EFFECT OF MECHANICAL SIDE DEEP FERTILIZATION TECHNOLOGY ON NUTRIENT ABSORPTION AND LOSS IN PADDY FIELDS
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机械侧深施肥技术对水稻养分吸收及稻田养分损失的影响

Zhenhua XU [1,2], Haiying LIU [1,2], Yanmin YU [1,2], Changjun DAI [3], Jing WANG [3], Ping YAN [1,2*]
[1] Biotechnology Institute, Heilongjiang Academy of Agricultural Sciences, Harbin, 150028, China
[2] Northeast Branch of National Center of Technology Innovation for Saline-Alkali Tolerant Rice, Harbin, 150028, China
[3] Quality and Safety Institute of Agricultural Products, Heilongjiang Academy of Agricultural Sciences, Harbin, 150028, China
Corresponding author: Ping Yan; E-mail: yany1960928@sina.com
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ABSTRACT
To investigate the effects of different fertilization treatments on rice growth, nutrient uptake, and nutrient loss in paddy fields, the study was conducted in Jiansanjiang Qixing Farm, Company 36, Jiamusi City, Heilongjiang Province as the experimental site. A total of six treatment groups (G1-G6) were set up with different fertilization methods and fertilizer application rates. The data demonstrated that the number of tillers increased by 61.4% in G2 and 80.4% in G3 compared to G1. The number of tillers in G6 was 489×104/hm2, which decreased by 13.6% compared to G3. During the tillering stage, the nitrogen content of G1, G2 and G3 stems was 2.08, 2.19 and 2.51%, respectively. The cumulative loss of potassium in paddy fields was 0.19 kg/hm2, 0.59 kg/hm2 and 0.41 kg/hm2 for G1, G2 and G3, respectively. The results indicated that the use of mechanical side deep fertilization could bring many advantages to rice compared to the traditional manual fertilization method, including an increase in the number of tillers and plant height, as well as an increase in the leaf area index and dry material accumulation. At the same level of fertilization, the mechanical side deep fertilization method resulted in less ammonia volatilization, which would contribute to reducing ammonia volatilization from the paddy field and allow more nitrogen to be stored by the paddy field. In addition, the cumulative loss of runoff from the paddy field was reduced by the mechanical side deep fertilization treatment compared to manual fertilization. The study provides a useful reference for optimizing rice cultivation techniques to improve yield and reduce nutrient losses.

摘要
为研究不同施肥处理对水稻生长、养分吸收和养分流失的影响，本研究以黑龙江省佳木斯市三十六连建三江七星农场为试验地。试验共设 6 个处理组（G1-G6），施肥方法和施肥量各不相同。数据表明，与 G1 相比，G2 的分蘖数增加了 61.4%，G3 增加了 80.4%。G6 的分蘖数为 489×104/hm^2，比 G3 减少了 13.6%。在分蘖期，G1、G2 和 G3 茎的含氮量分别为 2.08%、2.19% 和 2.51%。G1、G2 和 G3 的稻田钾累积损失量分别为 0.19 kg/hm^2、0.59 kg/hm^2 和 0.41 kg/hm^2。结果表明，与传统的人工施肥方法相比，使用机械侧深施肥能给水稻带来许多好处，包括增加分蘖数和株高、提高叶面积指数和干物质积累。在施肥量相同的情况下，机械侧深施肥法减少了氨的挥发，有助于减少稻田的氨挥发，使稻田储存更多的氮。此外，机械侧深层施肥处理还减少了水田径流的累积损失。

INTRODUCTION
With the continuous growth of global population and the acceleration of industrialization, the demand for food shows a continuous rise. In China, rice paddies are mainly distributed in regions such as Jiangnan and South China, where climatic conditions and water resources provide unique conditions for rice growth (*Mohidem et al., 2022*). However, the concentration of land resources in these areas has increased due to the growth of industrialization and urbanization. Therefore, it has become an important challenge in the field of agriculture to increase the unit yield of paddy fields (*Le Van and Jens, 2023; Xiao et al., 2022; Wu et al., 2023*). As one of the most important grains in China, the improvement of the yield of paddy fields is pivotal to ensure the food security of the country. To meet this need, scientists have devoted themselves to researching various methods to increase the yield and productivity of paddy fields so as to ensure a stable food supply for the country (*Jiaying et al., 2022*).

