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Effects of Different Rice Varieties and Water Management Practices on Greenhouse Gas (CH_4 and N_2O) Emissions in the Ratoon Rice System in the Upper Yangtze River Region, China

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Abstract: Ratoon rice can improve rice yield by increasing the multiple cropping index in China. However, the greenhouse gas (CH_4 and N_2O) emission characteristics from ratoon rice fields and the cultivation methods to reduce CH_4 and N_2O emissions are rarely reported. This study first conducted the analysis of genotype differences in greenhouse gas emission fluxes using five strong ratoon ability rice varieties in 2020. Second, water management methods, including alternating the wet–dry irrigation (AWD) pattern and conventional flooding irrigation (CF) during the main season, were carried out in 2021. CH_4 and N_2O emission flux, agronomic traits, and rice yield during both main and ratoon seasons were investigated. The results showed that the CH_4 emission flux during the main and ratoon seasons was 157.05–470.73 kg·ha^{-1} and 31.03–84.38 kg·ha^{-1}, respectively, and the total N_2O emission flux was 0.13–0.94 kg·ha^{-1} in the ratoon rice system over the two seasons (RRSTS). Compared with the main season, the CH_4 emission flux during the ratoon season was significantly reduced, thus decreasing the greenhouse gas global warming potential (GWP) and greenhouse gas emission intensity (GHGI) in the ratoon rice system. Cliangyouhuazhan (CLYHZ) showed a high yield, and the lowest GWP and GHGI values among the five rice varieties in RRSTS. Compared with CF, the AWD pattern reduced the CH_4 emission flux during the main and ratoon seasons by 67.4–95.3 kg·ha^{-1} and 1.7–5.1 kg·ha^{-1}, respectively, but increased the N_2O emission flux by 0.1–0.6 kg·ha^{-1} during the RRSTS. Further, compared with CF, the AWD pattern had a declined GWP by 14.3–19.4% and GHGI by 30.3–34.3% during the RRSTS, which was attributed to the significant reduction in GWP and GHGI during the main season. The AWD pattern significantly increased rice yield by 21.9–22.9% during the RRSTS, especially for YX203. Correlation analysis showed that CH_4, GWP, and GHGI exhibited significant negative correlations with spikelet number per m^2 and the harvest index during the main and ratoon seasons. Collectively, selecting the high-yield, low-emission variety CLYHZ could significantly reduce greenhouse gas emissions from ratoon rice while maintaining a high yield. The AWD pattern could reduce total CH_4 emission during the main season, reducing the GWP and GHGI while increasing the ratoon rice system yield. It could be concluded that a variety of CLYHZ and AWD patterns are worthy of promotion and application to decrease greenhouse gas emissions in the ratoon rice area in the upper reaches of Yangtze River, China.

Keywords: ratoon rice; CH_4 emission; global warming potential (GWP); greenhouse gas intensity (GHGI); alternating wet–dry irrigation (AWD); yield

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1. Introduction

Agricultural systems are important sources of greenhouse gasses (methane (CH_4) and nitrous oxide (N_2O)). CH_4 and N_2O emissions from agricultural sources account for 39.5% and 58.2% of global anthropogenic emissions, respectively [1]. Rice production systems emit the highest amount of greenhouse gasses among different crops. China's rice fields emit

6.4 Tg of CH_4 and 180 Gg of N_2O annually [2], with CH_4 emissions from rice cultivation accounting for approximately 21.9% of global CH_4 [3]. China is the world's largest rice producer and consumer. In China, the increase in rice production due to urbanization relies more on higher rice yield per unit area than on expanding cultivated land [4]. With the increase in rice production costs and the continuous reduction in rural labor, the traditional single-season rice yield increase model with high water and fertilizer inputs often causes multiple environmental problems, such as water pollution, soil degradation, and non-point source pollution. Thus, it can no longer meet the needs of current economic and social development. Therefore, the coordinated realization of increasing rice yield and reducing greenhouse gas emissions through light and simple rice farming technology is significant for China's food security, and economic and social development.

Ratoon rice refers to cultivating second-season rice by the dormant buds on the rice stubble after harvesting the main season crop. It eliminates the need for seedling-raising and transplanting, and increases the annual grain yield per unit area by increasing the harvest index. Ratoon rice is characterized by its labor efficiency, cost-effectiveness, high quality, high efficiency, and environmental protection, and it is widely distributed worldwide, including in China, Japan, India, Thailand, the Philippines, the United States, Brazil, and other countries [5]. In China, ratoon rice is mainly distributed in southern rice-growing areas. The ratoon rice cultivation area has exhibited a rapid year-on-year increase recently. In 2022, the ratoon rice planting area reached 1.2 million hectares in China, mainly distributed in Sichuan, Chongqing, Guizhou, Yunnan, Hunan, Hubei, Jiangxi, Anhui, Henan, Jiangsu, Fujian, and other provinces [6]. The latest analysis indicates that under the premise of keeping the current double-season rice area unchanged, the area of rice fields suitable for planting ratoon rice in China is 13.28 million hectares [7]. Currently, research on ratoon rice mainly focuses on improving rice regeneration ability [8], yield [9], and rice quality [10]. However, there are few reports on CH_4 and N_2O emissions from ratoon rice fields.

CH_4 and N_2O mainly enter the atmosphere from rice plants through aerenchyma transmission, bubble bursting, and liquid phase diffusion emissions, with approximately 60–90% of CH_4 emitted through the aerenchyma [11]. The differences in plant type among rice varieties tend to result in obvious differences in greenhouse gas emissions. CH_4 emissions from indica rice are significantly higher than those from japonica rice [12]. Sun et al. (2015) [13] have pointed out that hybrid rice increases grain yield and CH_4 emissions, but decreases N_2O emissions compared to conventional rice varieties. Ma et al. (2010) [14] have reported that hybrid rice reduces CH_4 emissions and attributed this effect to the superior root biomass and root oxygen secretion capacity of hybrid rice. Super-rice varieties exhibit a higher biomass and yield than ordinary rice varieties, but their CH_4 emissions are significantly lower [15–17]. Similarly, Yan et al. [18] have found that the grain yield and biomass of indica super-rice were significantly and negatively correlated with CH_4 emissions, but no significant correlation was observed in the japonica super-rice. Jiang et al. [19] have further pointed out that the impact of high-yielding new varieties on CH_4 emissions from rice fields depends on the level of organic matter in the rice field soil. When the rice field soil is poor (with an organic matter content of <1.4%), high-yield varieties will increase CH_4 emissions; in medium- and high-yield rice fields (with an organic matter content of >2.1%), high-yield new varieties can significantly reduce CH_4 emissions from rice fields. Bai et al. [20] compared the greenhouse gas warming potential (GWP) of the main rice varieties grown in the hilly areas of the central Sichuan province, China, and found that the GWP of various varieties ranked as follows (from highest to lowest): Rongyou 188 > Chuannongyou 3203 > Yixiangyou 1108 > Chuannongyou 498 > Fyou 498. However, the abovementioned studies mainly compare greenhouse gas emissions and single-season rice plant growth characteristics. Research conducted by Song et al. (2020) has demonstrated that in the hilly regions of the central Sichuan province, the film-mulching cultivation of ratoon rice yields a 22% increase in rice production compared to single-season rice, alongside an increase in total N_2O emissions. However, the CH_4 emissions per output unit were significantly reduced by 6% [21,22]. Sichuan and Chongqing, located in the upper reaches of Yangtze River, are traditional ratoon rice-planting areas in China, accounting for 20% of China's ratoon rice-planting area [23]. However, few studies have been conducted to investigate greenhouse gas emissions by comparing different rice varieties during the RRSTS in this region.

