



## Article

# Substituting Partial Chemical Fertilizers with Bio-Organic Fertilizers to Reduce Greenhouse Gas Emissions in Water-Saving Irrigated Rice Fields

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**Abstract:** Conventional water and fertilizer management practices have led to elevated greenhouse gas emissions from rice fields and decreased the efficiency of water and fertilizer utilization in agricultural land. The implementation of water-saving irrigation and the substitution of chemical fertilizers with organic alternatives can influence CH<sub>4</sub> and N<sub>2</sub>O emissions in rice fields. However, it remains unclear how the simultaneous application of both methods will affect the CH<sub>4</sub> and N<sub>2</sub>O emissions in rice fields. Therefore, two irrigation methods (F: flooded irrigation; C: controlled irrigation) and three fertilization modes (A: full chemical fertilizer; B: bio-organic fertilizer replacing 15% chemical nitrogen fertilizer; C: bio-organic fertilizer replacing 30% chemical nitrogen fertilizer) were set up through field experiments to explore the effect of greenhouse gas emission reduction in rice fields by combining controlled irrigation and bio-organic fertilizers. Substituting some chemical fertilizers with bio-organic fertilizers can lower the peak CH<sub>4</sub> and N<sub>2</sub>O fluxes in rice fields, leading to a decrease in the cumulative CH<sub>4</sub> and N<sub>2</sub>O emissions by 11.9~29.7% and 10.8~57.3%, respectively. The reductions led to a considerable decrease in the global warming potential (GWP) and the greenhouse gas emission intensity (GHGI) by 16.1~48.1% and 16.3~48.1%, respectively. Controlled irrigation significantly reduced CH<sub>4</sub> emissions by 55.2~69.4% compared with flooded irrigation in rice fields. However, it also increased N<sub>2</sub>O emissions by 47.5~207.9%, considerably reducing their GWPs by 11.8~45.5%. Neither bio-organic fertilizer substitution nor controlled irrigation significantly affected rice yield. Replacing 15% of chemical nitrogen fertilizers with bio-organic fertilizers in controlled irrigation rice fields can minimize rice GWP and GHGI. The study's results are of significant importance for enhancing the regulation of greenhouse gases in farmland and achieving sustainable agriculture through cleaner production.

**Keywords:** bio-organic fertilizer; controlled irrigation; rice; CH<sub>4</sub>; N<sub>2</sub>O



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## 1. Introduction

The escalating frequency and severity of extreme weather events and climate change, resulting from global warming, have become a pressing global social issue. Methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are major greenhouse gases in the atmosphere. In 2019, the global average atmospheric concentrations of CH<sub>4</sub> and N<sub>2</sub>O were estimated to be 1877 ppb and 332.0 ppb, respectively. These levels represent a 260% and 123% increase from pre-industrial levels [1]. From 2017 to 2021, there was an annual increase in global atmospheric greenhouse gas concentrations, and this trend is expected to continue [2]. Human activities are responsible for over 60% of greenhouse gas emissions, with a significant portion coming from agricultural production [3]. Greenhouse gases released from agricultural soils originate from biochemical processes caused by soil microbial activity [4,5]. The main pathway affecting soil biochemical processes is water and fertilizer management [6,7]. Rice fields account for 25% of the total greenhouse gas emissions from farmland, making them

the primary source of such emissions [8]. China is one of the world's major rice-producing countries, with the highest rice planting area and production. Chinese rice fields emit over 7.7 Tg of CH<sub>4</sub> and 138 Gg of N<sub>2</sub>O annually [9]. Therefore, it is important to investigate practical measures to decrease greenhouse gas emissions from rice paddies to achieve sustainable agricultural development.

Long-term mismanagement of fertilization has resulted in the loss of most of the nitrogen in chemical fertilizers to the atmosphere, surface water, and groundwater through volatilization, runoff, and leaching [10]. This poses a threat to the ecological environment of farmland and its surroundings [11], causing serious environmental pollution problems [12,13]. Therefore, in recent years, there has been extensive research on replacing a portion of chemical fertilizers with organic or slow- and controlled-release fertilizers [14,15]. This is done to ensure crop yields, improve fertilizer utilization, and alleviate pressure on farmland ecosystems. Among them, bio-organic fertilizers are made by deepening the treatment of organic materials and processing them with a variety of beneficial microbial agents. They are a superior option for soil improvement [16], reducing crop pests and diseases [17], and increasing yields and crop quality [18]. However, there have been fewer studies on the effect of bio-organic fertilizers on greenhouse gas emissions from rice fields. Organic fertilizers have a lower effective nitrogen source compared with conventional fertilizers, and this nitrogen is released slowly. This slow release may reduce the emission of N<sub>2</sub>O from agricultural soils [19,20]. Additionally, organic fertilizers are rich in organic matter, which stimulates soil microbial activity and promotes crop root respiration by improving soil structure [21]. Furthermore, it enhances the soil carbon/nitrogen ratio and facilitates the synthesis and emission of CH<sub>4</sub> [22–24]. How will the use of bio-organic fertilizer, which was derived from organic fertilizer, increase soil CH<sub>4</sub> emissions and reduce N<sub>2</sub>O emissions, similar to traditional organic fertilizers? How will the use of bio-organic fertilizers affect the overall greenhouse impact on soil greenhouse gases? Relevant issues deserve thorough discussion.

Flooded irrigation is commonly used in traditional rice cultivation in China. However, it causes water and nitrogen loss and is the main source of CH<sub>4</sub> emissions from rice fields [25], which has a significant impact on the environment. Currently, water-saving irrigation technology has been successfully promoted in China to alleviate the challenges of agricultural water usage and enhance water and fertilizer efficiency in rice fields. Water-saving irrigation practices can reduce water consumption [26] and stimulate soil microbial activity, which can alter soil aeration and influence greenhouse gas emissions from agricultural soils [27,28]. Controlled irrigation has been applied more frequently in rice fields in southern China. Studies have shown that it can effectively reduce ammonia volatilization and nitrogen leaching losses, lower the combined global warming potential of CH<sub>4</sub> and N<sub>2</sub>O, and contribute to an increase in rice yield [29–31].

Irrigation methods and fertilizer management are key factors affecting CH<sub>4</sub> and N<sub>2</sub>O emissions from farmland, and appropriate water and fertilizer management measures are important to ensure sustainable agricultural development. This study monitored greenhouse gas emissions from three different bio-organic fertilizer application modes in different irrigated rice fields through field experiments. The effects of bio-organic fertilizer on greenhouse gas emissions from rice fields in water-saving irrigation were explored, and the comprehensive greenhouse effect of water-saving irrigation rice fields with bio-organic fertilizer was evaluated in conjunction with the crop yields. The study's results enrich the means of greenhouse gas regulation in farmland, provide theoretical support for evaluating the application of bio-organic fertilizers in rice production, and provide a theoretical basis for realizing water-saving, efficient, and clean production in sustainable agriculture.

## 2. Materials and Methods

### 2.1. Experimental Site

The experiment was conducted at the Agricultural Hydrology and Hydroecology Experimental Field of Yangzhou University in Yangzhou City, Jiangsu Province, China

(119°23'24" E, 32°20'24" N). The region has a subtropical monsoon climate, with an average annual temperature of 14.8 °C, an average multi-year rainfall of 1025.6 mm, and an average multi-year evaporation of 937.7 mm. The experimental area had sandy loam soil with organic matter of 17.6 g kg<sup>-1</sup>, total nitrogen of 1.07 g kg<sup>-1</sup>, effective phosphorus of 56.42 mg kg<sup>-1</sup>, quick-acting potassium of 87.06 mg kg<sup>-1</sup>, a soil bulk density of 1.32 g kg<sup>-1</sup>, and a pH of 7.4. The average daily temperature during the rice growing period was 26.9 °C (11.5–36.5 °C), and the rainfall was 262.1 mm (Figure 1).