Urmi et al. (2022) used different treatment designs to investigate the impacts of integrated nutrient management on cropland's carbon sequestration, soil fertility, nutrient use efficiency, and rice yield. According to the findings, applying both organic and inorganic fertilizers at the same time increased soil fertility considerably and improved nutrient uptake and utilization efficiency. In a Basmati rice-wheat cropping system, Dhaliwal et al. evaluated the long-term impacts of applying fertilizer and manure together on wheat output, nutrient concentration, and absorption. The study's findings showed that applying farmyard manure in addition to 75% NPK considerably enhanced growth parameters and yield characteristics, as well as plant height, tiller count, chlorophyll content, and wheat yield (*Dhaliwal et al., 2023*). Using a greenhouse experiment, *Bhadwal et al. (2022)* assessed the impact of soil selenium treatment on metabolic alterations in rice under arsenic stress. According to the findings, selenium treatment greatly enhanced arsenic's harmful effects on grain yield, leaf dry weight, and rice plant height. *Litardo et al. (2022)* evaluated the effect of application of different mineral and organic amendments on rice growth and yield in saline soils of Yaguachi, Ecuador. The results indicated that the application of compost significantly increased rice yield and it promoted both nutritional and reproductive growth of rice. Therefore, it was considered as the best amendment in this type of soil. By comparing the varying nutrient consumption efficiencies of nitrogen, phosphorous, and potassium in rice and wheat under various integrated nutrient management regimes, Bihari et al. examined the impact of nutrient efficiency on crop yield. The findings showed that by enhancing soil fertility, raising sustainable crop yield, and enhancing nutrient uptake, the combined application of chemical and organic fertilizers can increase nutrient usage efficiency (*Bihari et al., 2022*).

However, traditional methods of fertilizer application in paddy fields often suffer from low nutrient utilization and serious fertilizer loss, which not only result in wastage of nutrients, but also cause pollution to the environment (*Lee et al., 2025*). Therefore, it is important to study new fertilization techniques to improve paddy yield and reduce environmental pollution. Paddy production has made extensive use of mechanical side deep fertilization (MSDF) techniques in recent years (*Assogba et al., 2025*). This technology enables fertilizer to be distributed more evenly in the paddy field by applying fertilizer at a depth of about 10 cm, thus improving the efficiency of nutrient utilization. *Wu et al.* compared the effects of manual versus mechanical side application of fertilizer under conventional tillage, minimum tillage and no-tillage conditions by machine transplanting rice. The results indicated that conservation tillage combined with mechanical side application of fertilizer can effectively improve fertilizer utilization, promote rice growth and increase yield (*Wu et al., 2022*). *Hou et al. (2023)* conducted a comparative experiment on different fertilizer depths using the side deep fertilization mode of machine transplanted rice. The results indicated that the optimum depth of side deep fertilization was 10 cm. This depth significantly increased rice yield and improved the efficiency of nitrogen and phosphorus utilization, while reducing nitrogen and phosphorus concentration and ammonia volatilization in surface water. Through field trials, *Zhong et al. (2024)* found that lateral depth fertilization of mechanically grown rice in double-season paddy fields in Hunan significantly reduced nitrogen losses. It also increased relative soil urease activity and reduced total N footprint. Using field tests and radioisotope tracer studies, *Wang et al. (2023)* investigated the effects of varying nitrogen fertilizer (NF) application rates on yield, nitrogen usage efficiency, and their physiological properties of mechanically potted rice transplants under deep-burrowing circumstances. According to the findings, rice output and NF use efficiency may be successfully increased by applying 135 kg N ha^{-1} of basal NF deep underground.

In summary, many studies have been done with many different designs and experiments for rice yield, nutrient utilization and mechanical fertilization, and results have been obtained. However, the impact of MSDF technology for rice growth and farmland nutrients is still controversial. In this context, the study will conduct experiments to analyze the specific impact effects of this technology, which will provide a scientific basis for paddy production, optimize paddy fertilization methods, increase paddy yield, and reduce environmental pollution. The innovativeness of the study is reflected in the fact that different ratios of the MSDF technology were used through field trials in Jiansanjiang Qixing Farm, Company 36, Jiamusi City, Heilongjiang Province. The nutrient uptake of rice and nutrient loss from paddy fields are also systematically measured and analyzed.

METHODS AND MATERIALS

Experimental sites and materials

A field trial was conducted between 2022 and 2023 at Jiansanjiang Qixing Farm (132°71′E, 47°28′N), Company 36, Jiamusi City, Heilongjiang Province, China. The annual average temperature in the area is 4.7 ℃, and the annual average precipitation is 567.3 millimeters, mainly concentrated in June, July, and August, accounting for 75% of the annual precipitation. The frost free period is about 120-140 days throughout the year.

The region has good agricultural conditions and is one of the important commodity grain bases in China (*Tang et al., 2022*). During the experiment, the rice varieties of Paddy Hualiang, Jilin Changbai Mountain Rice, and Heilongjiang Wuchang Rice were used. An aerial view of the experimental field is shown in Figure 1.

Fig. 1 – Bird's eye view of the test field

Compound fertilizer (slow-release fertilizer designed for rice) produced by Sinochem Fertilizer Co. Ltd. was selected as the base fertilizer. This fertilizer's composition of nitrogen, phosphorus, and potassium was 18:12:15., and the total nutrient content was not less than 45%. In addition, urea produced by Boda Field Fertilizer Co. Ltd. was used with a nitrogen content of not less than 46.4% (*Zhang et al., 2022*).

