Accelerated Straw decomposition and Mitigated methane emissions via Autumn puddling incorporation Enhance Soil health and Yield stability in Cold-Region rice systems of China

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Abstract

To investigate the effects of rice straw incorporation methods on methane emissions, soil properties, and yield in cold rice-growing regions of China, a two-year field experiment (2022–2023) was conducted in paddy fields in central Jilin Province. Three treatments were compared: no straw return (CK), spring puddling with water for straw incorporation (T1), and autumn puddling with water for straw incorporation (T2). The results demonstrated that the T2 treatment significantly enhanced the straw decomposition rate compared to T1 by extending the decomposition period, resulting in a 2.93% increase in straw weight loss after incorporation and a reduction in concentrated methane emissions during summer. T2 caused a smaller decline in soil redox potential, thereby alleviating soil reduction stress. Compared to CK, T2 significantly increased soil nitrogen, phosphorus, and calcium levels and maintained higher root activity and stem numbers compared to T1. While the grain yield under T2 showed no significant difference from CK, the yield under T1 was significantly reduced by 12.7%. These findings suggest that autumn puddling with water for straw incorporation in cold rice regions of China accelerates straw decomposition, reduces peak methane emissions in summer, mitigates soil reduction stress, improves nutrient supply, and represents an effective strategy for sustainable straw management and yield stability.

Introduction

Jilin Province is a major rice-producing region in China, where both the cultivation area and yield have shown sustained growth in recent years. By 2023, the rice planting area in Jilin reached 828,800 hectares, with a total yield of 6.8206 million tons and an average yield of 8229.260 kg ha^{-1} (Jilin 2025). However, the expansion of rice cultivation has brought about a significant challenge: the disposal of large quantities of rice straw (Alengebawy et al. 2023). Conventional straw disposal primarily involved open burning, but national environmental policy reforms have rendered this practice unviable (Li et al. 2022; Singh et al. 2021).

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Alternative methods to open burning for rice straw disposal have been widely studied (Singh & Brar 2021). Among these, the most effective and convenient method is direct straw incorporation into the field (Li et al. 2018). This method not only enhances soil nutrient levels and improves the soil environment (Ninkuu et al. 2025), but also increases nitrogen content across various soil layers (Cui et al. 2022) and supplements potassium content, leading to a 5.0% increase in rice yield (Li et al. 2023a). Additionally, it reduces emissions of fine particulate matter, carbon dioxide, methane, and other pollutants associated with straw burning (Bhattacharyya et al. 2021; He et al. 2020).

However, direct straw incorporation also generates substantial methane emissions (Wu et al. 2024). In addition, the decomposition process after incorporation lowers soil redox potential, resulting in strongly reducing soil conditions (Liu et al. 2021). This affects rice root activity (Peng et al. 2024) and low-position tillering, ultimately reducing rice yield (Tian et al. 2022).

Spring incorporation is also prone to causing concentrated methane emissions and more intense reduction stress (Zhang et al. 2023). On the other hand, autumn incorporation in China's cold regions often leads to incomplete decomposition of incorporated straw due to the prolonged low winter temperatures, thereby compromising the effectiveness of decomposition (He et al. 2024). Previous research has shown that continuous flooding can increase methane emissions by up to 90% (Sanchis et al. 2012). Additionally, water management during the winter fallow season can increase methane emissions by reducing the inhibition of acetotrophic methanogens (Zhang et al. 2013). Studies conducted in California, USA, have indicated that under straw incorporation, winter methane emissions from paddies maintained under flooded conditions accounted for approximately 50% of the annual emissions (Fitzgerald et al. 2000). Research in Jiangsu Province, China, also confirmed that methane emissions during the fallow season following straw incorporation ranged from 9.6% to 33.1% of the annual total (Zhang et al. 2011). However, few studies have examined the impact of this practice on rice agronomic traits and yield, and most existing research has focused on warmer southern regions (Martínez-Eixarch et al. 2018; Martínez-Eixarch et al. 2022; Vo et al. 2018). For the cold rice-growing areas of northern China, an important question arises: Can fields be immediately flooded and crushed straw plowed and incorporated through puddling after the autumn rice harvest? This approach could extend the straw decomposition period, potentially reducing concentrated methane emissions during the hot summer period while also mitigating high-intensity soil reduction stress, thereby achieving stable rice yields.