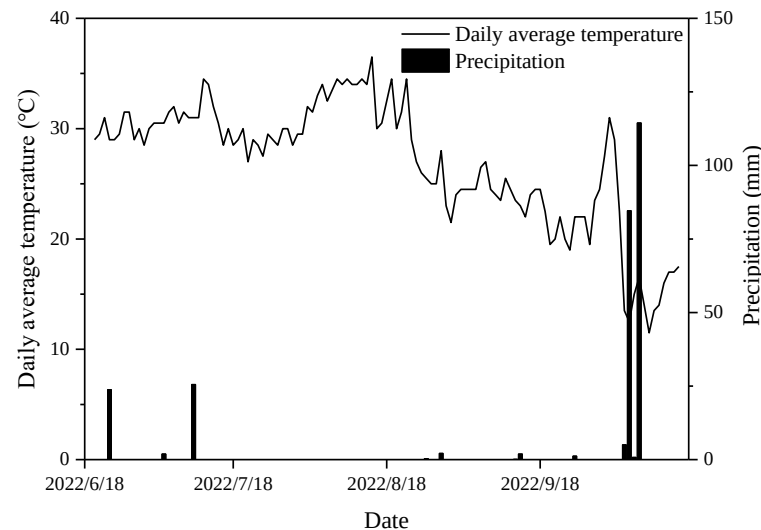


**Figure 1.** Daily average temperature and precipitation during the rice growing seasons in 2022.

## 2.2. Field Experiment Design

A field plot experiment was conducted to investigate the effects of irrigation mode and nitrogen fertilizer management using a split-zone design. The experiment employed two irrigation modes: flooded irrigation (F) and controlled irrigation (C). For flooded irrigation, a 10–50 mm layer of water was maintained on the field surface during the rice growing season, except for the late tillering stage and the 10 days before harvesting. For controlled irrigation, a water layer of 5–25 mm is maintained on the field surface only during the rice greening period. No water layer is present during the rest of the period, and the irrigation time is determined based on the water content of the soil in the rice rhizosphere [32].

The study evaluated three nitrogen fertilizer management systems: A (full application of chemical fertilizers at 300 kg N ha<sup>-1</sup>, substituting 15% of chemical nitrogen fertilizers with bio-organic fertilizers, B (15% nitrogen from bio-organic fertilizers and 85% from chemical fertilizers, and substituting 30% of chemical nitrogen fertilizers with bio-organic fertilizers, C (30% nitrogen from bio-organic fertilizers and 70% from chemical fertilizers). There were six treatments in total, each with three replications, resulting in 18 experimental plots. The chemical nitrogen fertilizer is applied in three stages at ratios of 30%, 40%, and 30% as base, tillering, and panicle fertilizers, respectively. Bio-organic fertilizer is applied at a ratio of 60% to 40% to replace the corresponding chemical nitrogen fertilizer as base fertilizer and panicle fertilizer.

Urea (N = 46%) was used as the chemical nitrogen fertilizer in all treatments, which hydrolyzes rapidly to ammonium nitrogen after application. Bio-organic fertilizer is made by mixing chicken manure with a small amount of Chinese medicine dregs (*Astragalus* and *Poria*). After the mixture is crushed and fermented, microbial bacteria (*Bacillus subtilis*, *Bacillus amyloliquefaciens*, and *Bacillus licheniformis*) are supplemented to cultivate the fertilizer. The bio-organic fertilizer contains total nitrogen, total phosphorus, total potassium, and organic matter at 3.5%, 2.7%, 2.5%, and 40%, and more than 20 million effective live bacteria per gram. Additionally, calcium superphosphate and potassium chloride were used to balance the phosphorus and potassium fertilizers across treatments at the same

level (75 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>, 75 kg K<sub>2</sub>O ha<sup>-1</sup>). The phosphorus fertilizer is entirely applied as base fertilizer, while the potassium fertilizer is divided equally between the base and panicle fertilization stages. The B and C treatments have an additional 298 kg ha<sup>-1</sup> and 596 kg ha<sup>-1</sup> of organic carbon, respectively, due to the substitution of partial chemical nitrogen fertilizers with bio-organic fertilizers.

The rice variety used in the test was “Nanjing 9108”. Seedlings were cultivated on 22 May 2022 and transplanted into 2 × 2.5 m plots with a spacing of 20 cm between plants and rows on 20 June. The crops were harvested on 16 October. Transparent rain shelters were installed above the plots to prevent rainfall from affecting the experiments.

### 2.3. Gas Collection and Measurement

Gas samples were collected on-site using the static chamber method. The static chamber consists of a chamber body and a base, both made of 4 mm-thick PVC material. The chamber body (length × width × height = 40 × 40 × (45 + 45) cm) is equipped with a fan and a thermometer at the top interior to mix the gas within the chamber during sampling and to measure the temperature inside the chamber, respectively. The base has an overall height of 15 cm, with the top 5 cm forming a groove. During sampling, water is poured into the groove to seal it, preventing gas exchange between the interior of the chamber and the external air. After rice transplanting, the base is buried in the plot (at a depth of 10 cm) and removed after rice harvesting. Gas samples were collected every 5–7 days, with more frequent sampling within the first week after fertilization. Sampling was conducted between 10:00 and 11:00 AM, with gas samples collected at 0, 10, 20, and 30 min after sealing the chamber using a 50 mL syringe equipped with a three-way valve. Gas sample concentrations were analyzed on the same day using a Shimadzu gas chromatograph (GC-2014C, Shimadzu, Tokyo, Japan). The temperature inside the static chamber was recorded concurrently with sampling to calculate the greenhouse gas flux. The cumulative emissions were obtained by integrating the gas flux over time. CH<sub>4</sub> and N<sub>2</sub>O fluxes, global warming potential (GWP), and greenhouse gas emission intensity (GHGI) were calculated according to the following formula [33,34],

$$F = \rho \cdot h \cdot \frac{273}{273 + T} \cdot \frac{dc}{dt}$$

$$\text{GWP} = E_{\text{N}_2\text{O}} \times 298 + E_{\text{CH}_4} \times 25$$

$$\text{GHGI} = \frac{\text{GWP}}{Y}$$

where  $F$  is the gas flux (mg m<sup>-2</sup> h<sup>-1</sup> for CH<sub>4</sub>, µg m<sup>-2</sup> h<sup>-1</sup> for N<sub>2</sub>O);  $\rho$  is the density of the gas in the standard state (g m<sup>-3</sup>);  $h$  is the height inside the static box, m;  $T$  is the temperature inside the static box during the sampling period (°C);  $dc/dt$  is the rate of change of the gas concentration inside the static box per unit time (mg m<sup>-2</sup> h<sup>-1</sup> for CH<sub>4</sub>, µg m<sup>-2</sup> h<sup>-1</sup> for N<sub>2</sub>O);  $E_{\text{N}_2\text{O}/\text{CH}_4}$  is the cumulative emission of N<sub>2</sub>O or CH<sub>4</sub> (kg hm<sup>-2</sup>); and  $Y$  is the yield of rice (kg hm<sup>-2</sup>).

### 2.4. Soil Sample Collection and Analysis

While collecting gas samples, we also collected soil samples from each neighborhood separately. Three soil samples at depths of 0–20 cm were collected from each plot using a soil auger and mixed together. These samples were stored in insulated boxes with ice packs for temporary storage and brought back to the laboratory for analysis. Soil water content was measured using the drying method. Soil nitrate (NO<sub>3</sub><sup>-</sup>-N) and ammonium nitrogen (NH<sub>4</sub><sup>+</sup>-N) were measured using Ultraviolet spectrophotometry and indophenol blue colorimetric method, respectively. The NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N content of the soil filtrate (extracted with 1 mol L<sup>-1</sup> KCl solution for 1 h) were measured using an Ultraviolet spectrophotometer (UVmini-1280, Shimadzu, Tokyo, Japan). These results were then used

in combination with the soil water content to calculate the  $\text{NO}_3^-$ -N and  $\text{NH}_4^+$ -N content in the soil.