Water management practices are closely related to greenhouse gas emissions from rice fields. For example, there are obvious seasonal changes in CH_4 production potential and pathways in perennially flooded rice fields, and they are mainly affected by soil-dissolved organic carbon and acetic acid [24]. At different years, seasons characterized by normal temperatures and increased precipitation exhibited 3.3 times the average of CH_4 emissions across different varieties in contrast to seasons with higher temperatures and reduced precipitation. In contrast, N_2O emissions during the rice season were short and rapid, related to fertilization and water management [25]. AWD is a water-saving and emission-reducing water management pattern, and this method can significantly reduce CH_4 emissions but significantly increases N_2O emissions [26]. In direct-seeded rice in the Hetao area of the Yellow River basin, China, ditch irrigation, a water-saving measure, significantly reduced CH_4 emissions, reducing the greenhouse gas emission flux per unit rice yield. Meanwhile, despite the increased N_2O emissions, ditch irrigation significantly increased water use efficiency (WUE) and rice yield [27]. Compared with long-term flooding irrigation, water-saving measures such as medium-term drying–wetting intermittent irrigation and humid irrigation can reduce CH_4 emissions from rice fields by 32.9–88.7% (with an average of 53.0%), although N_2O emissions are increased by 105%. Finally, the total greenhouse gas emissions decreased by 44% [3]. It has been reported that nearly 78% of rice fields in China have adopted the AWD pattern [28]; and thus, it is necessary to strengthen research on greenhouse gas emissions from rice fields using the water-saving irrigation method. It should be noted that the above research findings are only limited to the single-season rice cultivation model.

Ratoon rice is a rice cultivation technology that dates back to the West Jin Dynasty (265 CE–316). Chongqing, located in the upper reaches of Yangtze River, is a traditional ratoon rice-planting area in China. With the screening of strong ratoon ability rice varieties and the optimization of cultivation technology, the rice yield of ratoon rice has increased significantly. However, rice production usually adopts flooding irrigation all year in the Chongqing area, and the greenhouse gas emission potential is generally high. Little is known about how the ratoon rice system affects greenhouse gas emissions regarding seasonal and variety differences.

Based on the field experiments, these studies investigated the effects of different rice varieties and water management pattern in the main season on CH_4 and N_2O emissions during the RRSTS. The objectives of this study were to (1) reveal the seasonal variations in CH_4 and N_2O emissions, and their relationship with key agronomic traits during the RRSTS; (2) compare CH_4 and N_2O emissions during the RRSTS as affected by different rice varieties; and (3) assess water management pattern on the CH_4 and N_2O emissions during the RRSTS. Our findings will provide a theoretical basis and empirical evidence for exploring greenhouse gas emission reduction strategies in the ratoon rice area in the upper reaches of Yangtze River, China.

2. Materials and Methods

2.1. Experiment Site

The experiment was conducted between 2020 and 2021 at the Yuxi Crop Experiment Station, the Chongqing Academy of Agricultural Sciences in Nanhua Village, Weixinghu Street, Yongchuan District, Chongqing City, China (105.71° E, 29.75° N, 297 m above sea level). This crop experiment station is located in the western part of Chongqing, where there is a subtropical monsoon humid climate with an average annual temperature of 17.7 °C, total annual precipitation of 1015.0 mm, total annual sunshine hours of 1218.7 h, and an annual frost-free period of 317 d. The experimental soil was purple clay, and the soil physicochemical indicators at the 0–20 cm topsoil layer were as follows: soil pH—5.6; organic matter content—22.3 g·kg^{-1}; total nitrogen—1.31 g·kg^{-1}; available nitrogen—119.0 mg·kg^{-1}; available phosphorus—25.0 mg·kg^{-1}; available potassium—74.7 mg·kg^{-1}.

2.2. Meteorological Data

The average temperature during the RRSTS after transplanting was 23.6 °C in 2020, which was 0.6 °C higher than that in 2021, and the precipitation was 959.9 mm in 2020, which was 322.7 mm lower than that in 2021 (Figure 1). In 2020, the temperature and precipitation during the main season and the ratoon season were 24.0 °C and 22.8 °C and 683.8 mm and 276.1 mm, respectively (Figure 1A); in 2021, they were 22.7 °C and 23.8 °C and 1131.4 mm and 151.2 mm, respectively (Figure 1B).

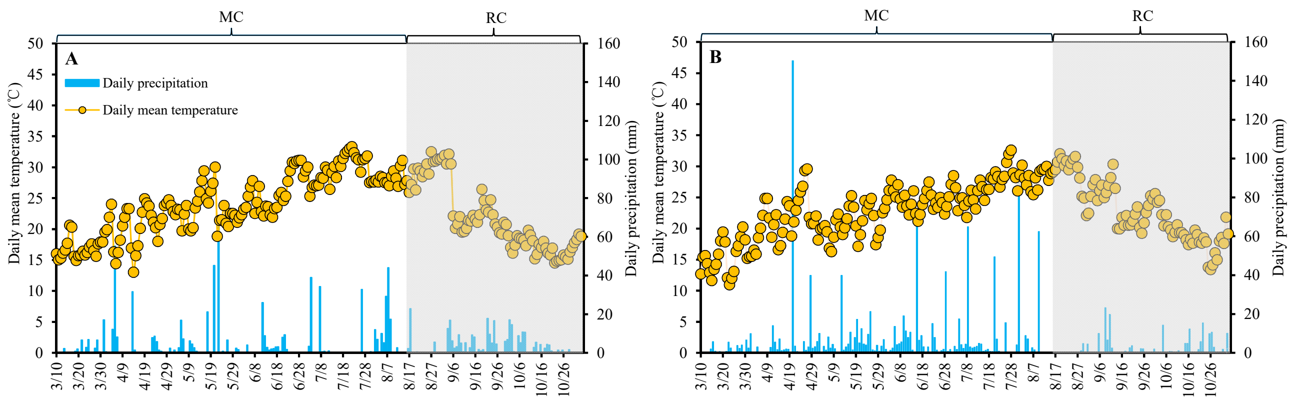

Figure 1. Daily precipitation and daily mean temperature during the RRSTS in 2020 (**A**) and 2021 (**B**).

2.3. Experimental Design

There were two field experiments in this study, with Experiment 1 and Experiment 2 exploring the effects of rice varieties and alternating dry–wet irrigation methods on greenhouse gas emissions from ratoon rice fields, respectively. Experiment 1 was implemented in 2020 with a randomized block design. The 5 varieties used in the field experiments included Huanghuazhan (HHZ), Cliangyouhuazhan (CLYHZ), Jingliangyou 534 (JLY534), Yuxiang 203 (YX203), and Yongyou 2640 (YY2640), all of which were local strong ratoon rice varieties. There were three replicates for each variety with 5 plots per replicate; and thus, there were a total of 15 plots with a plot area of 15 m^2 (3 m × 5 m). The ridges were built around the plots to prevent cross-fertilization among various treatments.

Experiment 2 was implemented in 2021 with a split-plot design, and the main plots were subjected to different water treatments. Conventional flooding (CF) irrigation refers to treating main-season rice from transplanting to harvesting, with a 4–5 cm water layer always maintained in the field until the main-season rice matures. The AWD pattern involves maintaining a 3–5 cm water layer in the field from the transplanting of the main-season rice until the tillering period. Then, the field water was drained from the middle tillering period to the early jointing stage, and the field underwent a 10-day mid-term soil drying. The field was re-irrigated with a 2–3 cm water layer and dried naturally. Once the field surface was dry, this dry state was maintained for 3–5 days, after which the field was re-irrigated with a 2–3 cm water layer until the main season rice was harvested [26].

The sub-plots underwent different rice variety experiments using the varieties Yuxiang 203 (YX203) and Jingliangyou 534 (JLY534). There were 4 different treatments with 3 replicates per treatment, and there were 12 plots with a plot area of 15 m^2 (3 m × 5 m). The field ridges were built around the plots to prevent cross-fertilization among treatments. Water management practices during the ratoon season were carried out with reference to the local high-yield cultivation technology plan for the ratoon rice system.