To test this hypothesis, this study selected paddy fields in central Jilin Province, using a locally dominant rice variety as the test cultivar. It comparatively analyzed methane emissions, soil redox conditions, rice agronomic traits, and yield under different straw incorporation practices. The aim was to clarify the effects of autumn puddling with water for straw incorporation on methane emissions, soil properties, and rice yield in cold rice-growing regions of China. Ultimately, the study aimed to identify the most suitable rice straw incorporation method for these areas, providing theoretical support and practical guidance for local rice production.

Materials & Methods

Experimental Site and Cultivar

The experiment was conducted at the off-campus experimental station of Jilin Agricultural Science and Technology University in Yongji County, Jilin City, Jilin Province (N43°836′, E126°113′; altitude 243 m). The station experiences a northern temperate continental monsoon climate, with an annual accumulated temperature of 2,790°C, an average annual precipitation of 690 mm, a frost-free period of approximately 130 days, and sunshine duration ranging from 2,500 to 2,900 hours. Three adjacent paddy fields with independent irrigation and drainage systems were selected, each approximately 1000 m^{-2} in area. According to the World Reference

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Base for Soil Resources (Group 2014), the soil type of the experimental paddies was classified as Clay Gleysols. The experiment was conducted over two years, from April 2022 to December 2023. The rice cultivar used was Jihong 9, a dominant variety in Jilin Province.

Experimental Design

Three treatments were established: Control (CK): No straw return. Rice straw was completely removed from the field after harvest. Spring Incorporation (T1): Straw was incorporated via puddling with water in the spring immediately before rice transplanting in the cultivation year (conducted on May 25, 2022, and May 27, 2023). Autumn Incorporation (T2): Straw was incorporated via puddling with water in the autumn immediately after rice harvest in the year preceding cultivation (conducted on September 28, 2021, and September 29, 2022). The straw incorporation amount for both T1 and T2 treatments was approximately 8,000 kg ha^{-1}. Air-dried straw was chopped into 7-10 cm segments, evenly spread over the plots, and then flooded to a water depth of 3-5 cm. A rotary tiller (Model 1JH-150, Mengcheng County Yutian Machinery Co., Ltd., Bozhou, China) was used to incorporate the straw into the 5-20 cm soil layer.

Based on previous research (He et al. 2024), a compound fertilizer（$N:P_2O_5:K_2O$ = 17:17:17）was applied at 650 kg ha^{-1} as a basal dressing before transplanting. Topdressing with urea ($N \geq 47\%$) was applied at 30 kg ha^{-1} during the tillering stage and 20 kg ha^{-1} during the heading stage. The total nutrient inputs were 150 kg ha^{-1} of N, 110 kg ha^{-1} of P_2O_5, and 110 kg ha^{-1} of K_2O.

Rice seedlings were transplanted on May 27, 2022, and May 29, 2023, at a density of 16.7 hills m^{-2}, with 3-4 seedlings per hill. A water depth of 3-5 cm was maintained from transplanting until approximately 30 days after heading. Fields were drained on September 13, 2022, and September 16, 2023. Pests, diseases, and weeds were strictly controlled throughout the experiment to prevent biomass and yield losses.

Sampling and Measurements

Meteorological Data

Temperature and sunshine duration data during the experimental period were provided by the Jilin City Meteorological Bureau.