Experimental design

Six treatment groups were used in the setup of the experiment. Three replicated trials were implemented for each treatment group. The area of each trial was 150 square meters. These six treatment groups included: G1 i.e. no fertilization of crop as blank control group. G2 was fertilized manually. G3 was fertilized by MSDF with the same amount of fertilizer as G2 group. G4, G5 and G6 were all fertilized by MSDF, but the amount of fertilizer applied was reduced by 10%, 20% and 30% compared to G2 and G3, respectively. The experimental treatment scheme is shown in Table 1.

Table 1

Test treatment scheme

Group	Base fertilizer application method	Amount of base fertilizer applied	Urea Fertilization Methods	Amount of urea fertilizer applied
G1	/	0	/	0
G2	Artificial fertilization	700 kg/hm^2	Artificial fertilization	70 kg/hm^2
G3	Mechanical side deep fertilization	700 kg/hm^2	Artificial fertilization	70 kg/hm^2
G4	Mechanical side deep fertilization	630 kg/hm^2	Artificial fertilization	70 kg/hm^2
G5	Mechanical side deep fertilization	560 kg/hm^2	Artificial fertilization	70 kg/hm^2
G6	Mechanical side deep fertilization	490 kg/hm^2	Artificial fertilization	70 kg/hm^2

Measurements and calculations

Rice plant height and stem tiller formation were measured during the experiment. The rice plant height was measured by timed measurement method using a tape measure during the rice growth process. Using the counting approach, the stem tillers was determined (*Dumitru et al., 2024*). Leaf area index (LAI), an important parameter for measuring plant growth, was measured using the HM-G30 LAI meter (*Ren et al., 2023*). The effect of fertilization techniques on leaf growth of rice was analyzed by measuring the LAI at different growth stages of rice. The chlorophyll concentration was measured using the soil and plant analyzer development (SPAD) value, which is a measure of how well plants are able to absorb nutrients.

The study was conducted using a handheld SPAD meter for measurement. Rice leaves were randomly sampled at different periods of rice growth. The chlorophyll content was determined using the SPAD meter, which in turn analyzed the effect of fertilization techniques on nutrient uptake in rice (*Gu et al., 2024*).

Dry material accumulation was determined using the harvest method for rice dry material. Rice was harvested at different periods of time. After 0.5 hours of withering at 105 ℃, dry at 80 ℃ until the weight remains unchanged. The dry material was weighed after cooling. Rice growth rate was an important index for evaluating the growth status of rice, and the study was carried out using a rice growth rate meter. To assess the plant's nutrient uptake status, nutrient accumulation dynamics were crucial indications. The experiment employed the extraction method to ascertain the rice nutrients. At various periods of rice growth, rice was harvested and the straw was extracted to determine the content of total nitrogen, phosphate, potassium ions and other nutrients (*Wang et al., 2022*). Yield and its constituent factors were the important indexes for evaluating the efficiency of rice production. Rice was harvested at the maturity stage. Moisture content was determined using grain moisture meter. Paddy was dried using air drying method (*Găgeanu et al., 2024*). Then it was weighed to obtain the rice yield.

The formula for calculating nutrient accumulation is shown in equation (1).

$$A = \eta \cdot m \tag{1}$$

In equation (1), nutrient accumulation is A. Nutrient content is η. dry material mass is m. Rice biomass is calculated as shown in equation (2).

$$B = m_s \cdot \rho \tag{2}$$

In equation (2), the rice biomass is B. The dry weight of the stem is m_S. The rice planting density is ρ. The growth rate is calculated as shown in equation (3).

$$C = \frac{B_t - B_{t-1}}{T} \tag{3}$$

In equation (3), the growth rate is C. The t th biomass is B_t. The $(t\text{-}1)$-th biomass is B_{t-1}. The time interval is T. The study was conducted using an ammonia detector. The paddy fields were sampled at different periods of rice growth. Ammonia volatilization was determined using ammonia detector and thus the effect of fertilization techniques on the ecology of paddy field was analyzed (*Lin et al., 2022*). Nutrient runoff loss from paddy fields was an important indicator for evaluating nutrient loss from paddy fields, and was measured using the drainage collection method. During the growth of rice, the paddy field was drained. To examine the impact of fertilization methods on nutrient loss from paddy fields, drainage water was gathered and measured (*Jat et al., 2022*).