The rice seedlings were cultivated using the plastic hard plate wet seedling method. The seeds were sown on 12 March and transplanted at the 4-leaf stage. The planting density was 30 cm × 18 cm, with 2 seedlings per hill. During the whole growth period of ratoon rice, 225 kg·ha^{-1} of pure nitrogen (N) was utilized, with 120 kg·ha^{-1} of N applied during the main season, using urea in a base fertilizer:tillering fertilizer:panicle fertilizer ratio of 4:4:2. A total of 60 kg·ha^{-1} of P_2O_5 was applied as a base phosphorus fertilizer, and 96 kg·ha^{-1} of K_2O was applied, with half as potassium chloride for base application and the other half as potassium chloride for panicle application. In total, 105 kg·ha^{-1} of N fertilizer was applied during the ratoon season, with a bud-promoting N fertilizer:tiller-promoting N fertilizer ratio of 6:4. During the main season, basal fertilizer was applied 1 day before transplanting, tillering fertilizer was applied 7 days after transplanting, and panicle fertilizer was applied at the panicle initiation stage. During the ratoon season, bud-promoting N fertilizer was applied at the full heading stage of the main-season rice, and tiller-promoting N fertilizer was applied three days after the main season rice was harvested. The main season rice was harvested on 15 August, and the stubble height of the ratoon rice was 35 cm. Field pest and weed control measures were uniformly implemented following local high-yield cultivation requirements to prevent yield losses.

2.4. Indicator Measurement

2.4.1. Yield

During the maturation period of the main-season rice and the ratoon season rice, the rice yield in the 5 m^2 sample plot was assessed following removing impurities from the grains, with a moisture content of 13.5%.

2.4.2. Agronomic Traits

A specific leaf weight method determined the leaf area index at the full heading stage during the main and ratoon rice seasons [29]. In addition, during the maturity stage of the main season rice and the ratoon rice, five hills of representative rice plants were selected from each plot. Samples were divided separately according to the stems, leaves, and panicles during the main season; and stems, leaves, panicles, and stubble during the ratoon season, respectively. They were placed in an oven at 105 °C for 0.5 h and dried at 80 °C to constant weight, and the dry weight of each aboveground part was measured [30]. The harvest index (HI) was calculated using the following formula:

$$\mathbf{HI}\,(\%) = \mathbf{DWG}\ /\ \mathbf{DWAB} \times 100\% \tag{1}$$

where DWG is dry weight of grains (t·ha^{-1}) and DWAB is the dry weight of aboveground biomass (t·ha^{-1}).

2.4.3. Greenhouse Gas Sampling

CH_4 and N_2O samples were collected using the static sealed chamber method, and the chamber was made of stainless steel [21]. The gas sampling chamber consisted of two parts, namely, chamber A (length × width × height = 0.4 m × 0.4 m × 1.1 m) and chamber B (length × width × height = 0.4 m × 0.4 m × 0.7 m). Chamber B was equipped with a sealed water tank for adding layers in the late growth period of the main-season rice. During the late growth period of the main-season and ratoon rice, the height of chamber B was raised to 1.6 m to ensure normal plant growth. The chamber covered an area of 0.16 m^2 (length × width = 0.4 m × 0.4 m). The base linebreak (length × width × height = 0.4 m × 0.4 m × 0.15 m) was buried in each plot before rice transplanting to ensure that the base was at the same level as the field surface. The samples were collected every 7 days during the rice growth period, and the sampling time was 9:00–11:00 a.m. Before sampling, the sealed chamber was covered with the pre-buried base, and clean water was added to the base groove to prevent air leakage. After the static chamber was sealed, a double-pass needle was used to introduce the gas in the chamber into an 18 mL vacuum glass bottle. Gas sampling was performed 4 times every 10 min, and the temperature in the chamber and the depth of the water layer on the field surface were measured.

2.4.4. Gas Sample Analysis

CH_4 and N_2O gas sample concentrations were measured using Agilent gas chromatography (Agilent 7890B, Santa Clara, CA, USA). Specifically, the CH_4 concentrations were measured using a hydrogen flame ionization detector (FID), and the N_2O concentrations were measured using a 63Ni electron capture detector (ECD). The standard CH_4 and N_2O mixed gas was provided by the China National Institute of Metrology. The Nanjing Institute of Soil Science and the Chinese Academy of Sciences analyzed the gas sample.

2.5. Data Processing

This study calculated the CH_4 and N_2O emission flux and total seasonal CH_4 and N_2O emissions using the methods reported.

The CH_4 (mg m^{-2} h^{-1}) or N_2O fluxes (μg m^{-2} h^{-1}) were calculated as follows according to the KBS LTER Protocol (https://lter.kbs.msu.edu/protocols/113, accessed on 25 January 2024):

$$\mathbf{F{=}\rho \times \frac{273}{(273{+}T)} \times \frac{V}{S} \times \frac{\Delta c}{\Delta h}} \quad (2)$$

where ρ represents the density of CH_4 (0.716 g L^{-1}) or N_2O (1.977 g L^{-1}) under standard atmospheric pressure; T denotes the sampling temperature (°C); V is the volume of the static closed chamber (m^3); and S is the surface area of the chamber (m^2). The term $\Delta c/\Delta h$ signifies the rate of change in CH_4 concentration per hour (μL L^{-1} h^{-1}). Seasonal CH_4 emissions were determined using the trapezoidal integration method.

Then, we used linear interpolation to calculate seasonal CH_4 emissions (kg ha^{-1}) and N_2O (kg ha^{-1}) emissions during the main season and ratoon season, respectively [31]. The greenhouse gas's global warming potential (GWP) was calculated using the following formula according to IPCC 2021 [1]:

$$\mathbf{GWP{=}CH_4 \times 27.9{+}N_2O \times 273} \quad (3)$$

In the formula, GWP (t CO_2–eq ha^{-1}) is the sum of the global warming potential of CH_4 and N_2O, and CH_4 and N_2O are the total seasonal emissions of CH_4 or N_2O (kg·ha^{-1}), respectively.

The greenhouse gas emission intensity (GHGI) was calculated using the following formula [32]:

$$\mathbf{GHGI{=}GWP/Y} \quad (4)$$

where GHGI (t CO_2–eq t^{-1} yield) is the greenhouse gas emission intensity; GWP (t CO_2–eq ha^{-1}) is the global warming potential of greenhouse gasses CH_4 and N_2O; and Y (t·ha^{-1}) is the rice yield.

2.6. Statistics

All statistical analyses were performed using IBM SPSS (Version 20.0, Chicago, IL, USA). Variance (ANOVA) was analyzed to identify the differences in CH_4 and N_2O emissions, GWP, GHGI, and rice yield across different treatments. Pearson's correlation analysis was carried out to assess the relationships among CH_4 emissions, GWP, GHGI, and agronomic traits. $p < 0.05$ was considered statistically significant.

3. Results

3.1. Rice Yield

In 2020, with Experiment 1 (Figure 2A), the main-season rice yield was 9.1–10.9 t·ha^{-1}, accounting for 71.2–82.3% of the total rice yield of the RRSTS, and ratoon rice yield was 2.0–3.7 t·ha^{-1}, accounting for 17.7–28.8% of the total rice yield of the RRSTS. In terms of rice varieties, the main-season rice yield followed the following order: YX203 > CLYHZ > YY2640 > HHZ > JLY534. The ratoon rice yield followed the following order: YY2640 > YX203 > CLYHZ > JLY534 > HHZ. In 2021, with Experiment 2 (Figure 2B), compared with CF treatment, AWD treatment significantly increased yield during both the main and ratoon seasons. Specifically, the JLY534 variety exhibited an increase of 23.5% and 21.6% during the main and ratoon seasons, and the YX203 variety had an increase of 24.0% and 18.0%, respectively.