Straw Weight Loss Rate and Breaking Force

The weight loss rate and breaking force of incorporated straw were measured using the nylon mesh bag method (Yan et al. 2019) from April 27 to September 16, 2022. One kilogram of pre-dried rice straw (7-10 cm in length) was placed into nylon mesh bags. Bags for T1 were buried at a depth of 15-20 cm on September 28, 2021, and T2 on May 27, 2022. Bags were retrieved monthly from April to September 2022 during the latter part of each month. Straw was rinsed to

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remove soil particles, oven-dried at 75°C and weighed. The straw weight loss rate was calculated using the following formula.

$$Straw\ weight\ loss\ rate\ (\%) = \frac{SWi - SWf}{SWi} \times 100$$

where SWi is the initial straw weight and SWf is the straw weight at different sampling times. Straw breaking force was measured using a plant stalk strength tester (Model YYD-1A, Zhejiang Top Cloud-agri Technology Co., Ltd., Hangzhou, China). Three replicates were conducted per treatment plot.

Rice Bleeding Sap Rate Measurement

The bleeding sap rate of rice was measured according to a previously described method (Ansari et al. 2004), during the early, mid, and late parts of each month from July 3 to September 25, 2022. Representative plants from each treatment plot were cut 20 cm above the soil surface. Pre-weighed absorbent cotton was placed over the cut stem, covered with polyethylene film, and secured with a rubber band. The cotton was collected and weighed after one hour. The number of stems on each cut plant was recorded. The bleeding sap rate per stem was calculated using the following formula.

$$Bleeding\ sap\ rate\ per\ stem = \frac{CWf - CWi}{SN}$$

where CWi is the initial cotton weight, CWf is the cotton weight after 1 hour, and SN is the number of stems.

Three replicates were conducted per treatment plot.

Methane Sampling and Measurement

Methane emission fluxes (CH_4) were measured using the static closed-chamber method (Ding et al. 2021) during the early, mid, and late parts of each month from May 27 (transplanting) to September 16, 2022. Before transplanting, stainless steel bases were installed in the sampling area, with two rice hills planted inside each base. A transparent polypropylene chamber (40 cm × 30 cm × 100 cm), equipped with a thermometer and a small fan, was placed over the base. Gas samples (100 ml) were collected at 0, 15, and 30 minutes between 9:00 and 11:00 AM on sampling days, ensuring no atmospheric exchange. Samples were stored in light-proof gas sampling bags and transported to the laboratory for analysis. Methane concentration was determined using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan). Methane emission fluxes were calculated according to a previously described method (Guan et al. 2024). Three replicates were conducted per treatment plot.

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Soil Redox Potential Measurement

Soil redox potential (ORP) was measured at the same time as methane sampling using a soil ORP meter (Model TR-901, INESA, Shanghai, China) around the static chambers. Three replicates were conducted per treatment plot.

Agronomic Trait Measurement

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Plant height, stem number per hill, and chlorophyll content (measured using a SPAD-502 PLUS meter, Konica Minolta, Tokyo, Japan) were recorded for 15 consecutive hills in each treatment plot approximately every 15 days from June 5 to September 20, 2022. Three replicates were conducted per treatment plot.

Soil Sampling and Analysis

Soil samples (0-20 cm depth) were collected from the experimental paddies after rice harvest in autumn 2022 and 2023 using a five-point sampling method, with sampling points spaced 5-10 m apart. Samples from each plot were thoroughly mixed to form a composite sample of approximately 500 g. Visible impurities were removed, and the soil was air-dried and passed through an 8 mm mesh sieve before analysis. Soil nutrients and chemical properties were determined as follows: alkali-hydrolyzable nitrogen (N) by the Kjeldahl method (Bao 2000); available phosphorus (P) by extraction with 0.5 M $NaHCO_3$ measured by molybdenum-antimony colorimetry (Bao 2000); available potassium (K) by extraction with 1 M ammonium acetate measured by flame photometry [30]; soil organic matter by the $K_2Cr_2O_7$-H_2SO_4 oxidation method (Bao 2000); exchangeable calcium (Ca) and magnesium (Mg) by extraction with ammonium acetate measured by atomic absorption spectrophotometry (Bao 2000). Three replicates were conducted per treatment plot.

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Yield Determination

Yield components were measured for each treatment plot on September 29, 2022, and September 28, 2023. Yield was calculated based on the number of panicles per square meter, number of grains per panicle, thousand-grain weight, and seed-setting rate. Three replicates were conducted per treatment plot.