## 2.5. Statistical Analyses

Microsoft Excel 2010 was used for data processing, OriginPro 9.1 was used to draw graphs and calculate the cumulative gas emissions, SPSS Statistics 22.0 was used for the statistical analysis of the experimental data, and the LSD method was used for the significance test.

## 3. Results

### 3.1. $\text{CH}_4$ Emissions

In general,  $\text{CH}_4$  fluxes in rice fields of all treatments showed a bimodal emission trend of increasing and then decreasing, with the peak of  $\text{CH}_4$  fluxes occurring in the middle of rice fertility (Figure 2). The  $\text{CH}_4$  flux levels varied considerably between the fields subjected to different water management and fertilizer applications. Prior to tillering fertilizer application,  $\text{CH}_4$  emissions remained low across all treatments, with fluxes approaching zero. The application of tillering fertilizer marked the onset of a gradual rise in  $\text{CH}_4$  emissions, culminating in a peak during the late tillering phase. Notably, controlled irrigation treatments prompted an early  $\text{CH}_4$  peak, 5 to 10 days sooner than the flooded irrigation treatments. Compared with the FA treatment ( $2.00 \text{ mg m}^{-2} \text{ h}^{-1}$ ), the CA treatment experienced a 22.8% higher peak flux. In stark contrast, the peaks under treatments with CB and CC were significantly lower by 40.7% and 33.1% ( $p < 0.05$ ), respectively, relative to the corresponding FB ( $2.51 \text{ mg m}^{-2} \text{ h}^{-1}$ ) and FC ( $3.05 \text{ mg m}^{-2} \text{ h}^{-1}$ ) treatments. However, in controlled irrigation, the first peak values of  $\text{CH}_4$  fluxes were reduced by 16.8% to 39.5% with the application of bio-organic fertilizer. On the other hand, in flooded irrigation, the first peak values of  $\text{CH}_4$  fluxes increased by 25.0% to 52.4% with the application of bio-organic fertilizer.

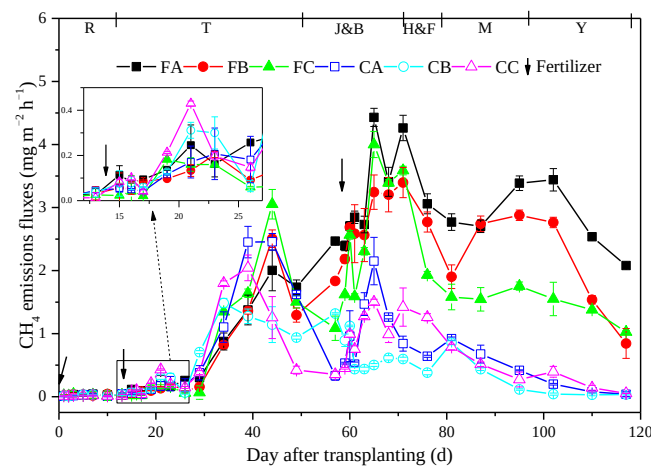


**Figure 2.** Variation of  $\text{CH}_4$  fluxes in rice fields. Note: The capital letters R, T, J & B, H & F, M, and Y in the figure represent the re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk-ripe stage, and yellow ripeness stage of rice, respectively.

Upon completion of rice tillering, drainage led to a decrease in  $\text{CH}_4$  emissions across all treatments. The flooded irrigation demonstrated a more moderate flux reduction and experienced a subsequent increase upon re-watering. On the contrary,  $\text{CH}_4$  fluxes in the fields with controlled irrigation quickly fell to lower levels. With the regulation of spike fertilization and irrigation,  $\text{CH}_4$  fluxes gradually increased, and a second emission peak occurred in all treatments. At this time, both bio-organic fertilizer substitution and controlled irrigation significantly reduced the peak values of  $\text{CH}_4$  fluxes by 9.7~47.8% and 51.4~67.0% ( $p < 0.05$ ), respectively. As the rice reached maturity, we observed a decline in  $\text{CH}_4$  emissions in all treatments. In controlled irrigation,  $\text{CH}_4$  fluxes from the rice

fields gradually decreased to zero during the rice maturity to harvest stage and were not significantly affected by bio-organic fertilizer substitution. At the rice maturity stage,  $\text{CH}_4$  emissions from the rice fields in flooded irrigation remained high. The  $\text{CH}_4$  fluxes in the bio-organic fertilizer treatment were significantly lower than those in the full chemical fertilizer treatment.

### 3.2. $\text{N}_2\text{O}$ Emissions

Controlled irrigation treatments exhibited notably higher  $\text{N}_2\text{O}$  emissions from the rice fields than the conventional flooded irrigation treatment (Figure 3). The  $\text{N}_2\text{O}$  emissions under flooded irrigation were predominantly observed following basal fertilization and remained low during subsequent stages. In controlled irrigation, the  $\text{N}_2\text{O}$  fluxes from the rice fields increased rapidly and reached a peak after tiller fertilization, had a small increase after spike fertilization, and remained at a low level during the remaining stages. However, in the CA treatment, the  $\text{N}_2\text{O}$  fluxes showed a substantial increase when the rice field water layer first receded after the re-greening stage. The highest  $\text{N}_2\text{O}$  flux in rice fields occurred in the CA treatment ( $1965.47 \mu\text{g m}^{-2} \text{h}^{-1}$ ), while the other treatments showed a significant reduction of 57.7~92.7% compared with the CA treatment ( $p < 0.05$ ). Additionally, the peak values of  $\text{N}_2\text{O}$  fluxes from rice fields increased significantly by 3.6~11.7 times in controlled irrigation compared with flooded irrigation ( $p < 0.05$ ). At the same time, replacing chemical fertilizers with bio-organic fertilizers also resulted in a significant reduction of the peak values for  $\text{N}_2\text{O}$  fluxes from the rice fields by 52.4~57.7% in controlled irrigation ( $p < 0.05$ ).

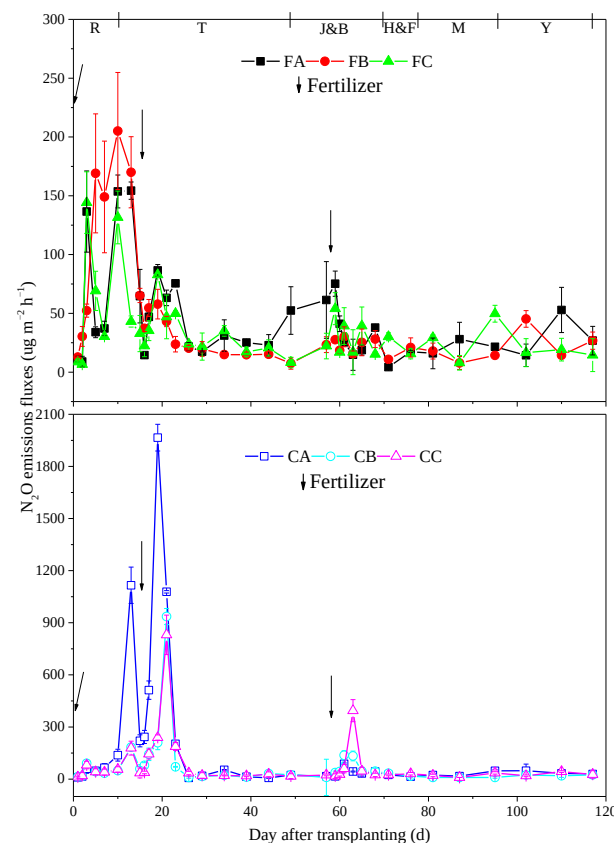


**Figure 3.** Variation of  $\text{N}_2\text{O}$  fluxes in rice fields. Note: The capital letters R, T, J&B, H&F, M, and Y in the figure represent the re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk-ripe stage, and yellow ripeness stage of rice, respectively.