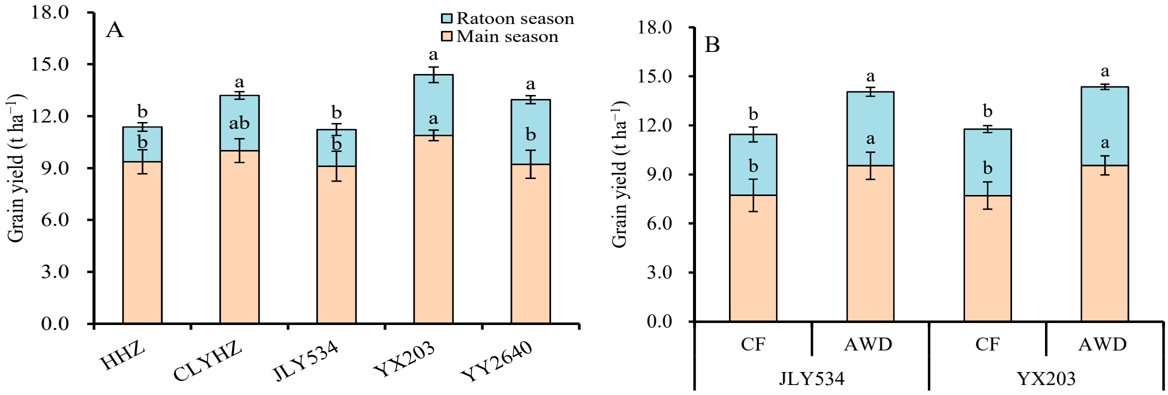

Figure 2. The rice yield of the ratoon rice system over the two seasons as affected by different rice varieties in 2020 (**A**) and water management in 2021 (**B**). Different lowercase letters indicate that there were significant at the 0.05 significance level.

3.2. CH_4 and N_2O Emissions

CH_4 emissions are mainly concentrated during the main season, and the emission peaks vary yearly. In 2020, with Experiment 1 (Figure 3A), the CH_4 emissions peaked at the end of the tillering stage during the main season, then gradually decreased and fluctuated from the booting stage to the maturity stage. CH_4 emissions peaked in the early stage of the ratoon season and then gradually decreased. As for the varieties, YX203 and HHZ exhibited high CH_4 emission fluxes, YY2640 displayed a medium flux, and CLYHZ and JLY534 displayed low CH_4 emission fluxes. In 2021, with Experiment 2 (Figure 3C), CH_4 emissions peaked in the early jointing, booting, and middle grain-filling stages of the rice's main season. There were no obvious emission peaks in the ratoon season. Generally, the JLY534 showed lower CH_4 emissions than that of YX203. Compared with CF treatment, AWD treatment reduced CH_4 emissions flux at the rice growth stage to a certain extent, and there was a much higher reduction in CH_4 emission flux during the main season. Among all the varieties, YX203 exhibited the greatest reduction in the CH_4 emission flux (Figure 3C).

N_2O emissions showed obvious fluctuations, with large inter-annual differences. In 2020, with Experiment 1 (Figure 3B), N_2O emissions were mainly concentrated in the main season and peaked at the middle tillering, jointing, and late grain-filling stages. Among all the varieties, HHZ exhibited the highest N_2O emission among the five varieties. In 2021, with Experiment 2 (Figure 3D), N_2O emissions were mainly concentrated during the ratoon season. Compared with CF treatment, AWD treatment increased N_2O emissions. Among the varieties, JLY534 displayed a significant increase in N_2O emissions during the RRSTS, with a more pronounced increase during the ratoon season under AWD treatment, while YX203 displayed a relatively small increase in N_2O emissions during the RRSTS (Figure 3D).

In 2020, with Experiment 1 (Table 1), CH_4 emissions ranged from 157.05 to 408.77 kg ha^{-1} during the main season, accounting for 76.2–85.8% of the RRSTS. Among the varieties, YX203 and YY2640 during the main season exhibited significantly higher CH_4 emissions than HHZ, CLYHZ, and JLY534: 408.77 kg ha^{-1} and 379.53 kg ha^{-1}, respectively. And CH_4 emissions during the ratoon season ranged from 31.03 to 84.38 kg ha^{-1}, accounting for 14.2–23.8% of the RRSTS. Among different varieties, YX203 and HHZ during the ratoon season displayed significantly higher CH_4 emissions than CLYHZ, JLY534, and YY2640: 84.38 kg ha^{-1} and 81.67 ha^{-1}, respectively. N_2O emissions were mainly concentrated during the main season, with an emission flux of 0.13–0.28 kg·ha^{-1}, accounting for 81.2–97.3% of the RRSTS. During the ratoon season, N_2O emissions ranged from 0.01 kg·ha^{-1} to 0.04 kg·ha^{-1}. Among the varieties, YX203 and JLY534 showed relatively low N_2O emissions, ranging from 0.13 kg·ha^{-1} to 0.16 kg·ha^{-1}, significantly lower than HHZ.

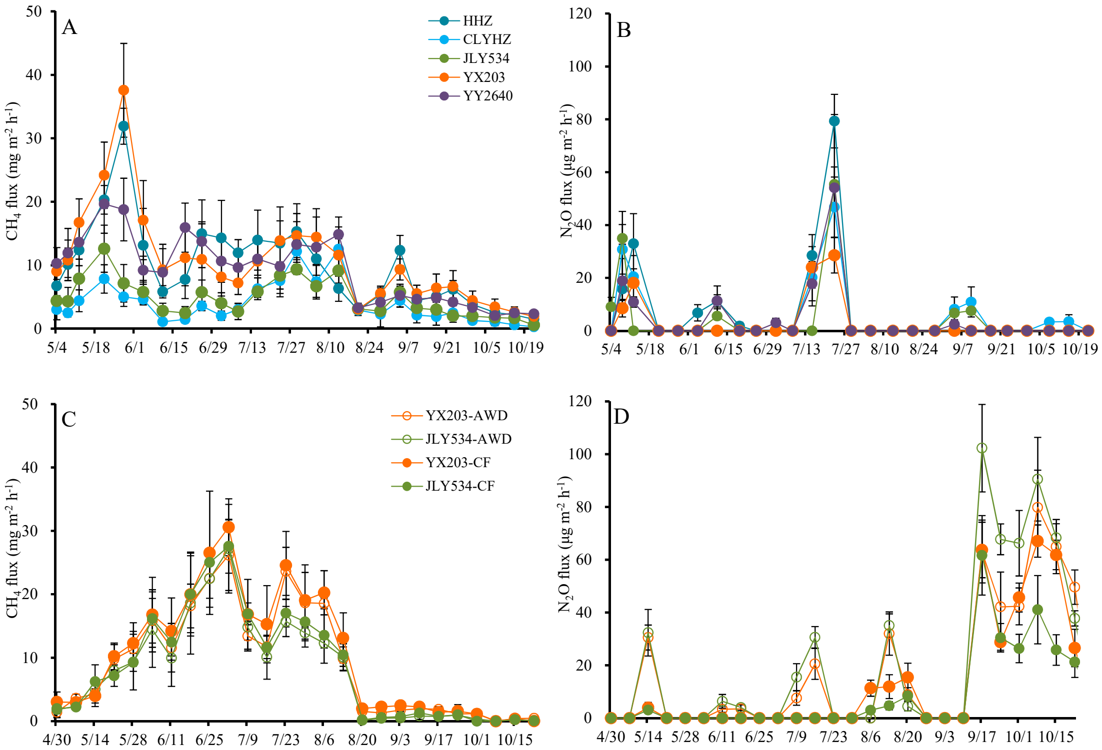

Figure 3. The CH_4 (**A**,**C**) and N_2O (**B**,**D**) emission flux of the ratoon rice system over the two seasons as affected by different rice varieties in 2020 (**A**,**B**) and water management in 2021 (**C**,**D**).

Table 1. Effects of different rice varieties on CH_4 ($kg \cdot ha^{-1}$) and N_2O ($kg \cdot ha^{-1}$) emissions in the ratoon rice system over the two seasons in 2020.