Statistical Analysis

Experimental data were collated and initially processed using WPS software (Version 365, Kingsoft Office Software, Co., Ltd., Zhuhai, China). Analysis of variance (ANOVA), correlation analysis, and significance tests for differences among treatments, years, and treatment × year interactions were performed using the standard least squares method in JMP software (Version 18.0 Pro, SAS Institute, Cary, NC, USA). Differences between treatment means were assessed using Tukey's HSD test at the $p < 0.05$ significance level. Figures were generated using Origin software (Version 2025, OriginLab Corporation, Northampton, MA, USA).

Results

Climate Conditions

Figure 1 shows the changes in air temperature and sunshine duration during the experimental period at 10-day intervals. Mean temperatures during most intervals in 2022 and 2023 were generally higher than the 2018–2023 average (referred to as Normal). In 2022, temperature fluctuations were more pronounced, with peak temperatures occurring in early July and late September and exceeding the Normal by 1.22℃ and 1.7℃, respectively. In 2023, temperatures during most intervals remained consistently above the Normal average. Temperatures after the heading stage in mid-August were significantly higher than Normal. Specifically, early April and late October were 3.3℃ and 2.4℃ warmer than the corresponding Normal periods. The only significantly lower-than-average temperature occurred in late April, which was 3.3℃ below Normal.

Total sunshine duration in 2022 was higher than Normal but exhibited greater overall fluctuations, especially from late August onward. In contrast, total sunshine duration in 2023 was lower than Normal, displaying a clear downward trend from early July to early August. In particular, during early August, sunshine duration was only 17.3 hours, significantly lower than Normal.

CH_4 and ORP

Figure 2 shows CH_4 and ORP during the experimental period in 2022. Significant negative correlations were observed between CH_4 and ORP across all treatments, with correlation coefficients of -0.819 for CK, -0.730 for T1, and -0.590 for T2. Significant differences in CH_4 were observed among treatments. CH_4 from CK remained relatively stable throughout the experimental period, reaching a peak of 10.783 mg m^{-2} h^{-1} on August 3. Before August 3, CH_4 from CK were significantly lower than those from the other treatments. T1 emissions peaked at 34.767 mg m^{-2} h^{-1} on June 28. Moreover, from June 6 to July 15, CH_4 from T1 were significantly higher than those from both CK and T2. T2 emissions reached the first peak of 16.840 mg m^{-2} h^{-1} on June 28. After a slight decline, a second peak of 16.403 mg m^{-2} h^{-1} occurred on July 27. The second peak showed no significant difference from the T1 emission level (16.247 mg m^{-2} h^{-1}) on the same date but was significantly higher than CK.

ORP for all treatments exhibited a similar trend of initial decline followed by an increase during the experimental period, with significant differences observed among treatments. In CK, ORP declined continuously from May 27 to June 28. After a slight increase, it dropped again, reaching a minimum value of -233.670 mV on August 14, which was 11 days after the CH_4 peak in CK. From May 27 to July 15, ORP values in CK were significantly higher than those in T1 and T2. ORP dynamics for T1 and T2 were similar in the early phase of the experiment. Both treatments reached their minimum ORP values on July 3, five days after the first CH_4 peak occurred on June

28, with -298.33 mV for T1 and -245.67 mV for T2. Starting from July 3, the ORP of T1 was significantly lower than that of T2. However, the ORP of T2 showed a brief decline on August 14, 11 days after its second CH_4 peak. From then until September 16, no significant differences in ORP were observed between T1 and T2.

Straw Decomposition

Figure 3 presents the changes in straw weight loss rate and breaking force after incorporation under different treatments in 2022. Significant negative correlations were observed between straw weight loss rate and breaking force for all treatments, with correlation coefficients of -0.983 for T1 and -0.941 for T2. Straw weight loss rates differed significantly between T1 and T2, with T2 exhibiting a consistently higher rate.

The weight loss rate of T1 straw gradually increased from June 28 onward, showing substantial growth between June and July, reaching 38.700% by September 16. In contrast, T2 straw began losing weight as early as April 27 (9.333%), with the loss rate progressively increasing to 41.633% by September 16.