Equation (4) illustrates how the ammonia volatilization flux from the paddy field was determined.

$$E = \frac{M}{100 \cdot S \cdot d} \tag{4}$$

In equation (4), the ammonia volatilization flux is E. The measured ammonium nitrogen content is M. The cross-sectional area of the device is S. The continuous measurement time is d. The nutrient balance equation is shown in Eq. (5).

$$F = f_{in} - f_{out} \tag{5}$$

In equation (5), the nutrient in dynamic equilibrium is F. The output nutrient is f_{in}. The output nutrient is f_{out}. The output nutrient is calculated as shown in equation (6).

$$f_{out} = l_1 + l_2 + l_3 \tag{6}$$

In equation (6), nutrients removed by crops are l_1. Nutrients lost by ammonia volatilization are l_2. Nutrients lost by runoff are l_3.

Data processing methods

SPSS 26.0 software was used to process the experimental data. In the process of data processing, the data were first cleaned and organized, and outliers and missing data were eliminated. Then, descriptive statistics were applied to analyze the data, and statistical quantities such as mean, standard deviation, and correlation coefficient between groups were calculated (*Chinthamu and Karukuri, 2023*).

RESULTS

Rice growth and nutrient uptake

Figure 2 compares the quantity of rice tillers with plant height. Figure 2(a) displays the comparison of the number of tillers in rice at the peak tillering stage. In the control group, the number of tillers was 311×104/hm^2 in G1, 502×104/hm^2 in G2, and 566×104/hm^2 in G3. Compared with G1, the number of tillers increased by 61.4% in G2 and 80.4% in G3. Under MSDF, the number of tillers decreased in tandem with the amount of fertilizer applied. The number of tillers in G4 was 532×104/hm^2, which was 6.1% less compared to G3. The number of tillers in G5 was 501×104/hm^2, which was 11.5% less compared to G3. The number of tillers in G6 was 489 × 104/hm^2, which decreased by 13.6% compared to G3. Figure 2(b) shows the comparison of rice plant height in each period. At the tillering stage, the plant heights of G1, G2, G3, G4, G5, and G6 were 44.6 cm, 56.1 cm, 56.9 cm, 56.1 cm, 56.0 cm, and 55.3 cm, respectively. At the nodulation stage, the plant heights of G1, G2, G3, G4, G5, and G6 were 84.1 cm, 99.1 cm, 106.9 cm, 98.3 cm, 95.4 cm, and 92.1 cm. At the spike stage, the plant heights of G1, G2, G3, G4, G5, and G6 were 104.1 cm, 116.2 cm, 129.3 cm, 120.2 cm, 115.1 cm, and 113.2 cm, respectively. At the spike stage, the plant heights of G1, G2, G3, G4, G5, and G6 were 126.1 cm, 149.6 cm, 158.3 cm, 153.3 cm, 143.8 cm, and 140.3 cm. The findings indicated that, in comparison to the manual fertilization method and the blank control group, MSDF could greatly increase the number of stem tillers and plant height of rice.

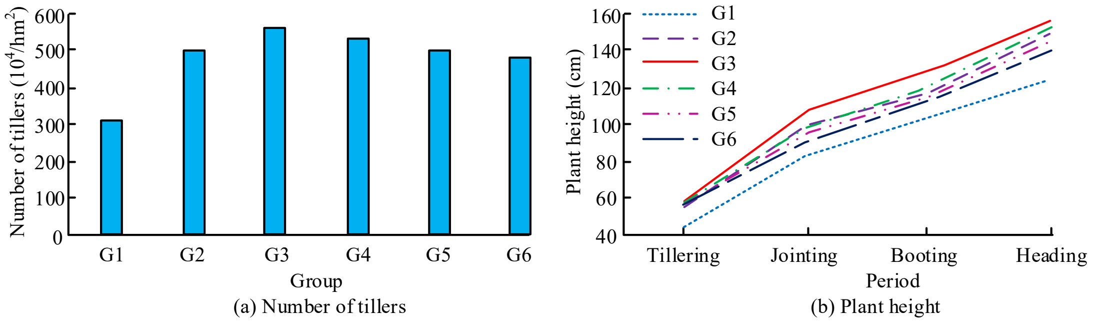

Fig. 2 - Rice contrast between tiller number and plant height

The variation of LAI in rice is shown in Figure 3. In the figure, 0-6 categorized rice growth into seven periods. 0 indicated the seedling stage, 1 indicated the tillering stage, 2 indicated the nodulation stage, 3 indicated the gestation stage, 4 indicated the tasseling stage, 5 indicated the milky ripening stage, and 6 indicated the maturity stage.