Treatment	Main Season		Ratoon Season		Whole Season	
	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O
HHZ	262.10 ± 13.93 b	0.28 ± 0.07 a	81.67 ± 15.14 a	0.01 ± 0.00 c	343.77 ± 28.81 d	0.28 ± 0.08 a
CLYHZ	157.05 ± 20.40 c	0.18 ± 0.04bc	31.03 ± 4.80 c	0.04 ± 0.02 a	188.07 ± 23.79 d	0.22 ± 0.02 ab
JLY534	181.64 ± 32.14 c	0.16 ± 0.03 c	40.32 ± 5.05 c	0.02 ± 0.01 ab	221.96 ± 37.12 c	0.19 ± 0.02 bc
YX203	408.77 ± 17.18 a	0.13 ± 0.06 c	84.38 ± 7.95 a	0.01 ± 0.00 c	493.15 ± 23.18 a	0.13 ± 0.06 c
YY2640	379.53 ± 22.70 a	0.17 ± 0.05bc	63.01 ± 6.25 b	0.01 ± 0.01 c	422.54 ± 18.85 b	0.18 ± 0.05 bc

HHZ—Huanghuazhan; CLYHZ—Cliangyouhuazhan; JLY534—Jingliangyou 534; YX203—Yuxiang 203; YY2640—Yongyou 2640; different lowercase letters within the same column indicate significant differences ($p < 0.05$).

In 2021, with Experiment 2 (Table 2), compared with CF treatment, AWD treatment significantly reduced CH_4 emissions during the RRSTS in both varieties but increased the N_2O emissions. Additionally, especially for JLY534, AWD treatment had significantly higher N_2O emissions than CF treatment. The two water treatments exhibited a substantial difference in CH_4 emissions during the main season, and CH_4 emissions for JLY534 and YX203 under AWD treatment were reduced by 16.8% and 20.2%, respectively. On the contrary, AWD treatment significantly increased the N_2O emission flux during the RRSTS, except that YX203 during the ratoon season exhibited no significant difference. During the main season, the N_2O emission flux of JLY534 and YX203 was 7.6 times and 2.1 times higher, respectively, under AWD treatment than under CF treatment.

Table 2. Effects of different water managements on CH_4 (kg·ha^{-1}) and N_2O (kg·ha^{-1}) emissions in the ratoon rice system over the two seasons in 2021.

Treatment	Main Season		Ratoon Season		Whole Season	
	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O
JLY534						
CF	401.48 ± 18.02 a	0.02 ± 0.02 b	8.95 ± 2.89 a	0.35 ± 0.09 b	410.43 ± 20.76 a	0.38 ± 0.07 b
AWD	334.12 ± 14.59 b	0.21 ± 0.06 a	7.24 ± 1.24 a	0.73 ± 0.18 a	341.36 ± 13.86 b	0.94 ± 0.24 a
YX203						
CF	470.73 ± 20.64 a	0.06 ± 0.04 b	23.61 ± 4.57 a	0.53 ± 0.10 a	494.04 ± 22.50 a	0.59 ± 0.13 a
AWD	375.40 ± 12.49 b	0.17 ± 0.06 a	18.54 ± 1.85a	0.55 ± 0.12 a	393.94 ± 12.88 b	0.73 ± 0.16 a

CF—conventional flooding; AWD—alternating wet–dry irrigation; JLY534—Jingliangyou 534; YX203—Yuxiang 203; different lowercase letters within the same column indicate significant differences (p < 0.05).

3.3. GWP and GHGI

In 2020, with Experiment 1 (Table 3), the GWP during the RRSTS ranged from 4.79 t to 12.38 t CO_2–eq ha^{-1}, of which the GWP of the main-season rice was 4.00–10.27 t CO_2–eq ha^{-1}, following the subsequent order: YX203 > YY2640 > HHZ > JLY534 > CLYHZ. The GWP of the ratoon rice ranged from 0.79 to 2.11 t CO_2–eq ha^{-1}, following the subsequent order: YX203 > HHZ > YY2640 > JLY534 > CLYHZ. In addition, the GHGI of the RRSTS ranged from 0.38 to 0.86 t CO_2–eq t^{-1} yield, and the GHGI of the main-season rice ranged from 0.40 to 1.01 t CO_2–eq t^{-1} yield, following the subsequent order: YY2640 > YX203 > HHZ >JLY534 > CLYHZ. The GHGI of the ratoon rice ranged from 0.32 to 1.03 t CO_2–eq t^{-1} yield, following the subsequent order: HHZ > YX203 > JLY534 > YY2640 > CLYHZ.

Table 3. Effects of different rice varieties on global warming potential (GWP, t CO_2–eq ha^{-1}) and greenhouse gas emission intensity (GHGI, t CO_2–eq t^{-1} yield) in the ratoon rice system over the two seasons in 2020.

Treatment	Main Season		Ratoon Season		Whole Season	
	GWP	GHGI	GWP	GHGI	GWP	GHGI
HHZ	6.67 ± 0.37 b	0.71 ± 0.05 b	2.04 ± 0.38 a	1.03 ± 0.26 a	8.71 ± 0.73 b	0.77 ± 0.04 a
CLYHZ	4.00 ± 0.51 c	0.40 ± 0.05 c	0.79 ± 0.11 c	0.32 ± 0.06 c	4.79 ± 0.59 c	0.38 ± 0.05 b
JLY534	4.61 ± 0.79 c	0.51 ± 0.13 c	1.02 ± 0.13 c	0.48 ± 0.03 bc	5.63 ± 0.92 c	0.50 ± 0.10 b
YX203	10.27 ± 0.45 a	0.94 ± 0.03 a	2.11 ± 0.20 a	0.60 ± 0.02 b	12.38 ± 0.60 a	0.86 ± 0.01 a
YY2640	9.60 ± 0.57 a	1.01 ± 0.12 a	1.58 ± 0.15 b	0.42 ± 0.04 bc	11.18 ± 0.47 a	0.85 ± 0.09 a

Different lowercase letters within the same column indicate significant differences (p < 0.05).

In 2021, with Experiment 2 (Table 4), AWD treatment significantly reduced the GWP and GHGI of the RRSTS, primarily attributed to a significant reduction during the main season, despite the GWP and GHGI of the ratoon rice showing no significant difference. Under AWD treatment, YX203 and JLY534 exhibited consistent changing trends in GWP and GHGI. Further, during the main season, AWD treatment reduced the GWP and GHGI values of the JLY534 variety by 16.0% and 32.1%, and the YX203 variety by 19.8% and 35.7%, respectively.

3.4. Agronomic Traits

There were significant differences in agronomic traits among different varieties during the RRSTS in 2020 with Experiment 1 (Table 5). Specifically, the LAI of main-season rice and ratoon rice was 5.35–8.36 and 0.90–1.31, respectively, and the LAI value of YX203 was significantly higher than other varieties. The number of population spikelets of the main-season rice and ratoon rice was 44.04–53.73 × 10^3 m^{-2} and 20.04–34.86 × 10^3 m^{-2}, respectively. CLYHZ (main season) and YY2640 (ratoon season) exhibited a significantly larger population spikelet number than the other varieties. The biomass in the main-season rice and ratoon rice was 14.58–17.98 t·ha^{-1} and 5.96–8.24 t·ha^{-1}, respectively, and YX203 displayed a significantly higher biomass than the other varieties. In addition, the harvest index (HI) of the main-season rice and ratoon rice was 54.57–63.00% and 33.67–46.33%, respectively, and the HI of CLYHZ during the main season was much higher than that of other varieties.

Table 4. Effects of different water management on global warming potential (GWP, t CO_2–eq ha^{-1}) and greenhouse gas emission intensity (GHGI, t CO_2–eq t^{-1} yield) in the ratoon rice system over the two seasons in 2021.

Treatment	Main Season		Ratoon Season		Whole Season	
	GWP	GHGI	GWP	GHGI	GWP	GHGI
JLY534						
CF	10.05 ± 0.45 a	1.31 ± 0.11 a	0.37 ± 0.08 a	0.10 ± 0.03 a	10.42 ± 0.51 a	0.91 ± 0.06 a
AWD	8.44 ± 0.39 b	0.89 ± 0.09 b	0.49 ± 0.07 a	0.11 ± 0.01 a	8.93 ± 0.44 b	0.64 ± 0.05 b
YX203						
CF	11.78 ± 0.52 a	1.55 ± 0.20 a	0.81 ± 0.15 a	0.20 ± 0.05 a	12.60 ± 0.60 a	1.08 ± 0.13 a
AWD	9.46 ± 0.33 b	0.99 ± 0.07 b	0.69 ± 0.10 a	0.15 ± 0.02 a	10.15 ± 0.36 b	0.71 ± 0.02 b

Different lowercase letters within the same column indicate significant differences ($p < 0.05$).