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Breaking force also varied significantly between treatments, with T1 demonstrating substantially higher values than T2. The breaking force of T1 straw gradually decreased from May 27 onward, mirroring its weight loss pattern with a pronounced decline during June–July, reaching 94.000 N by September 16. In comparison, the breaking force of T2 started decreasing from April 27 and maintained a relatively consistent downward trend throughout the growing season, declining to 55.000 N (58.511% of T1) by September 16.

Agronomic Traits

Figure 4 illustrates the dynamics of bleeding sap rates under different treatments during the 2022 experimental period. Prior to July 27, no significant differences in bleeding sap rates were observed among treatments. After July 27, CK exhibited a progressively increasing trend, ultimately showing significantly higher values than both T1 and T2 until September 2. The bleeding sap rate of CK peaked at 0.311 g stem^{-1} h^{-1} on August 27. At that time, the values for T1 and T2 were 0.158 g stem^{-1} h^{-1} and 0.171 g stem^{-1} h^{-1}, respectively, representing only 50.804% and 54.984% of the CK value.

Compared to T1, T2 exhibited greater fluctuation in bleeding sap rates. Although no significant differences were observed between T1 and T2 before August 27, T2 consistently maintained slightly higher values than T1. All treatments showed pronounced declines in bleeding sap rates after field drainage on September 13. Notably, T1 displayed a transient increase post-drainage, a trend not observed in T2.

Figure 5 shows changes in plant height, stem number, and leaf color among different treatments during the 2022 experiment. No significant differences in plant height were observed between treatments. Plant height increased steadily throughout the growth period, with the rate of increase accelerating after June 22. Growth gradually slowed down after August 4, entering a plateau phase after September 4. On September 20, the final plant heights were 129.10 cm for CK, 129.37 cm for T1, and 125.33 cm for T2.

Stem number increased in all treatments beginning on June 5, with a rapid increase after June 22 and a peak on July 8. At this time, stem numbers were 546.090 stems m^{-2} for CK, 472.610 stems m^{-2} for T1, and 518.819 stems m^{-2} for T2. The stem number in CK was significantly higher than that of T1. Stem numbers gradually declined. However, except for July 22, the stem number in CK remained significantly higher than T1. On September 20, the final stem numbers were 371.291 stems m^{-2} for CK, 345.139 stems m^{-2} for T1, and 361.271 stems m^{-2} for T2.

The trend in leaf color changes was similar to that of stem number across treatments. Leaf color increased rapidly starting from June 22, peaked on July 8, and then gradually declined. On August 4, leaf color values were 31.533 SPAD for CK, 28.967 SPAD for T1, and 31.900 SPAD for T2. The leaf color of T2 was significantly higher than that of T1 at this time. On September 20, the final leaf color values were 22.233 SPAD for CK, 20.667 SPAD for T1, and 21.633 SPAD for T2. The leaf color of CK was significantly higher than that of T1.

Soil Properties

Figure 6 shows differences in soil properties among treatments during the 2022 and 2023 trials. No significant year-to-year variation was observed for any soil properties. Additionally, K, and organic matter content showed no significant differences between treatments. N under T2 was 175.7 mg kg^{-1} in 2022 and 176.7 mg kg^{-1} in 2023, while N levels under CK were 167.967 mg kg^{-1} in 2022 and 164.9 mg kg^{-1} in 2023. N was significantly higher under T2 than under CK, with increases of 4.604% and 7.156%, respectively. P under T2 was 26.9 mg kg^{-1} in 2022, significantly higher than the 23.3 mg kg^{-1} recorded under CK. Ca also showed significant differences among treatments in both 2022 and 2023. In 2022, Ca under T2 was 26.367 cmol kg^{-1}, significantly higher than the 25.533 cmol kg^{-1} observed under CK. In 2023, Ca ranked from highest to lowest as follows: 26.7 cmol kg^{-1} under T2, 26.233 cmol kg^{-1} under T1, and 25.067 cmol kg^{-1} under CK. In 2022, Mg content was 9.5 cmol kg^{-1} under T2 and 9.267 cmol kg^{-1} under T1, with T2 being significantly higher than T1.

