-scaled GWP, these treatments can be ordered as follows: Broadcast-SWP < Liquid fertiliser-SWP = Broadcast-AWD < Liquid fertiliser-AWD. Differences in N_2O emissions were the main drivers of the significant differences in yield-scaled GWP between the different treatments.

5. Conclusions

Irrigation and fertilisation methods significantly affected the yield, water use and greenhouse gas emissions in rice production. The AWD water regime was found to be the better option in terms of yield than SWP. Yet SWP irrigation scheduled plots with reduced-tillage (irrespective of fertilisation technique) decreased irrigation water use, CH_4 and N_2O emissions compared with AWD, although some form of trade-off for yield should be expected. The SWP irrigation scheduling with broadcast urea application can be recommended as the most effective climate-smart option to have emerged from this study. Regardless, both AWD and SWP irrigation scheduling showed very low yield-scaled *GWP* compared with that of conventional continuously flooded rice reported globally, indicating their rather large mitigation potential. Liquid fertilisation (mimicking fertigation) was found to be a promising technique, which had lower CH_4 emissions compared with its broadcast counterpart in both water regimes. However, in terms of reducing N_2O emission, liquid fertilisation was only effective under SWP irrigation scheduling. There has been very limited research to date on liquid fertilisation or fertigation in Asian rice agroecosystems, especially in association with different water management regimes that could have beneficial impacts on emissions. In this study, AWD represents a low-tech, low-cost, easily adaptable water-saving technique for smallholder farmers. On the other hand, adoption of SWP with liquid fertilisation/fertigation may be limited by the initial investment required and its knowledge-intensive nature, and thus may not be feasible for everyone. In addition to the AWD irrigation technique, smallholder farmers can also easily adopt non-puddling reduced-tillage land establishment to save more water and reduce labour requirements. Finally, the no-plant treatments indicated that the presence of rice plants reduced N_2O emissions but increased CH_4 emissions, which should be considered in terms of fertilisation and water management strategies during the growing season as well as in fallow periods. This study concludes that improvements in water management and careful application of N fertiliser can reduce both water use and greenhouse gas emissions with a minimum effect on yield. This experiment was conducted in the dry season when soil moisture conditions can be effectively controlled, but more long-term experimental data under variable environmental conditions including groundwater measurements would be beneficial in order to shed light on the full scope and impact of these approaches.

Abbreviations

AWD	Alternate wetting and drying
C	Carbon
CH_4	Methane
DAT	Days after transplanting
GHG	Greenhouse gas
GWP	Global warming potential
N	Nitrogen
N_2O	Nitrous oxide
NH_4^+	Ammonium
NO	Nitric oxide
NO_3^-	Nitrate
SWP	Soil water potential

CRediT authorship contribution statement

Syed Faiz-ul Islam: Conceptualization, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Bjoern Ole Sander:**Methodology, Investigation, Writing - review & editing.**James R. Quilty:**Methodology, Investigation, Writing - review & editing.**Andreas de Neergaard:**Writing - review & editing.**Jan Willem van Groenigen:**Writing - review & editing.**Lars Stoumann Jensen:**Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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