Table 5. Agronomic traits of the aboveground part, including leaf area index (LAI), spikelet number per m^2, biomass, and harvest index (HI) under different water treatments in the ratoon rice system over the two seasons in 2021.

Treatment	LAI	Spikelet Number per m^2	Biomass ($t \cdot ha^{-1}$)	HI (%)
Main season rice				
HHZ	5.72 ± 0.88 bc	48.85 ± 2.07 bc	15.51 ± 0.74 b	60.40 ± 4.08 ab
CLYHZ	6.00 ± 0.05 bc	53.73 ± 2.84 a	15.88 ± 0.52 b	63.00 ± 4.48 a
JLY534	6.36 ± 0.42 b	50.32 ± 2.90 ab	15.58 ± 1.09 b	58.33 ± 3.81 ab
YX203	8.36 ± 0.05 a	45.55 ± 1.12 cd	17.98 ± 1.06 a	61.67 ± 2.35 ab
YY2640	5.35 ± 0.27 c	44.04 ± 1.74 d	14.58 ± 0.62 b	54.67 ± 4.12 b
Ratoon season rice				
HHZ	1.15 ± 0.36 b	20.04 ± 1.08 c	6.04 ± 0.77 c	33.67 ± 7.57 b
CLYHZ	1.21 ± 0.11 b	23.54 ± 2.15 bc	6.74 ± 0.19 cd	37.33 ± 4.14 ab
JLY534	0.90 ± 0.03 b	20.30 ± 2.93 c	5.96 ± 0.34 c	35.66 ± 6.80 b
YX203	1.88 ± 0.37 a	24.52 ± 1.72 b	8.24 ± 0.13 a	42.33 ± 5.24 ab
YY2640	1.31 ± 0.03 b	34.86 ± 0.97 a	7.04 ± 0.38 b	46.33 ± 0.75 a

Different lowercase letters within the same column indicate significant differences ($p < 0.05$).

In 2021, with Experiment 2 (Table 6), compared with CF treatment, AWD treatment had no significant effects on the HI value of main and ratoon seasons but increased population spikelet numbers. Specifically, the population spikelet number of the main-season rice YX203 variety increased significantly under AWD treatments. AWD treatment significantly increased the biomass of main-season rice and ratoon rice, and the biomass of the JLY534 variety was increased by 22.67% and 17.54% during the main season and ratoon season, and that of the YX203 variety increased by 14.72% and 18.09%, respectively. Compared with CF treatment, AWD treatment significantly reduced the LAI of the main-season rice, with JLY534 and YX203 exhibiting a decrease of 15.97% and 6.61%, respectively, but significantly increased the LAI of the ratoon rice, with JLY534 and YX203 displaying an increase of 9.09% and 46.09%, respectively.

Correlation analysis showed that during the main season, the population spikelet number and HI were significantly negatively correlated with CH_4 emissions, GWP, and GHGI, and the rice yield was extremely significantly negatively correlated with GHGI. However, LAI was significantly positively correlated with CH_4 emissions and GWP (Table 7). During the ratoon season, biomass, rice yield, population spikelet number, and HI were significantly negatively correlated with CH_4 emissions, GWP, and GHGI, respectively. LAI had no significant correlation with CH_4 emissions, GWP, and GHGI.

Table 6. Aboveground agronomy traits, including leaf area index (LAI), spikelet number per m^2, biomass, and harvest index (HI) among different water treatments in the ratoon rice system over the two seasons in 2021.

Variety	Treatment	LAI	Spikelet Number per m^2	Biomass ($t \cdot ha^{-1}$)	HI (%)
JLY534	Main season				
	CF	6.45 ± 0.45 a	49.27 ± 2.54 a	15.35 ± 1.00 b	0.50 ± 0.04 a
	AWD	5.42 ± 0.17 b	57.58 ± 2.29 a	18.83 ± 1.93 a	0.51 ± 0.02 a
	Ratoon season				
	CF	1.54 ± 0.06 b	30.89 ± 2.41 a	8.55 ± 0.17 b	0.44 ± 0.03 a
	AWD	1.68 ± 0.11 a	32.83 ± 1.47 a	10.05 ± 0.47 a	0.45 ± 0.01 a
YX203	Main season				
	CF	7.41 ± 1.11 b	39.12 ± 2.71 b	15.62 ± 0.51 b	0.49 ± 0.05 a
	AWD	6.92 ± 0.44 a	42.35 ± 1.79 a	17.92 ± 0.83 a	0.53 ± 0.04 a
	Ratoon season				
	CF	1.28 ± 0.09 b	22.08 ± 2.76 a	9.01 ± 0.60 b	0.45 ± 0.02 a
	AWD	1.87 ± 0.23 a	26.59 ± 2.35 a	10.64 ± 0.99 a	0.45 ± 0.02 a

Different lowercase letters within the same column indicate significant differences ($p < 0.05$).

Table 7. Correlation analysis between cumulative CH_4 emission, warming potential (GWP), greenhouse gas intensity (GHGI), and the aboveground agronomic traits or grain yield of the main- and ratoon-season rice.

Index	Spikelet Number per m^2	Biomass ($t \cdot ha^{-1}$)	LAI	HI (%)	Grain Yield ($t \cdot ha^{-1}$)
Main season					
CH_4 ($kg\ ha^{-1}$)	−0.378 *	0.119	0.436 *	−0.479 **	−0.172
GWP ($t\ CO_2$–eq ha^{-1})	−0.374 *	0.119	0.438 *	−0.474 **	−0.166
GHGI ($t\ CO_2$–eq t^{-1} yield)	−0.488 **	−0.114	0.213	−0.687 **	−0.544 **
Ratoon season					
CH_4 ($kg\ ha^{-1}$)	−0.432 *	−0.437 *	0.137	−0.585 **	−0.575 **
GWP ($t\ CO_2$–eq ha^{-1})	−0.421 *	−0.391 *	0.209	−0.569 **	−0.500 **
GHGI ($t\ CO_2$–eq t^{-1} yield)	−0.517 **	−0.547 **	−0.026	−0.754 **	−0.722 **

* indicate significant differences ($p < 0.05$), ** indicate significant differences ($p < 0.05$).

4. Discussion

4.1. CH_4 Emission

Our data showed obvious inter-annual and variety differences in CH_4 emissions, and CH_4 emissions were mainly concentrated during the main season (Figure 3). In 2020, the CH_4 emissions peaked at the end of the tillering stage of the main season and the ratoon season. In 2021, the CH_4 emission peaks were mainly concentrated during the main season; as the growth progressed during the main season, the CH_4 emission flux gradually increased and reached the peak at the early jointing stage, booting stage, and middle grain-filling stage, respectively, with the highest value observed at the booting stage. In 2021, CH_4 emission flux during the main season reached between 334.12 and 470.73 $kg \cdot ha^{-1}$, exhibiting an increase of 61.96–177.07 $kg \cdot ha^{-1}$, compared with 157.05–408.77 $kg \cdot ha^{-1}$ in 2020. This indicated that inter-annual meteorological factors significantly affected CH_4 emissions from ratoon rice system fields. Our analysis of meteorological factors also revealed that in 2021, the precipitation from the transplanting to the maturity period during the main season was 1060.3 mm, 500.5 mm higher than in 2020. The continuous precipitation from April to early August flooded the main-season rice soil for a long time, which might be a key factor in explaining the increase in CH_4 emission flux in rice fields in 2021 (Figure 1). During the ratoon season, the CH_4 emission flux in 2021 was much lower than in 2020 by 23.78–60.77 $kg \cdot ha^{-1}$ due to the significantly lower level of precipitation in 2020 than in 2021. Our results contradict previous reports on the high temperature and the low rainfall resulting in increased CH_4 emission in the rice system [25]. The possible reason for different observations in the two studies might be that the long-term rain in

2021 caused the rice fields to be flooded for a long time, putting the soil in an anaerobic state, thus increasing the activity of methanogenic bacteria and decreasing the activity of methanotrophic bacteria, eventually promoting CH_4 production [32,33]. Furthermore, rice root biomass decreased under long-term flooding conditions, aerenchyma reduced, and root oxygen secretion capacity lowered [34].