Yield and Yield Components

Figure 7 shows the yield components and yield under different treatments during 2022 and 2023. Panicle number showed no significant differences among treatments or between years. However, the mean panicle numbers for 2022 and 2023 were 355.94 panicles m^{-2} for CK, 328.10 panicles m^{-2} for T1, and 340.35 panicles m^{-2} for T2. The panicle number under CK was significantly higher than that under T1.

In 2022, the number of grains per panicle was 116.8 for CK, 108.6 for T1, and 114.3 for T2. Both CK and T2 had a significantly higher number of grains per panicle than T1. In 2023, the corresponding values were 113.5 for CK, 108.6 for T1, and 110.4 for T2. CK had a significantly higher number of grains per panicle than both T1 and T2. The mean number of grains per panicle over the two years was 115.17 for CK, 108.6 for T1, and 112.33 for T2. Both CK and T2 had significantly higher mean values than T1.

No significant differences were observed in seed setting rate or thousand-grain weight among treatments. However, the mean seed setting rate across treatments was 93.227% in 2022 and 92.413% in 2023. The seed setting rate in 2022 was significantly higher than that in 2023.

The yields under CK were 9412.9 kg ha^{-1} in 2022 and 8990.5 kg ha^{-1} in 2023, both significantly higher than those under T1 (8171.5 kg ha^{-1} in 2022 and 7814.0 kg ha^{-1} in 2023). The mean yield over the two years was 9201.7 kg ha^{-1} for CK, 7992.8 kg ha^{-1} for T1, and 8622.9 kg ha^{-1} for T2. Significant differences in yield were observed among treatments.

Discussion

Methane Emissions and ORP

Compared to no straw return, rice straw incorporation can significantly increase methane emissions (Hou et al. 2013). In this study, methane emissions showed significant differences between treatments (Fig. 2). Previous research has shown that because methanogen activity is temperature-dependent, methane emissions from ecosystems, including paddy fields, significantly increase with seasonal temperature rise (Yvon-Durocher et al. 2014). Furthermore, straw return leads to an earlier peak in methane emissions compared to treatments without straw incorporation (Hu et al. 2016). The results of this study are consistent with these trends. T1 and T2, which implemented straw return, exhibited substantial methane emissions during the warmer months of June and July, with peak emissions occurring on June 28. In contrast, the peak methane emission for CK, without straw return, occurred in early August when temperatures were highest (Fig. 1a). This resulted in concentrated methane emissions during the early warm season. The peak methane emission for T1 was 2.065 times that of T2 and 3.224 times that of CK. Water management during the rice fallow period has also been shown to significantly increase methane emissions (Sander et al. 2018). Concurrently, returned rice straw serves as a substrate for methane production (Ye et al. 2015), and its degree of decomposition is closely correlated with methane emissions (Contreras et al. 2012; Yuan et al. 2014). In this study, the total methane emissions over the entire growth period were 62.077 mg m^{-2} for CK, 183.007 mg m^{-2} for T1, and 123.897 mg m^{-2} for T2. The total emissions from CK were approximately 33.921% of those from T1, while T2 emissions were approximately 67.701% of T1. This difference occurred because T2 incorporated the straw using rotary tillage immediately after the

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autumn harvest in 2021, whereas T1 incorporated straw in late May 2022. Temperatures remained above 0°C until mid-November 2021 and rose above 0°C again by late March 2022 (Fig. S1). Soil temperature after straw incorporation should be higher than ambient air temperature. Previous studies indicate that the minimum temperature for straw decomposition under natural conditions is approximately 7°C (Yan et al. 2019). Compared to T1, which incorporated straw in late May 2022, T2 extended the decomposition period after incorporation by about seven months. Based on previous estimates (Saptomo et al. 2004), the deep soil temperature remained above 7°C for about 50 days during this extended period, which greatly accelerated straw decomposition after incorporation. Previous research has also confirmed that in the Tohoku region of Japan, elevated soil temperature during the non-rice-growing season promoted rice straw decomposition and reduced methane emissions in the subsequent rice-growing season (Tang et al. 2016). In this study, straw weight loss under T2 began earlier, on April 27, and the straw weight loss rate throughout the growth period was significantly higher for T2 than for T1 (Fig. 3). A significant negative correlation was observed between straw weight loss rate and straw breaking force. The straw breaking force under T2 was consistently lower than that under T1 throughout the growth period. These findings collectively demonstrate that T2 accelerated straw decomposition by extending the decomposition period after straw incorporation.