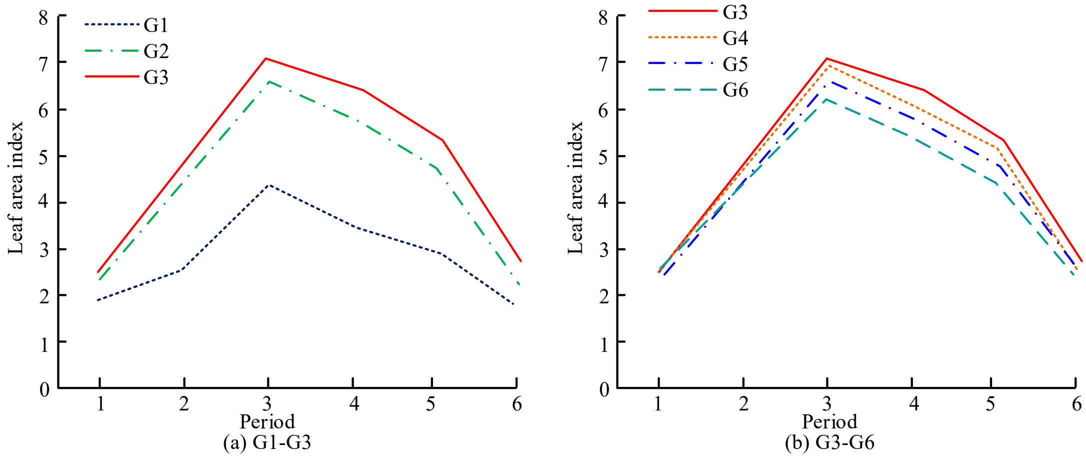

Fig. 3 - Leaf area index change in rice

Rice's LAI had an increasing and subsequently falling trend as it grew. The maximum value of rice LAI appeared at the pregnant spike stage. The rice leaf area indices of G1, G2, G3, G4, G5, and G6 were 4.51 cm, 6.62 cm, 7.19 cm, 6.88 cm, 6.19 cm, and 6.01 cm, respectively. Compared to G1, the rice leaf area indices of G2 at the pregnant spike stage increased by 2.11, and those of G3 increased by 2.68. At tillering and maturity stages, there was little difference in rice LAI between the groups. Compared with G1, the rice LAI increased by 1.81 for G2 at the nodulation stage and 2.23 for G3.

Compared with G1, the rice LAI increased by 2.39 for G2 at the tasseling stage and 3.12 for G3. The results indicated that the rice LAI varied with growth stages. During the gestation period, the rice LAI achieved its maximum value, and when the rice reached the growth stage, it steadily dropped. Additionally, rice LAI was impacted by the fertilization technique. Under MSDF, the rice LAI gradually decreased with the decrease of fertilizer application.

Figure 4 depicts the changes in SPAD in rice leaves. Figure 4(a) shows the comparison of G1, G2 and G3 groups. Figure 4(b) shows the comparison of G3, G4, G5 and G6 groups. With the growth of rice, SPAD showed an increase and then a decrease. The spike stage was when the value peaked, and the maturity stage was when the value decreased. At the gestation stage, the SPAD of rice leaves of G1, G2, G3, G4, G5, and G6 were 37.1, 40.9, 44.1, 43.3, 40.9, and 40.1, respectively. The outcomes indicated that MSDF could raise photosynthetic capability and chlorophyll content, which led to the development of high yield and high quality. However, reducing the fertilization amount would result in lower chlorophyll content, which might affect yield stabilization.

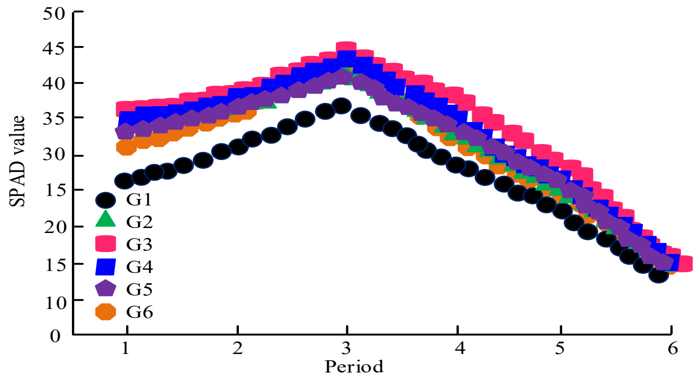

Fig. 4 - The SPAD changes in rice leaves

Figure 5 illustrates how the amount of dry particles that accumulated in rice fluctuated. As rice grew, the accumulation of dry material grew progressively and reached its maximum value at the maturity stage. The accumulation of dry material at the seedling stage was close to 0 in all groups. The accumulation of dry material at the tillering stage did not differ significantly in all groups. When entering the nodulation stage, the differences in the accumulation of dry material in rice became more obvious. At the nodulation stage, the accumulation of dry material in rice was 0.63 t/hm^2, 2.49 t/hm^2, 2.51 t/hm^2, 2.50 t/hm^2, 2.48 t/hm^2, 2.39 t/hm^2 in G1, G2, G3, G4, G5, and G6, respectively. At the maturity stage, the accumulation of dry material in rice in G1, G2, G3, G4, G5, and G6 were 5.58 t/hm^2, 9.93 t/hm^2, 11.72 t/hm^2, 10.97 t/hm^2, 10.29 t/hm^2, and 9.11 t/hm^2, respectively. The results showed that compared with the control group, all fertilizer treatments significantly increased the accumulation of aboveground dry material in rice. However, the decrease in the amount of MSDF resulted in lower dry material accumulation.