### 3.3. Soil $\text{NO}_3^-$ -N and $\text{NH}_4^+$ -N Contents

In all treatments, the soil  $\text{NO}_3^-$ -N contents in the rice fields either remained high or increased rapidly after basal fertilization, followed by a gradual decline (Figure 4b). After

the rice re-greening period, the water layer was no longer present in controlled irrigation. At this point, the soil  $\text{NO}_3^-$ -N contents increased rapidly in the CA and CB treatments, while there was no significant change in the CC treatment. At this time, the soil  $\text{NO}_3^-$ -N content of the flooded irrigation treatment only slightly increased in the FB treatment but continued to decrease in the FA and FC treatments. The soil  $\text{NO}_3^-$ -N contents in the rice fields increased rapidly with the application of tillering fertilizer in all treatments, followed by a gradual decrease until the late stage of rice tillering when it dropped to a lower level. At this stage, the soil  $\text{NO}_3^-$ -N contents of controlled irrigation treatments were significantly higher than that of flooded irrigation. However, the bio-organic fertilizer substitution treatments effectively reduced the soil  $\text{NO}_3^-$ -N contents. The soil  $\text{NO}_3^-$ -N contents were minimally impacted by the spike fertilization in all treatments and exhibited less variation than in the first two applications. The soil  $\text{NO}_3^-$ -N contents exhibited slight fluctuations during the rice maturation period before decreasing to a lower level and stabilizing at that point.

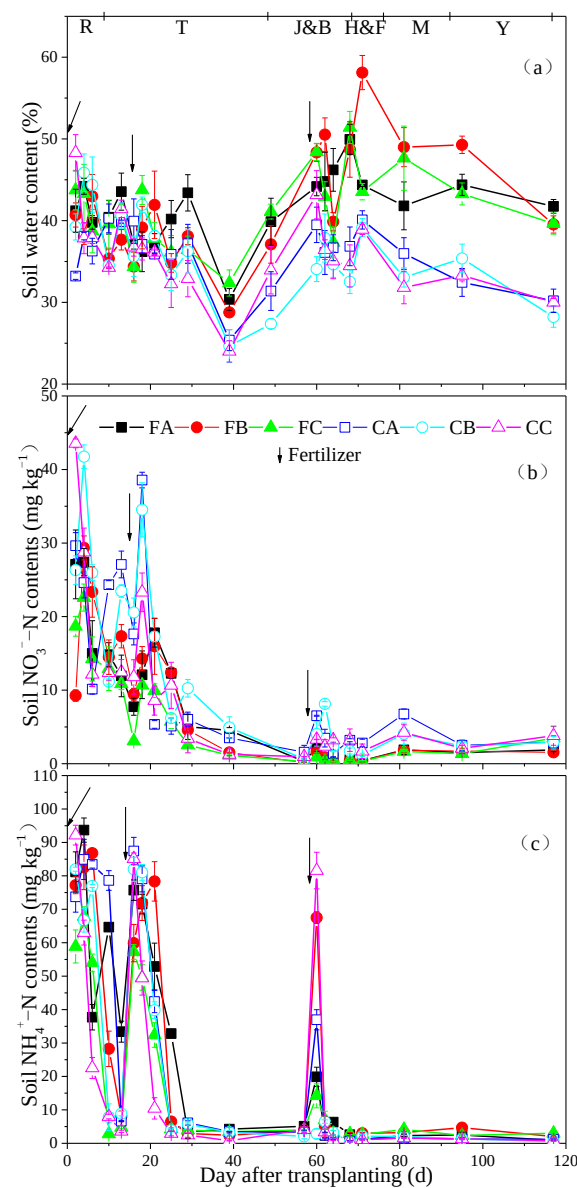


**Figure 4.** Changes in soil water content (a),  $\text{NO}_3^-$ -N (b), and  $\text{NH}_4^+$ -N (c) contents. Note: The capital letters R, T, J & B, H & F, M, and Y in the figure represent the re-greening stage, tillering stage, jointing and booting stages, heading and flowering stages, milk-ripe stage, and yellow ripeness stage of rice, respectively.

The soil  $\text{NH}_4^+\text{-N}$  contents in all treatments were primarily influenced by fertilization, and they increased significantly after basal and tillering fertilizers, but then decreased rapidly and fell to lower levels during the middle of the rice tillering stage (Figure 4c). The soil  $\text{NH}_4^+\text{-N}$  contents varied significantly among the treatments after spike fertilization. The FB, CA, and CC treatments showed a greater increase in soil  $\text{NH}_4^+\text{-N}$  contents, while the other treatments showed smaller changes. Subsequently, the soil  $\text{NH}_4^+\text{-N}$  contents in the rice fields of all treatments remained at a low level until rice harvest.

### 3.4. Relationships between $\text{CH}_4$ and $\text{N}_2\text{O}$ Fluxes with Impact Factors

The application of fertilizer had a significant impact on the cumulative emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  from the rice fields ( $p < 0.05$ ), particularly on the cumulative emissions of  $\text{N}_2\text{O}$  ( $p < 0.001$ ). Irrigation had a highly significant effect on both  $\text{CH}_4$  and  $\text{N}_2\text{O}$  cumulative emissions from the rice fields ( $p < 0.001$ ). Ultimately, the interaction of fertilizer and irrigation also had a highly significant effect on the cumulative  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions from the rice fields ( $p < 0.001$ , Table 1).

**Table 1.** Effect of fertilizer, irrigation and their interaction effects on cumulative  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions from rice fields.

| Factor                         | $\text{CH}_4$ |          | $\text{N}_2\text{O}$ |          |
|--------------------------------|---------------|----------|----------------------|----------|
|                                | <i>F</i>      | <i>p</i> | <i>F</i>             | <i>p</i> |
| Fertilizer                     | 6             | 0.014    | 216                  | <0.001   |
| Irrigation                     | 681           | <0.001   | 613                  | <0.001   |
| Fertilizer $\times$ Irrigation | 16            | <0.001   | 244                  | <0.001   |

In flooded irrigation, there was a significant positive correlation between the  $\text{CH}_4$  fluxes and soil water content in the rice fields ( $p < 0.05$ , FC treatments were excluded, Table 2). Additionally, there was a significant negative correlation between the  $\text{CH}_4$  fluxes and the soil  $\text{NO}_3^-\text{-N}$  and  $\text{NH}_4^+\text{-N}$  contents ( $p < 0.05$ ). However, the relationship between the  $\text{N}_2\text{O}$  fluxes and their influencing factors was the opposite. It was significantly correlated with soil  $\text{NO}_3^-\text{-N}$  content only in the FB and FC treatments ( $p < 0.05$ ). Under controlled irrigation conditions, the  $\text{CH}_4$  fluxes showed a negative correlation with soil water content,  $\text{NO}_3^-\text{-N}$ , and  $\text{NH}_4^+\text{-N}$  contents in the rice fields. The correlation with soil  $\text{NO}_3^-\text{-N}$  and  $\text{NH}_4^+\text{-N}$  contents was significant ( $p < 0.05$ ). On the other hand, the  $\text{N}_2\text{O}$  fluxes showed a positive correlation with soil water content,  $\text{NO}_3^-\text{-N}$ , and  $\text{NH}_4^+\text{-N}$  contents, but the correlation was usually not significant ( $p > 0.05$ ). Additionally, the use of bio-organic fertilizers in controlled irrigation reduced the correlation between the  $\text{CH}_4$  and  $\text{N}_2\text{O}$  fluxes, soil moisture, and nitrogen nutrients in the rice fields. As the amounts of bio-organic fertilizers replacing the chemical fertilizers increased, the correlation coefficients decreased accordingly.