For T1, following straw incorporation on May 25, both straw weight loss rate and breaking force increased rapidly during the warmer months of June and July as temperatures gradually rose. This also led to concentrated methane emissions from T1 during this period (Fig. 2). Between June 16 and July 27, methane emissions from T1 totale 135.067 $mg\ m^{-2}$, accounting for 73.804% of T1's total methane emissions during the growth period. This amount was approximately 5.758 times greater than that from CK and 1.864 times greater than that from T2 during the same period. Consistent with previous research (Huang et al. 2005), a significant negative correlation between methane emissions and ORP was observed in this study. Previous studies have demonstrated that carbon input reduces ORP (Mattila 2024). , and that methane emissions are closely linked to ORP, with straw incorporation accelerating the decline in redox potential (Minamikawa & Sakai 2006). Therefore, the concentrated methane emissions from T1 likely caused a substantial decrease in ORP during this period. The lowest ORP value observed for T1 was significantly lower than that of T2. The mean ORP values during the growth period were -148.222 mV for CK, -175.945 mV for T1, and -155.473 mV for T2. The soil under T1 exhibited stronger reducing conditions compared to the other treatments.

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Soil Nutrients

Although numerous studies have reported that straw return increases total organic carbon content in soil (Jin et al. 2020; Nakajima et al. 2016; Wang et al. 2017), the results from this two-year experiment did not reflect this trend (Fig. 6d). Previous research has shown that total soil nitrogen content is significantly higher following autumn puddling and rotary tillage incorporation compared to treatments with no straw return (Wang et al. 2023). In this study, N under T2 was significantly higher than that under CK in both 2022 and 2023 (Fig. 6a). Furthermore, other studies have shown that straw return can increase soil phosphorus content by 39.7% compared to no straw return (Jin et al. 2020). In this study, P and Ca levels under T2 in 2022 were also significantly higher than those under CK, while T1 did not show such an increase (Fig. 6b, e). As mentioned previously, this can be attributed to the fact that in the T2 treatment, irrigation was applied immediately following straw incorporation in the previous year. This allowed decomposition to begin earlier than in T1. By late April 2022, before transplanting, nearly one-tenth of the straw in T2 had already decomposed. Furthermore, on September 16, the weight loss rate in T2 was 2.933% higher than in T1 (Fig. 3). This enabled more nutrients from the decomposed T2 straw to be released into the soil, thereby increasing the soil nutrient content.

Agronomic Traits

A decrease in ORP increases anaerobic respiration in rice roots (Tolley et al. 1986). Waterlogged soil generates toxins at lower redox potentials, inhibiting plant growth [(Tokarz & Urban 2015), primarily through soil phytotoxins and other reductive byproducts that cause severe stress to plant roots (Pezeshki & DeLaune 2012). In this study, differences in ORP among treatments also affected sap exudation rate, an indicator of root activity, with significant differences observed across treatments (Fig. 4). The sap exudation rate in CK (no straw return) was significantly higher than those in T1 and T2. Research shows that rice root morphological and physiological traits are negatively correlated with methane emission flux (Chen et al. 2019). In this study, during June and July—the period of concentrated methane emissions and the lowest ORP values (Fig. 2)—the sap exudation rates across all treatments, including CK, remained at relatively low levels. Although sap exudation rates in T1 and T2 increased slightly 13–14 days after reaching their lowest ORP values, they remained significantly lower than those in CK. This suggests that the lower ORP associated with straw return imposed persistent stress on rice roots.