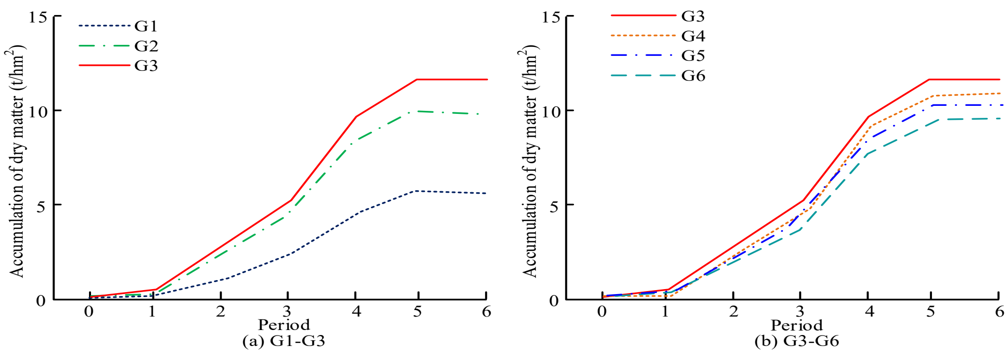

Fig. 5 - Accumulated change of dry material in rice

Rice growth rate comparisons are shown in Figure 6. Figure 6(a) shows the stem growth rate comparison. The maximum growth rate occurred from the tillering stage to the tasseling stage, and the growth rates of G1, G2, and G3 were 143.1 kg/hm^2/d, 249.6 kg/hm^2/d, and 271.3 kg/hm^2/d, respectively. Figure 6(b) shows the comparison of the growth rates of leaves. The maximum growth rate occurred from tillering stage to nodulation stage.

The growth rates of G1, G2, and G3 were 66.2kg/hm²/d, 159.7kg/hm²/d, and 183.2kg/hm²/d, respectively. Figure 6(c) shows the comparison of spike growth rates. The maximum growth rate occurred at the tasseling to milk maturity stage. The growth rates of G1, G2, and G3 were 99.3 kg/hm²/d, 154.9 kg/hm²/d, and 181.3 kg/hm²/d, respectively. The outcomes revealed that fertilizer application could promote the growth rates of rice stems, leaves, and spikes. Stem, leaf and spike growth rates increased significantly after MSDF treatment compared to manual fertilization treatment.

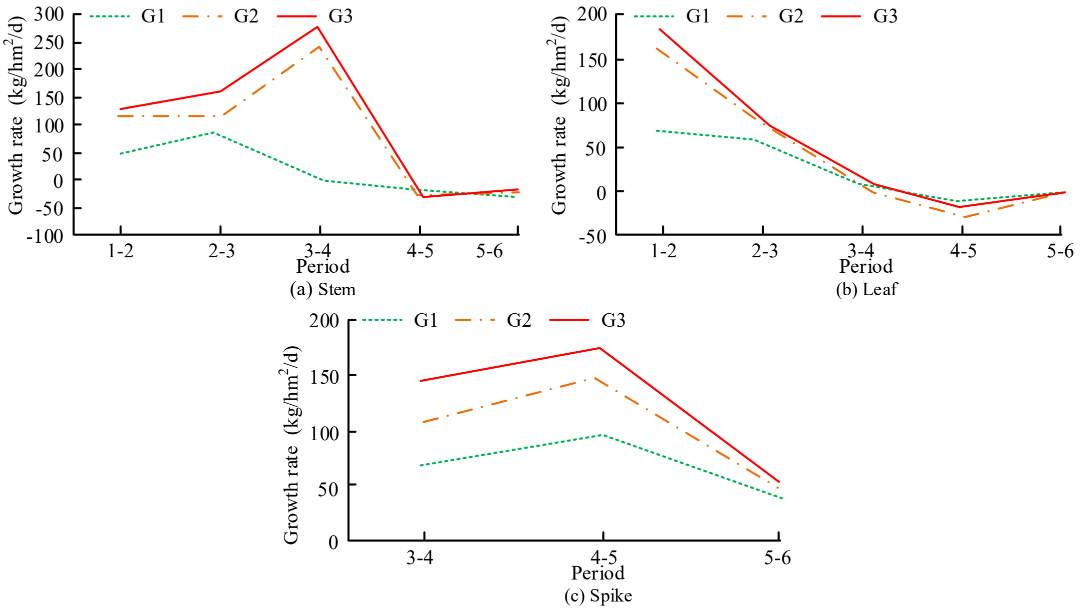

Fig. 6 - Comparison of rice growth rates

Figure 7 illustrates how the nutritious content of rice has changed.