**Table 2.** Correlation between  $\text{CH}_4$  and  $\text{N}_2\text{O}$  fluxes with impact factors.

| Treatment | Gas                  | Soil Water Content | $\text{NO}_3^-\text{-N}$ | $\text{NH}_4^+\text{-N}$ |
|-----------|----------------------|--------------------|--------------------------|--------------------------|
| FA        | $\text{CH}_4$        | 0.531 *            | −0.764 **                | −0.736 **                |
|           | $\text{N}_2\text{O}$ | −0.105             | 0.257                    | 0.309                    |
| FB        | $\text{CH}_4$        | 0.693 *            | −0.740 **                | −0.506 *                 |
|           | $\text{N}_2\text{O}$ | −0.290             | 0.799 **                 | 0.379                    |
| FC        | $\text{CH}_4$        | 0.392              | −0.686 **                | −0.531 *                 |
|           | $\text{N}_2\text{O}$ | −0.024             | 0.459 *                  | 0.123                    |
| CA        | $\text{CH}_4$        | −0.426             | −0.572 **                | −0.574 **                |
|           | $\text{N}_2\text{O}$ | 0.218              | 0.597 **                 | 0.288                    |
| CB        | $\text{CH}_4$        | −0.577 **          | −0.567 **                | −0.514 *                 |
|           | $\text{N}_2\text{O}$ | 0.214              | 0.218                    | 0.188                    |
| CC        | $\text{CH}_4$        | −0.331             | −0.542 *                 | −0.318                   |
|           | $\text{N}_2\text{O}$ | 0.084              | 0.013                    | −0.103                   |

Note: \* and \*\* indicate significant differences at  $p < 0.05$  and  $p < 0.01$ , respectively.

### 3.5. Rice Yield and Cumulative Gas Emissions

There was no significant difference in rice yield in different water and fertilizer management. Under the same fertilization method, controlled irrigation reduced the CH<sub>4</sub> emissions by 55.2~69.4% but increased the N<sub>2</sub>O emissions by 47.5~207.9%. This ultimately resulted in a significant reduction in their GWP by 11.8~45.5% ( $p < 0.05$ , Table 3). Under the same irrigation pattern, replacing some chemical fertilizers with bio-organic fertilizers had a negligible effect (less than 1%) on rice yields compared with full chemical fertilizers. However, it significantly reduced the CH<sub>4</sub> (11.9~29.7%) and N<sub>2</sub>O (10.8~57.3%) emissions from rice fields, resulting in a significant reduction in the GWP of 16.1~48.1% ( $p < 0.05$ ). By using different water-fertilizer combinations, the combined greenhouse effect in rice fields can be reduced while also affecting rice yields. Thus, when evaluating the greenhouse gas emission intensity (GHGI) of rice fields in conjunction with rice yield, it was found that replacing some chemical fertilizers with bio-organic fertilizers significantly reduced the GHGI by 16.3% to 48.1% compared with the full chemical fertilizer treatment ( $p < 0.05$ ). The GHGI of CB treatment was significantly reduced by 16.9~54.0% ( $p < 0.05$ ) compared with other treatments. Although the yield also decreased, it was much lower than that of GWP and GHGI. In conclusion, replacing 15% chemical nitrogen fertilizer with bio-organic fertilizer under controlled irrigation conditions can minimize the GWP and GHGI in rice fields while ensuring rice yield.

**Table 3.** Rice yield, cumulative gas emissions, GWP, and GHGI for all treatments.

| Treatment                                                    | FA       | FB       | FC       | CA       | CB       | CC       |
|--------------------------------------------------------------|----------|----------|----------|----------|----------|----------|
| Yield (kg ha <sup>-1</sup> )                                 | 9247.8 a | 9271.5 a | 9232.7 a | 9212.2 a | 9205.2 a | 9135.3 a |
| Cumulative CH <sub>4</sub> emissions (kg ha <sup>-1</sup> )  | 55.2 a   | 45.6 b   | 38.8 c   | 19.7 d   | 14.0 e   | 17.4 d   |
| Cumulative N <sub>2</sub> O emissions (kg ha <sup>-1</sup> ) | 1.1 c    | 1.0 cd   | 0.9 d    | 3.4 a    | 1.5 b    | 1.7 b    |
| GWP (kg CO <sub>2</sub> ha <sup>-1</sup> )                   | 1710.2 a | 1434.7 b | 1226.6 c | 1507.6 b | 782.3 e  | 934.8 d  |
| GHGI (kg CO <sub>2</sub> t <sup>-1</sup> )                   | 184.9 a  | 155.7 b  | 132.9 c  | 163.7 b  | 85.0 e   | 102.3 d  |

Note: Different lowercase letters in the table indicate significant differences between treatments ( $p < 0.05$ ).

## 4. Discussion

### 4.1. Effect of Water and Fertilizer Management on CH<sub>4</sub> Emissions

The emissions of CH<sub>4</sub> from rice fields were significantly affected by fertilization, irrigation, and their interactions (Table 1) [35]. Generally, the application of nitrogen fertilizer promotes the conversion of acetic acid to CH<sub>4</sub> in the soil, which in turn increases CH<sub>4</sub> emissions [36]. However, the chemical nitrogen fertilizers (especially urea), through their hydrolysis, lead to ample NH<sub>4</sub><sup>+</sup>-N accumulation, which paradoxically stimulates methane oxidation bacteria, thereby reducing CH<sub>4</sub> emissions [37]. In contrast, organic fertilizers enhance the soil's carbon content, providing substrates for methanogens and thus promoting CH<sub>4</sub> production [38,39]. This is different from our experimental results. Our study found that although bio-organic fertilizers were derivatives of organic fertilizers, substituting a portion of chemical nitrogen fertilizers with bio-organic fertilizers reduces CH<sub>4</sub> emissions from rice fields (Table 3). During the production process, bio-organic fertilizers undergo full ripening and fermentation, causing their organic substances to decompose and transform into more stable organic matter [40]. This matter is not easily decomposed by microorganisms in the soil and degrades slowly, which is conducive to being utilized by crop growth [41]. In our experiment, the bio-organic fertilizer was applied by spreading, which consumed part of the organic matter through aerobic decomposition [42] before entering the soil with the water movement. Additionally, organic fertilizers can promote the growth of phototrophs when exposed to light after application, and they will inhibit the production of CH<sub>4</sub> at the soil-water interface [43]. Chemical nitrogen fertilizers can promote rice plant growth, increase soil organic acid content in the root system, improve the environment for methanogenic bacterial activity, promote CH<sub>4</sub> production [44], and provide an effective channel for CH<sub>4</sub> emission [34]. This also explains the lower peak CH<sub>4</sub> fluxes in the rice fields with the bio-organic fertilizer replacement treatment compared with the full chemical