Previous studies suggest that straw return treatments can increase rice plant height and stem number (Luo et al. 2024). However, this study found no significant differences in plant height among treatments (Fig. 5a). Additionally, following the peak in stem number on July 8, CK consistently exhibited significantly higher stem numbers than T1 except on July 22 (Fig. 5b). As mentioned earlier, stem number was affected by treatment-specific variations in ORP. T1 experienced stronger soil reducing conditions from July 3 to August 3 compared to CK and T2 (Fig. 2), leading to reduced formation of lower-position tillers (Gao et al. 2004), thereby decreasing the total stem number. In contrast, T2 maintained higher ORP than T1, particularly after July 27. Moreover, as previously noted, T2's enhanced straw decomposition (Fig. 3) facilitated greater nitrogen release into the soil, improving nutrient availability (Fig. 6a). As a result, although T2 experienced reductive stress (resulting in fewer stems than CK), the difference was not statistically significant. Owing to T2's higher sap exudation rate (Fig. 4) and improved soil nutrient conditions (Fig. 6) by August 3, its leaf color was significantly higher than T1 at the heading stage on August 4 (Fig. 5c).

Yield and Yield Components

An increase in ORP promotes a higher panicle number in rice, thereby enhancing yield (Minamikawa & Sakai 2006). In this study, CK exhibited a significantly higher panicle number than T1 (Fig. 7a), consistent with CK's trend of greater stem numbers throughout the growth period (Fig. 5b). Research conducted in Jiangsu, China, has shown that rice straw return increases total nitrogen uptake, particularly during the panicle differentiation stage, promoting the development of larger panicles and potentially higher yield (Li et al. 2023b). However, as previously stated, the significant decrease in ORP under T1 induced pronounced reductive stress. This resulted in significantly higher leaf color for CK and T2 compared to T1 during the late growth stage, as well as a higher sap exudation rate for CK than T1 after heading in early August (Fig. 4). As a result, both CK and T2 had a significantly higher number of grains per panicle than T1 (Fig. 7b). The mean seed setting rate across treatments in 2023 was significantly lower than in 2022. This decline may be attributed to high temperatures beginning in mid-August 2023 (Fig. 1), causing high-temperature-induced sterility (Fahad et al. 2019) and reducing seed setting rate (Fig. 7c).

Although numerous studies have demonstrated that straw return can enhance rice yield (Hou et al. 2021; Li et al. 2023b; Wang et al. 2015), the T1 treatment in this study yielded significantly less than CK. While the yield under T2 was slightly lower than that of CK, no significant difference existed between them (Fig. 7e). The underlying reasons can be explained as follows: Different straw return treatments reduced ORP, impairing root activity and lower-position tillering capacity, thereby limiting panicle number formation and reducing yield. However, compared to T1, T2 extended the straw decomposition period, improving decomposition efficiency. This mitigated the adverse effects of soil reduction while enriching soil nutrients. As a result, T2 maintained higher leaf color than T1 during the late growth stage, supporting better grain formation per panicle and alleviating the extent of yield reduction.

Conclusions

A significant negative correlation was observed between CH_4 and ORP following straw return, with methane's impact on ORP exhibiting a temporal lag. Among treatments, the rapid decomposition of T1 straw during the high temperatures of summer triggered concentrated methane emissions, substantially reducing ORP and inducing soil reductive stress. This impaired tiller formation and root activity, ultimately reducing yield. In contrast, T2 extended the decomposition period, preventing concentrated methane emissions during the growth period and mitigating reductive stress induced by straw return. Additionally, enhanced decomposition in T2 facilitated the release of nutrients from straw, significantly increasing soil nutrient content and ensuring adequate nutrient supply for late-stage rice growth. In summary, incorporating rice straw through puddling and rotary tillage immediately after the autumn harvest effectively extends decomposition time, promotes decomposition, reduces concentrated methane emissions, alleviates soil reductive stress, and improves soil nutrients, thereby stabilizing rice yield. This practice has the potential for integration into local carbon-neutral farming policies.

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