In this study, total CH_4 emissions during the whole season's ratoon rice system in Chongqing (the upper reaches of Yangtze River) were between 188.1 and 494.0 kg·ha^{-1}, which is 85.1–94.0 kg·ha^{-1} higher than the total CH_4 emissions during the ratoon rice season in the hilly area of central Sichuan (103.0–400.0 kg·ha^{-1}) [32], and it was increased nearly by half on average compared with total CH_4 emissions (209.0–289.0 kg·ha^{-1}) during rice production in the Taihu rice area (Tables 1 and 2) [35], but it was much lower than total CH_4 emissions (1034.7–1331.7 kg·ha^{-1}) during rice season in the Chaohu ratoon rice area [36]. The possible reason might be that in this study, the ratoon rice fields were flooded all year round and the soil pH was only 5.6, which was 2.0 and 0.7 lower than those in the hilly area of the central Sichuan and Taihu rice area, respectively, and 0.8 higher than that in the Chaohu ratoon rice area. Previous studies have indicated that the optimal pH for the growth of methanotrophic bacteria is between 6 and 7, and at a lower soil pH, the higher acetate content in soil helped increase CH_4 emissions [24].

In this study, CH_4 emissions during the ratoon season were between 7.24 and 84.38 kg·ha^{-1}, accounting for 2.12–23.76% of the total CH_4 emissions during the RRSTS, which is much lower than 157.05–470.73 kg·ha^{-1} during the main season (Tables 1 and 2). This is consistent with reports on the ratoon rice system in the hilly areas of central Sichuan [32,37], central China [38], and the Taihu rice planting area [35]. The reasons for this may include the following aspects. First, the temperature and precipitation during the ratoon season were 23.3 °C and 213.7 mm, respectively, 1.6 °C and 596.4 mm lower than those during the main season (Figure 1). Lower temperature and precipitation were conducive to lowering soil temperature and humidity, thereby reducing the activity of soil methanogens and ultimately reducing the decomposition rate of soil organic matter and the CH_4 transmission rate to a certain extent [37,39]. Second, this phenomenon was related to the plant growth characteristics during the ratoon season. Ratoon rice is a rice crop formed from germinating axillary buds on the rice stubble after the main-season rice is harvested. Thus, ratoon rice's plant height, biomass, and leaf area index were significantly lower than those of the main-season rice, reducing the CH_4 transmission level and eventually decreasing CH_4 emissions during the ratoon season [32]. Third, the growth period of the ratoon season is only about half that of the main-season rice, and the shortened growth period reduces the CH_4 emission cycle to a certain extent [38].

CH_4 emissions are the main contributors to greenhouse gasses in rice fields, accounting for about 90%. The rice agronomy traits, including LAI, biomass, and HI, affect yield and CH_4 emissions [40]. In this study, YX203 exhibited the highest total CH_4 emissions during the RRSTS, reaching 493.15 kg·ha^{-1}, but CLYHZ displayed the lowest value at 188.07 kg·ha^{-1} in 2020. The extreme difference in CH_4 emissions in the main season among different varieties reached 251.72 kg·ha^{-1} (Table 1). In addition, the YX203 variety exhibited the highest total rice yield during the two seasons, followed by CLYHZ (Figure 2). This indicated that selecting high-yield and low-emission rice varieties such as CLYHZ can reduce the total CH_4 emissions of the whole ratoon rice system by reducing CH_4 emissions during the main season. Previous studies have found that the photosynthetic products of the current season's rice are one of the main substrates for CH_4 emissions from rice fields, and raising biomass will increase the CH_4 synthesis substrates for methanogens, thereby significantly enhancing CH_4 emissions from rice fields [41,42]. In this study, the biomass of YX203 during the main season was significantly higher than that of other varieties, which aligns with the high CH_4 emission trend in the variety YX203 during the main season (Table 5). The reason may be that in this study, rice was under continuously flooded anaerobic irrigation conditions in 2020, thus increasing the activity of rice methanogens.

Moreover, the high aboveground biomass increased the below-ground biomass to a certain extent, thus providing sufficient substrate for CH_4 emission.

Further, our correlation analysis showed that CH_4 emissions had a significant positive correlation with LAI during the main season (r = 0.398 *). However, they showed a negative correlation (not significant) with LAI during the ratoon season (Table 7), suggesting that a high LAI during the main season increased rice photosynthesis, thus increasing biomass, eventually increasing CH_4 emissions, which was consistent with the findings by Yan et al. (2013) [18]. Our data showed that the LAI of different varieties during the ratoon season was only 0.90–1.31, significantly lower than that during the main season, reducing biomass and CH_4 emissions. The population spikelet number is an important indicator that affects rice yield and CH_4 emissions of the RRSTS, and it is affected by the panicle number per m^2 and spikelet number per panicle [19]. In this study, CH_4 emissions during the main season were significantly or extremely significantly negatively correlated with HI (r = −0.455 *) and population spikelet numbers (r = −0.553 **) (Table 7), and were negatively correlated with rice yield, indicating that increasing the spikelet number during the main season contributed to increasing HI, thus promoting the distribution and transfer of photosynthetic products to the grains, finally increasing panicle weight and yield, while reducing CH_4 emissions. During the ratoon season, although the correlation between CH_4 emissions and HI (r = −0.208) was not significant, CH_4 emissions had a significant or extremely significant negative correlation with biomass (r = −0.493 **) and rice yield (r = −0.479 *), implying that increasing biomass in the ratoon season would be conducive to the CH_4 emission decrease and rice yield increase during the ratoon season.

4.2. N_2O Emissions

Our data showed that total N_2O emissions during the RRSTS were between 0.19 and 0.28 kg·ha^{-1} in 2020, and between 0.38 and 0.94 kg·ha^{-1} in 2021, respectively. In 2020, N_2O emissions were mainly concentrated during the main season, accounting for 81.2–97.3% of the RRSTS, while in 2021, N_2O emissions were mainly concentrated during the ratoon season, accounting for 76.4–93.5% of the RRSTS (Tables 1 and 2). This was highly in accordance with the inter-annual precipitation change trend during the main and ratoon seasons. For example, the precipitation during the 2021 ratoon season was 151.2 mm, 124.9 mm less than that in 2020. Accordingly, the soil moisture decreased, thus increasing the soil redox potential and N_2O emissions [43,44].

Nitrogen fertilizer can provide nitrogen for digestion and denitrification reactions in paddy soil. In addition, drainage and soil drying measures during the rice growth period can easily lead to drastic changes in soil moisture. Therefore, soil moisture and nitrogen application are key factors affecting N_2O emissions [38]. In this study, the peak of N_2O emissions from the main season occurred during nitrogen fertilizer application and mid-term soil drying (Figure 3B,D). This was consistent with the findings by Fan et al. (2022) [35]. In particular, after applying bud-promoting fertilizer in early July during the 2020 main season, obvious N_2O emission peaks from all rice varieties were observed. This might be because high temperature and low rainfall during this period increased soil temperature. In addition, applying nitrogen fertilizer provided more substrates for N_2O production, thereby promoting N_2O emissions. The third reason might be that due to the differences in nitrogen nutrient absorption and utilization among different rice varieties, the amount of substrates involved in nitrification and denitrification was affected, affecting N_2O emissions [13]. In this study, the N_2O emissions produced by hybrid rice varieties during the main season (2020) were between 0.13 and 0.18 kg·ha^{-1}, significantly lower than the 0.28 kg·ha^{-1} emitted by the conventional rice variety HHZ (Table 1). One possible reason might be that the root biomass of hybrid rice varieties is generally higher than that of conventional rice, which is conducive to the hybrid rice plants absorbing more nitrogen, thus reducing the supply of nitrogen sources to soil microorganisms to a certain extent, finally resulting in a reduction in N_2O emissions from the main-season hybrid rice [45].