fertilizer treatment after spike fertilization (Figure 1). Similar results have been found in previous studies. For instance, Liao et al. [34] discovered that substituting partial chemical nitrogen fertilizer with organic fertilizer could decrease CH<sub>4</sub> emissions from rice fields. And, CH<sub>4</sub> emissions from rice fields with 50% organic fertilizer replacement were higher than those with 25% organic fertilizer replacement [34]. Furthermore, moisture management affects gas permeability and the redox status of soil, which in turn influences soil CH<sub>4</sub> production, oxidation, and emissions [28]. Under flooded conditions that create an anaerobic environment, methanogens thrive, amplifying CH<sub>4</sub> production [28,45]. However, during the rice re-greening stage, we observed consistently low CH<sub>4</sub> fluxes. This may result from inhibited CH<sub>4</sub> diffusion due to water coverage and compacted soil [27], along with heightened activity of methane oxidation bacteria fueled by substantial soil NH<sub>4</sub><sup>+</sup>-N levels post-fertilization [37]. As rice grows, the leaf area index increases, which provides a channel for CH<sub>4</sub> emission [34]. Therefore, CH<sub>4</sub> fluxes gradually increase during the tillering stage in rice fields. At the end of rice tillering, the drainage of rice fields results in a rapid increase in CH<sub>4</sub> emissions, followed by a decrease in CH<sub>4</sub> fluxes as soil moisture continues to subside. This is due to the fact that during the initial period of rice field drainage, soil permeability increases, causing concentrated emissions of CH<sub>4</sub> that have accumulated in the soil [27]. As soil moisture decreases, the available carbon source is quickly degraded to CO<sub>2</sub> in aerobic conditions, resulting in a decrease in CH<sub>4</sub> emissions [46]. In controlled irrigation, the rice field was typically free of a water layer after the rice re-greening stage. However, the soil moisture remains high, which means that controlled irrigation does not completely suppress CH<sub>4</sub> production, but it does result in lower CH<sub>4</sub> emissions compared with flooded irrigation [34]. Controlled irrigation increases the soil permeability of rice fields, which reduces the activity of methanogenic microorganisms and increases the activity of methane oxidation bacteria, thereby reducing CH<sub>4</sub> emissions [29,47]. While water-saving irrigation can decrease CH<sub>4</sub> emissions from rice fields, the extent of CH<sub>4</sub> reduction varies depending on the technique used. According to Liao et al. [34], water-saving irrigation reduces CH<sub>4</sub> emissions by 24.8% to 49.2% compared with flooded irrigation. In water-saving irrigation, a water layer appears in the rice field after each irrigation, which inhibits CH<sub>4</sub> to a lesser extent than in controlled irrigation.

#### 4.2. Effect of Water and Fertilizer Management on N<sub>2</sub>O Emissions

Soil moisture drives N<sub>2</sub>O production, while nitrogen fertilizer levels determine differences in N<sub>2</sub>O emission intensity [48]. Soil moisture status affects N<sub>2</sub>O production and emission primarily by influencing soil nitrification and denitrification, as well as soil permeability. The N<sub>2</sub>O fluxes in rice fields remained consistently low under flooded irrigation treatment (Figure 2). Due to the anaerobic conditions and low permeability of rice soils in flooded irrigation, N<sub>2</sub>O emissions from denitrification are limited, allowing for sufficient time for further reduction to N<sub>2</sub> [28]. In controlled irrigation, the soil water content in rice fields was typically above 70% saturation, and there was no water layer present. When soil nitrification and denitrification reactions occurred simultaneously, N<sub>2</sub>O emissions were higher when compared with the flooded irrigation treatment [49]. Nitrogen fertilizer provides the substrate for soil N<sub>2</sub>O emissions [50]. In flooded irrigation, N<sub>2</sub>O fluxes were only slightly increased after basal fertilizer application. However, in controlled irrigation, N<sub>2</sub>O emissions were elevated after each fertilizer application and dramatically increased only after tiller fertilizer application (Figure 3). During the entire growth period of rice in flooded irrigation and the re-greening stage of rice in controlled irrigation, the presence of a water layer restricted N<sub>2</sub>O emissions [28]. In contrast, in controlled irrigation, when tiller fertilizer was applied, the water level of the rice field gradually dropped below the field surface. This process generated a large amount of N<sub>2</sub>O, which was susceptible to emission peaks during the decrease in soil water content [51,52]. This also explained the large increase in N<sub>2</sub>O fluxes in the CA treatment when the field water layer dried up for the first time after the rice re-greening stage (Figure 3). However, spike fertilizer had less effect on the N<sub>2</sub>O fluxes in rice fields under controlled irrigation. This phenomenon has been

observed in previous studies [48,53]. On the one hand, this difference may be due to the lower nitrogen content in spike fertilizer compared with tiller fertilizer. On the other hand, there was a higher emission of  $\text{CH}_4$  after spike fertilizer (Figure 2), and the methanogenic microorganisms consumed nitrogen for the production of  $\text{CH}_4$  [36]. Additionally, substituting a portion of chemical nitrogen fertilizers with bio-organic fertilizers can decrease  $\text{N}_2\text{O}$  emissions from rice fields. This is because bio-organic fertilizers release nitrogen slowly, resulting in lower effective nitrogen content in the soil compared with conventional fertilizer treatments. As a result, the soil nitrification–denitrification process is curtailed, leading to a reduction in  $\text{N}_2\text{O}$  emissions [54,55]. This is similar to the findings of previous studies [19,34]. Additionally, substituting a portion of chemical nitrogen fertilizers with bio-organic fertilizers had a greater inhibitory effect on  $\text{N}_2\text{O}$  emissions under controlled irrigation conditions. Specifically,  $\text{N}_2\text{O}$  emissions from rice fields were significantly lower in the CB and CC treatments compared with CA treatments, while no significant difference was observed under flooded irrigation. In flooded irrigation, bio-organic fertilizer does not significantly reduce  $\text{N}_2\text{O}$  emissions from rice fields. This is because the total amount of  $\text{N}_2\text{O}$  emission from the rice fields is already low, and sufficient soil moisture accelerates the release of nutrients from organic fertilizers and improves the soil carbon-to-nitrogen ratio, which in turn affects  $\text{N}_2\text{O}$  fluxes [53,56]. This suggests that combined water and fertilizer management have an interactive effect on  $\text{N}_2\text{O}$  emissions from rice fields [57].

## 5. Conclusions

Substituting some chemical fertilizers with bio-organic fertilizers can decrease the peak values of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  fluxes in rice fields and lower the cumulative emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , which in turn could lead to a significant reduction in the global warming potential. Whereas controlled irrigation can reduce  $\text{CH}_4$  emissions from rice fields compared with flooded irrigation, it increases  $\text{N}_2\text{O}$  emissions, and ultimately, its GWP shows a decreasing trend. Meanwhile, the greenhouse gas emission intensity from rice fields where bio-organic fertilizers replaced part of the chemical fertilizers was significantly lower than that of full chemical fertilizers and had no significant effect on rice yield. In addition, the substitution of chemical fertilizers with bio-organic fertilizers can further contribute to the reduction of greenhouse gas emissions from rice fields under controlled irrigation. The substitution of 15% chemical nitrogen fertilizers with bio-organic fertilizers in controlled irrigation can minimize the global warming potential and greenhouse gas emission intensity in rice paddies.

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## References

1. World Meteorological Organization. *WMO Greenhouse Gas Bulletin No. 16: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2019*; World Meteorological Organization: Geneva, Switzerland, 2019.
2. World Meteorological Organization. *United in Science 2021: A Multi-Organization High-Level Compilation of the Latest Climate Science Information*; World Meteorological Organization: Geneva, Switzerland, 2021.
3. Saunio, M. The Global Methane Budget 2000–2017. *Earth Syst.* **2020**, *12*, 1561–1623. [[CrossRef](#)]
4. Lal, R. Intensive Agriculture and the Soil Carbon Pool. *J. Crop. Improv.* **2013**, *27*, 735–751. [[CrossRef](#)]