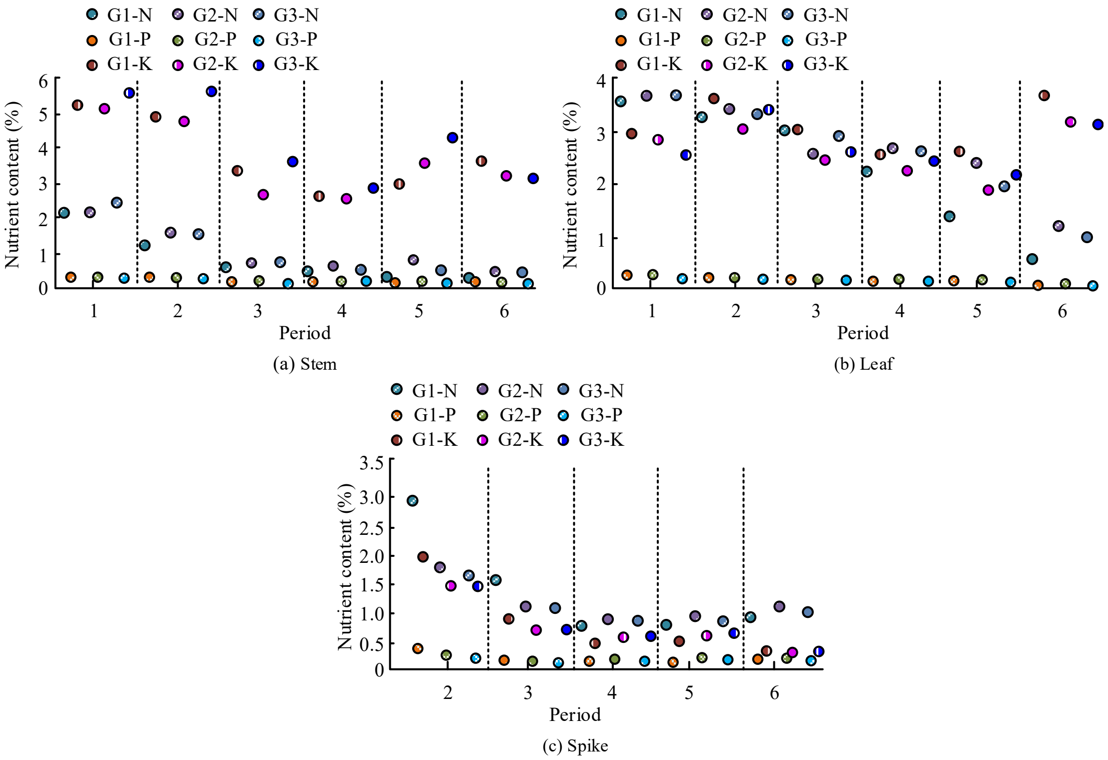

Fig. 7 - Changes in nutrient content in rice

Figure 7(a) displays the changes in nutrient content of stems in each period. Nitrogen, phosphorus and potassium contents in stems gradually decreased during rice growth. At the tillering stage, the nitrogen contents of G1, G2 and G3 were 2.08%, 2.19% and 2.51%, respectively.

At the tillering stage, the phosphorus contents of G1, G2, and G3 were 0.29%, 0.30%, and 0.28%, respectively, and their potassium contents were all around 5.5%. At the nodulation stage, the nitrogen contents of G1, G2 and G3 were 1.31%, 1.58% and 1.51%, respectively. The phosphorus content was all around 0.24%. Potassium content was 4.89, 4.91 and 5.53%, respectively. The G3 group outperformed the G2 group in promoting nitrogen uptake and utilization in the pre-emergent stems of rice at the same rate of fertilizer treatment. Figure 7(b) shows the variation of nutrient content of leaves in each period. Nitrogen content was greatest at the tillering stage, with 3.58%, 3.61% and 3.65% in G1, G2 and G3, respectively. Relative to manual fertilization treatments, MSDF resulted in an increase in rice leaf nitrogen content from at tillering to spike stage. However, its N content showed a decreasing trend in the remaining periods. Meanwhile, the phosphorus content of rice with MSDF decreased at all fertility stages, while the nitrogen content at the spike stage and potassium content at the tasseling and milking stages increased.

Figure 7(c) shows the variation of nutrient content in rice spike, which had reduced spike nitrogen content in G3 compared to G2. Meanwhile, phosphorus content decreased by 0.02% and 0.05% at the spike stage and maturity stage, respectively. However, potassium content increased by 0.02% and 0.05% at tasseling and milk maturity stages, respectively. The findings demonstrated that during the rice growth stage, fertilization treatments had a substantial impact on the nutritional levels of the stem, leaf, and spike. When compared to the manual fertilization treatment, the MSDF treatment greatly raised the N content of the stems and leaves of rice during the tillering and spike stage. However, its nitrogen, phosphorus and potassium contents were reduced at other growth stages.