4.3. Response of CH_4 and N_2O Emissions to Water Management

As an important water-saving irrigation method, the AWD pattern is widely used in Asian regions such as China, the Philippines, Vietnam, and India [26]. Compared with continuous flooding (CF) treatment, the AWD pattern can reduce CH_4 emissions from early rice by 21% and from late rice by 42% [46]. In addition, a mild AWD pattern can significantly reduce CH_4 emissions from rice fields during the dry and rainy seasons in Vietnam, the Philippines, Thailand, and Indonesia, but excessive rain during the rainy season will weaken the CH_4 emission reduction effect [26]. However, compared with CF treatment, the AWD pattern often leads to drastic changes in the soil environment, thus increasing N_2O emissions by as much as 30–45 times [47]. Although there are many studies on the effects of water management on CH_4 and N_2O emissions from rice fields [48–51], few studies on the ratoon rice system exist.

In this study, compared with the CF treatment, the AWD pattern during the main season significantly reduced the total CH_4 emissions, even though the reduction in CH_4 emissions during the ratoon season was smaller, with the Yuxiang 203 variety exhibiting a greater reduction (Table 4). The results indicate that in the ratoon rice system, the AWD pattern was beneficial to CH_4 emission reduction during the main season and had a certain emission reduction effect during the ratoon season. The possible reason might be because the soil drying treatment reduced soil moisture, improved soil permeability, promoted the diffusion of atmospheric O_2 into the soil, and increased the oxidation level of CH_4, thereby inhibiting and reducing CH_4 emissions [3,52]. In addition, soil drying was also beneficial to the growth of the main-season rice root system, resulting in larger root biomass and deeper root distribution, which was conducive to the secretion of oxygen by the root system, thereby indirectly weakening CH_4 emissions during the ratoon season [26,34,49]. In contrast, AWD treatment significantly increased N_2O emissions from the ratoon rice system. Under the AWD pattern, N_2O increased significantly by 2.1–7.6 times during the main season and 0.05–1.1 times during the ratoon season (Table 2). This was in line with the findings of most previous studies of single-season rice that although the AWD pattern tends to increase N_2O emissions, N_2O only accounts for 12% of total greenhouse gas emissions, thus significantly reducing the total greenhouse gas emissions per unit rice planting area [53].

4.4. GWP and GHGI

In this study, the annual GWP and GHGI of the RRSTS were much lower than those of double-season rice [38] in Chongqing (the upper reach of Yangtze River), which was comparable to the annual GWP and GHGI of ratoon rice in the hilly areas of central Sichuan [32]. It has been reported that in rice field systems, the contribution of CH_4 emissions to GWP reaches 84–90% [3], while the contribution of N_2O emissions to GWP is smaller [54,55]. In this study, the GWP of the main season and the ratoon season was between 4.00 and 11.78 t CO_2-eq ha^{-1}, and between 0.79 and 2.11 t CO_2-eq ha^{-1}, respectively, accounting for 83.5–93.6% and 3.6–16.5% of the annual GWP, respectively (Tables 3 and 4). Further correlation analysis also showed that the correlation coefficient (r) between the GWP of the RRSTS and CH_4 or N_2O emissions during the main season was 0.965 ** and -0.022, respectively, and the correlation coefficients (r) between the GWP of the RRSTS and CH_4 and N_2O emissions during the ratoon season were 0.275 and 0.361 *, respectively This indicated that CH_4 emissions during the main season were the main source of GWP in the RRSTS, while CH_4 and N_2O emissions during the ratoon season had little impact on GWP. The significantly reduced CH_4 emissions during the ratoon season reduced the GWP of the ratoon season, thus decreasing the GWP of the two seasons for the ratoon rice system to a certain extent.

Our correlation analysis showed that GWP and GHGI during the main season were significantly negatively correlated with population spikelet number and HI, respectively. They were significantly positively correlated with LAI, although the correlation coefficient between GHGI and LAI did not reach a significant level (Table 7), indicating that a lower

LAI, high population spikelet number, and high HI during the main season were the main pathways to reduce GWP and GHGI. During the ratoon season, although the correlation between GWP and biomass was not significant, GWP and GHGI were significantly negatively correlated with the population spikelet number, biomass, and HI, suggesting that a high population spikelet number, biomass, and HI during the ratoon season were important pathways to reduce GWP and GHGI. The GWP and GHGI of the main and ratoon seasons were significantly negatively correlated with rice yield, respectively, although the correlation between GWP and yield during the main season was not significant, implying that increasing the yield of the RRSTS, especially the yield during the ratoon season, was beneficial to reducing the annual GWP and GHGI of ratoon rice. In this study, CLYHZ exhibited the lowest annual GWP and GHGI values, and the yield of the ratoon rice system during the two seasons reached 13.2 t·hm^{-2}, which was not significantly different from the yield of the high-yield variety YX203. The above results indicated that CLYHZ could achieve the synergetic goals of high yield and carbon emission reduction in the ratoon rice system; and thus, this variety was suitable for large-scale planting in ratoon-rice areas.

The AWD irrigation pattern affects rice yield by producing water stress. It has been reported that compared with conventional flooding (CF) irrigation, a mild AWD (with a soil water potential threshold of 15 $\pm$ 5 kPa at a soil depth of 15–20 cm) could result in a more stable rice yield and an increase to a certain degree [26], while a heavy AWD (with a soil water potential threshold of 30 $\pm$ 5 kPa) could significantly reduce the rice yield [56,57]. In this study, significantly more precipitation in the main-season rice in 2021 reduced the water stress effect of AWD on rice plants to a certain extent (Figure 1). Compared with the continuous flooding treatment, the AWD pattern significantly increased the panicle rate, effective panicle number, population spikelet number, and biomass during the main season, increasing the rice yield. In addition, under the AWD pattern, more effective panicles of the main-season rice provided a better material basis for ratoon rice growth, significantly increasing the LAI and biomass of ratoon rice, thereby increasing ratoon rice yield (Table 6).

The greenhouse gas emission intensity (GHGI) is the ratio of global warming potential to yield, representing the greenhouse gas effect per unit rice yield. As mentioned above, the AWD pattern reduced the GWP level in the RRSTS by reducing CH_4 emissions, especially during the main season. In addition, the increase in rice yield during the two seasons under the AWD pattern significantly decreased the overall GHGI during the whole season of ratoon rice compared with that under CF treatment (Table 4).

5. Conclusions

Our results showed that the CH_4 emissions during the main season were 157.05–470.73 kg·ha^{-1}, accounting for 83.5–95.3% of the total CH_4 emissions during the RRSTS; and thus, the CH_4 emissions were the main source of greenhouse gasses in the ratoon rice system. CH_4 emissions during the ratoon season were only 31.03–84.38 kg·ha^{-1}, accounting for 14.2–17.1% of the total CH_4 emissions, resulting in a decrease in the GWP and GHGI of the RRSTS. The total emissions of N_2O during the RRSTS were 0.13–0.94 kg·ha^{-1}, which had little effect on the GWP and GHGI of the ratoon rice system. The CLYHZ showed the high-yielding, and the lowest GWP and GHGI values among five rice varieties during the RRSTS. These findings indicate that the CLYHZ variety of ratoon rice exhibited reduced greenhouse gas emissions while maintaining a high rice yield. The AWD pattern further reduced the GWP and GHGI values of ratoon rice in the RRSTS by reducing the CH_4 emissions during the main season, increasing rice yield during both seasons. Our findings provide valuable references for promoting and applying ratoon rice in China's upper reaches of Yangtze River.

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