5. Li, C.S.; Mosier, A.; Wassmann, R.; Cai, Z.C.; Zheng, X.H.; Huang, Y.; Tsuruta, H.; Boonjawat, J.; Lantin, R. Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Global Biogeochem. Cycles* **2004**, *18*, 1–19. [\[CrossRef\]](#)
6. Huang, S.; Pant, H.K.; Lu, J. Effects of water regimes on nitrous oxide emission from soils. *Ecol. Eng.* **2007**, *31*, 9–15. [\[CrossRef\]](#)
7. Bouwman, A.F. Direct emission of nitrous oxide from agricultural soils. *Nutr. Cycl. Agroecosyst.* **1996**, *46*, 53–70. [\[CrossRef\]](#)
8. Liang, H.; Xu, J.; Hou, H.; Qi, Z.; Yang, S.; Li, Y.; Hu, K. Modeling CH<sub>4</sub> and N<sub>2</sub>O emissions for continuous and noncontinuous flooding rice systems. *Agric. Syst.* **2022**, *203*, 1–13. [\[CrossRef\]](#)
9. Sun, H.; Feng, Y.; Ji, Y.; Shi, W.; Yang, L.; Xing, B. N<sub>2</sub>O and CH<sub>4</sub> emissions from N-fertilized rice paddy soil can be mitigated by wood vinegar application at an appropriate rate. *Atmos. Environ.* **2018**, *185*, 153–158. [\[CrossRef\]](#)
10. Duchemin, M.; Hogue, R. Reduction in agricultural non-point source pollution in the first year following establishment of an integrated grass/tree filter strip system in southern Quebec (Canada). *Agric. Ecosyst. Environ.* **2009**, *131*, 85–97. [\[CrossRef\]](#)
11. Lu, H.; Xie, H. Impact of changes in labor resources and transfers of land use rights on agricultural non-point source pollution in Jiangsu Province, China. *J. Environ. Manag.* **2018**, *207*, 134–140. [\[CrossRef\]](#)
12. Li, X.; Weller, D.E.; Jordan, T.E. Watershed model calibration using multi-objective optimization and multi-site averaging. *J. Hydrol.* **2010**, *380*, 277–288. [\[CrossRef\]](#)
13. Du, X.; Li, X.; Zhang, W.; Wang, H. Variations in source apportionments of nutrient load among seasons and hydrological years in a semi-arid watershed: GWLF model results. *Environ. Sci. Pollut. R.* **2014**, *21*, 6506–6515. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Guo, X.; Liu, J.; Xu, L.; Sun, F.; Ma, Y.; Yin, D.; Gao, Q.; Zheng, G.; Lv, Y. Combined Organic and Inorganic Fertilization Can Enhance Dry Direct-Seeded Rice Yield by Improving Soil Fungal Community and Structure. *Agronomy* **2022**, *12*, 1213. [\[CrossRef\]](#)
15. Yang, Y.; Liu, B.; Ni, X.; Tao, L.; Yu, L.; Yang, Y.; Feng, M.; Zhong, W.; Wu, Y. Rice productivity and profitability with slow-release urea containing organic-inorganic matrix materials. *Pedosphere* **2021**, *31*, 511–520. [\[CrossRef\]](#)
16. Ansari, R.A.; Mahmood, I. Optimization of organic and bio-organic fertilizers on soil properties and growth of pigeon pea. *Sci. Hortic.* **2017**, *226*, 1–9. [\[CrossRef\]](#)
17. Huang, N.; Wang, W.W.; Yao, Y.L.; Zhu, F.X.; Wang, W.P.; Chang, X.J. The influence of different concentrations of bio-organic fertilizer on cucumber Fusarium wilt and soil microflora alterations. *PLoS ONE* **2017**, *12*, e0171490. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Wang, J.F.; Li, X.L.; Xing, S.Z.; Ma, Z.Y.; Hu, S.J.; Tu, C. Bio-organic Fertilizer Promotes Plant Growth and Yield and Improves Soil Microbial Community in Continuous Monoculture System of *Chrysanthemum morifolium* cv. Chuju. *Int. J. Agric. Biol.* **2017**, *19*, 563–568. [\[CrossRef\]](#)
19. Li, Y.; Zheng, Q.; Yang, R.; Zhuang, S.; Lin, W.; Li, Y. Evaluating microbial role in reducing N<sub>2</sub>O emission by dual isotopocule mapping following substitution of inorganic fertilizer for organic fertilizer. *J. Clean Prod.* **2021**, *326*, 129442. [\[CrossRef\]](#)
20. Ma, Q.Y.; Li, J.W.; Aamer, M.; Huang, G.Q. Effect of Chinese Milk Vetch *Astragalus sinicus* and Rice Straw Incorporated in Paddy Soil on Greenhouse Gas Emission and Soil Properties. *Agronomy* **2020**, *10*, 717. [\[CrossRef\]](#)
21. Thuries, L.; Pansu, M.; Larre-Larrouy, M.C.; Feller, C. Biochemical composition and mineralization kinetics of organic inputs in a sandy soil. *Soil Biol. Biochem.* **2002**, *34*, 239–250. [\[CrossRef\]](#)
22. Yuan, J.; Yuan, Y.; Zhu, Y.; Cao, L. Effects of different fertilizers on methane emissions and methanogenic community structures in paddy rhizosphere soil. *Sci. Total Environ.* **2018**, *627*, 770–781. [\[CrossRef\]](#)
23. Kim, S.Y.; Pramanik, P.; Gutierrez, J.; Hwang, H.Y.; Kim, P.J. Comparison of methane emission characteristics in air-dried and composted cattle manure amended paddy soil during rice cultivation. *Agric. Ecosyst. Environ.* **2014**, *197*, 60–67. [\[CrossRef\]](#)
24. Linquist, B.A.; Adviento-Borbe, M.A.; Pittelkow, C.M.; Van Kessel, C.; Van Groenigen, K.J. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Res.* **2012**, *135*, 10–21. [\[CrossRef\]](#)
25. Zhang, X.; Zhou, S.; Bi, J.; Sun, H.; Wang, C.; Zhang, J. Drought-resistance rice variety with water-saving management reduces greenhouse gas emissions from paddies while maintaining rice yields. *Agric. Ecosyst. Environ.* **2021**, *320*, 107592. [\[CrossRef\]](#)
26. Zhuang, Y.; Zhang, L.; Li, S.; Liu, H.; Zhai, L.; Zhou, F.; Ye, Y.; Ruan, S.; Wen, W. Effects and potential of water-saving irrigation for rice production in China. *Agric. Water Manag.* **2019**, *217*, 374–382. [\[CrossRef\]](#)
27. Song, C.C.; Zhang, J.B.; Wang, Y.Y.; Wang, Y.S.; Zhao, Z.C. Emission of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O from freshwater marsh in northeast of China. *J. Environ. Manag.* **2008**, *88*, 428–436. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Zou, J.W.; Huang, Y.; Jiang, J.Y.; Zheng, X.H.; Sass, R.L. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Glob. Biogeochem. Cycles* **2005**, *19*, 1–9. [\[CrossRef\]](#)
29. Peng, S.; Yang, S.; Xu, J.; Gao, H. Field experiments on greenhouse gas emissions and nitrogen and phosphorus losses from rice paddy with efficient irrigation and drainage management. *Sci. China Technol. Sci.* **2011**, *54*, 1581–1587. [\[CrossRef\]](#)
30. Hou, H.J.; Yang, S.H.; Wang, F.T.; Li, D.; Xu, J.Z. Controlled irrigation mitigates the annual integrative global warming potential of methane and nitrous oxide from the rice-winter wheat rotation systems in Southeast China. *Ecol. Eng.* **2016**, *86*, 239–246. [\[CrossRef\]](#)
31. Xu, J.; Liu, B.; Wang, H.; Liu, W.; Li, Y.; Dai, Y.; Lu, T. Ammonia volatilization and nitrogen leaching following top-dressing of urea from water-saving irrigated rice field: Impact of two-split surge irrigation. *Paddy Water Environ.* **2019**, *17*, 45–51. [\[CrossRef\]](#)
32. Hou, H.J.; Peng, S.Z.; Xu, J.Z.; Yang, S.H.; Mao, Z. Seasonal variations of CH<sub>4</sub> and N<sub>2</sub>O emissions in response to water management of paddy fields located in Southeast China. *Chemosphere* **2012**, *89*, 884–892. [\[CrossRef\]](#)
33. Qian, H.; Chen, J.; Zhu, X.; Wang, L.; Liu, Y.; Zhang, J.; Deng, A.; Song, Z.; Ding, Y.; Jiang, Y.; et al. Intermittent flooding lowers the impact of elevated atmospheric CO<sub>2</sub> on CH<sub>4</sub> emissions from rice paddies. *Agric. Ecosyst. Environ.* **2022**, *329*, 107872. [\[CrossRef\]](#)

34. Liao, B.; Cai, T.; Wu, X.; Luo, Y.; Liao, P.; Zhang, B.; Zhang, Y.; Wei, G.; Hu, R.; Luo, Y.; et al. A combination of organic fertilizers partially substitution with alternate wet and dry irrigation could further reduce greenhouse gases emission in rice field. *J. Environ. Manag.* **2023**, *344*, 118372. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Wang, J.; Zhang, X.; Xiong, Z.; Khalil, M.A.K.; Zhao, X.; Xie, Y.; Xing, G. Methane emissions from a rice agroecosystem in South China: Effects of water regime, straw incorporation and nitrogen fertilizer. *Nutr. Cycl. Agroecosyst.* **2012**, *93*, 103–112. [\[CrossRef\]](#)
36. Cai, Z.; Shan, Y.; Xu, H. Effects of nitrogen fertilization on CH<sub>4</sub> emissions from rice fields. *Soil Sci. Plant Nutr.* **2007**, *53*, 353–361. [\[CrossRef\]](#)
37. Zhou, M.H.; Zhu, B.; Wang, X.G.; Wang, Y.Q. Long-term field measurements of annual methane and nitrous oxide emissions from a Chinese subtropical wheat-rice rotation system. *Soil Biol. Biochem.* **2017**, *115*, 21–34. [\[CrossRef\]](#)
38. Kumaraswamy, S.; Ramakrishnan, B.; Sethunathan, N. Methane production and oxidation in an anoxic rice soil as influenced by inorganic redox species. *J. Environ. Qual.* **2001**, *30*, 2195–2201. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Lin, S.; Zhang, S.; Shen, G.; Shaaban, M.; Ju, W.; Cui, Y.; Duan, C.; Fang, L. Effects of inorganic and organic fertilizers on CO<sub>2</sub> and CH<sub>4</sub> fluxes from tea plantation soil. *Elementa-Sci. Anthropol.* **2021**, *9*, 090. [\[CrossRef\]](#)
40. Jeong, S.T.; Kim, G.W.; Hwang, H.Y.; Kim, P.J.; Kim, S.Y. Beneficial effect of compost utilization on reducing greenhouse gas emissions in a rice cultivation system through the overall management chain. *Sci. Total Environ.* **2018**, *613*, 115–122. [\[CrossRef\]](#)
41. Zhang, T.; Liu, H.; Luo, J.; Wang, H.; Zhai, L.; Geng, Y.; Zhang, Y.; Li, J.; Lei, Q.; Bashir, M.A.; et al. Long-term manure application increased greenhouse gas emissions but had no effect on ammonia volatilization in a Northern China upland field. *Sci. Total Environ.* **2018**, *633*, 230–239. [\[CrossRef\]](#)
42. Wassmann, R.; Lantin, R.S.; Neue, H.U.; Buendia, L.V.; Corton, T.M.; Lu, Y. Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutr. Cycl. Agroecosyst.* **2000**, *58*, 23–36. [\[CrossRef\]](#)
43. Harada, N.; Otsuka, S.; Nishiyama, M.; Matsumoto, S. Influences of indigenous phototrophs on methane emissions from a straw-amended paddy soil. *Biol. Fert. Soils.* **2005**, *41*, 46–51. [\[CrossRef\]](#)
44. Chen, Y.; Li, S.; Zhang, Y.; Li, T.; Ge, H.; Xia, S.; Gu, J.; Zhang, H.; Lu, B.; Wu, X.; et al. Rice root morphological and physiological traits interaction with rhizosphere soil and its effect on methane emissions in paddy fields. *Soil Biol. Biochem.* **2019**, *129*, 191–200. [\[CrossRef\]](#)
45. Matsuda, S.; Nakamura, K.; Tran, H.; Le Xuan, Q.; Haruhiko, H.; Pham Thanh, H.; Nguyen Dang, H.; Hama, T. Paddy ponding water management to reduce methane emission based on observations of methane fluxes and soil redox potential in the Red River Delta, Vietnam\*. *Irrig. Drain.* **2022**, *71*, 241–254. [\[CrossRef\]](#)
46. Chen, D.; Wang, C.; Shen, J.; Li, Y.; Wu, J. Response of CH<sub>4</sub> emissions to straw and biochar applications in double-rice cropping systems: Insights from observations and modeling. *Environ. Pollut.* **2018**, *235*, 95–103. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Oo, A.Z.; Sudo, S.; Inubushi, K.; Mano, M.; Yamamoto, A.; Ono, K.; Osawa, T.; Hayashida, S.; Patra, P.K.; Terao, Y.; et al. Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India. *Agric. Ecosyst. Environ.* **2018**, *252*, 148–158. [\[CrossRef\]](#)
48. Liao, B.; Wu, X.; Yu, Y.; Luo, S.; Hu, R.; Lu, G. Effects of mild alternate wetting and drying irrigation and mid-season drainage on CH<sub>4</sub> and N<sub>2</sub>O emissions in rice cultivation. *Sci. Total Environ.* **2020**, *698*, 134212. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Xia, L.; Lam, S.K.; Yan, X.; Chen, D. How Does Recycling of Livestock Manure in Agroecosystems Affect Crop Productivity, Reactive Nitrogen Losses, and Soil Carbon Balance? *Environ. Sci. Technol.* **2017**, *51*, 7450–7457. [\[CrossRef\]](#)
50. Huang, T.; Gao, B.; Hu, X.-K.; Lu, X.; Well, R.; Christie, P.; Bakken, L.R.; Ju, X.-T. Ammonia-oxidation as an engine to generate nitrous oxide in an intensively managed calcareous Fluvo-aquic soil. *Sci. Rep.* **2014**, *4*, 3950. [\[CrossRef\]](#)
51. Peng, S.; Hou, H.; Xu, J.; Mao, Z.; Abudu, S.; Luo, Y. Nitrous oxide emissions from paddy fields under different water managements in southeast China. *Paddy Water Environ.* **2011**, *9*, 403–411. [\[CrossRef\]](#)
52. Cai, Z.; Laughlin, R.J.; Stevens, R.J. Nitrous oxide and dinitrogen emissions from soil under different water regimes and straw amendment. *Chemosphere* **2001**, *42*, 113–121. [\[CrossRef\]](#)
53. Shan, J.; Xu, X. Effects of crop residue returning on nitrous oxide emissions in agricultural soils. *Atmos. Environ.* **2013**, *71*, 170–175. [\[CrossRef\]](#)
54. Tao, R.; Li, J.; Guan, Y.; Liang, Y.; Hu, B.; Lv, J.; Chu, G. Effects of urease and nitrification inhibitors on the soil mineral nitrogen dynamics and nitrous oxide (N<sub>2</sub>O) emissions on calcareous soil. *Environ. Sci. Pollut. Res. Int.* **2018**, *25*, 9155–9164. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Li, Y.; Xu, J.; Liu, X.; Qi, Z.; Wang, H.; Li, Y.; Liao, L. Nitrification inhibitor DMPP offsets the increase in N<sub>2</sub>O emission induced by soil salinity. *Biol. Fertility Soils.* **2020**, *56*, 1211–1217. [\[CrossRef\]](#)
56. Ma, J.; Li, X.L.; Xu, H.; Han, Y.; Cai, Z.C.; Yagi, K. Effects of nitrogen fertiliser and wheat straw application on CH<sub>4</sub> and N<sub>2</sub>O emissions from a paddy rice field. *Aust. J. Soil Res.* **2007**, *45*, 359–367. [\[CrossRef\]](#)
57. Li, J.; Li, Y.E.; Wan, Y.; Wang, B.; Waqas, M.A.; Cai, W.; Guo, C.; Zhou, S.; Su, R.; Qin, X.; et al. Combination of modified nitrogen fertilizers and water saving irrigation can reduce greenhouse gas emissions and increase rice yield. *Geoderma* **2018**, *315*, 1–10. [\[CrossRef\]](#)

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