Figure 8 depicts the buildup of nutrients in rice. Figure 8(a) displays the nutrient accumulation of stems, and nitrogen accumulation reached its maximum value at the tasseling stage. Compared to G2, the nitrogen accumulation in G3 increased by about 3.25 kg/hm2. Similarly, phosphorus accumulation reached its maximum value at the tasseling stage, and the phosphorus accumulation in G2 and G3 was almost the same. Compared to G1, phosphorus accumulation in G3 increased by 5.13 kg/hm^2. Potassium accumulation reached its maximum value at the milky stage. Compared with G1 and G2, potassium accumulation in G3 increased by 48.11 kg/hm^2 and 36.32 kg/hm^2, respectively.

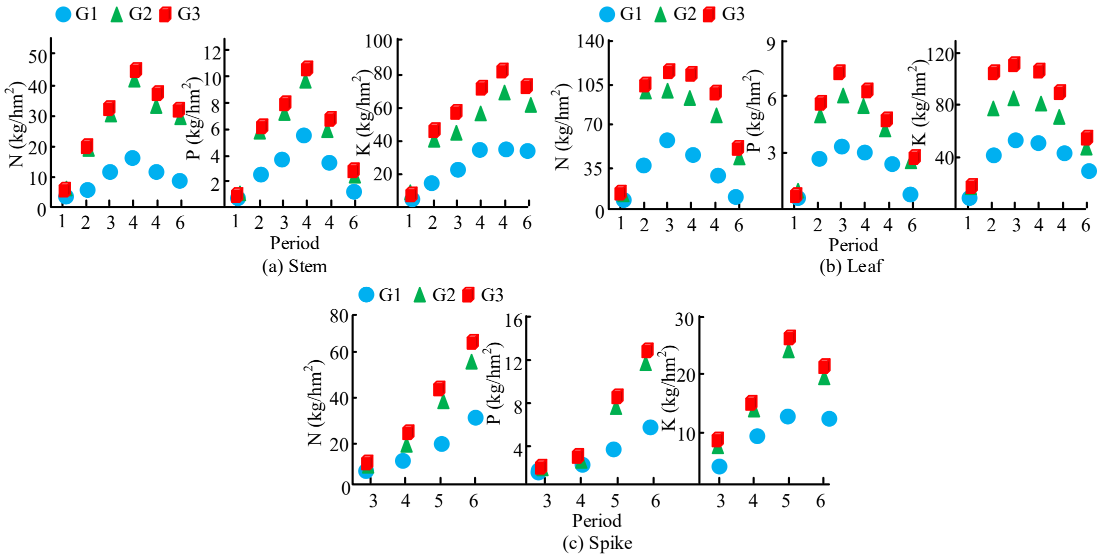

Fig. 8 - Nutrient accumulation in rice

Figure 8(b) shows the nutrient accumulation in leaves. Nitrogen accumulation reached its maximum at the nodulation stage, while phosphorus and potassium accumulation reached their maximum at the spike stage. At the nodulation stage, the nitrogen accumulation of G3 was 119.31 kg/hm^2, which was elevated by 9.37 kg/hm^2 and 59.52 kg/hm^2 compared with G1 and G2, respectively. At the spikelet stage, the phosphorus accumulation of G2 and G3 was basically the same, which was 7.41 kg/hm^2. At panicle initiation stage, potassium accumulation of G3 was 109.67 kg/hm^2, which was elevated by 56.56 kg/hm^2 and 20.83 kg/hm^2 compared to G1 and G2. Figure 8(c) shows the nutrient accumulation of spikes. Nitrogen and phosphorus accumulation both reached their maximum values at maturity, while potassium accumulation reached its maximum value at milk maturity. At the same fertilizer application rate, nitrogen, phosphorus and potassium accumulation of rice spikes increased in MSDF compared to manual fertilization, with an increase ranging from 10% to 19%.

Nutrient loss from paddy fields

Figure 9 displays the ammonia volatilization data from the paddy field. The ammonia volatilization flux from the paddy field is displayed in Figure 9(a). The ammonia volatilization flux of G1 was basically maintained around 0 due to the lack of fertilizer application. The ammonia volatilization flux of G2 reached the maximum value of 5.27 kg·N/hm^2/d around day 5, and the ammonia volatilization flux of G3 reached the maximum value of 1.42 kg·N/hm^2/d around day 8. Compared with G2, the ammonia volatilization flux of G3 decreased by 3.85 kg·N/hm^2/d, which was 73.1%. Comparison of different fertilization treatments showed that MSDF was able to reduce ammonia volatilization loss, delay the peak appearance time, and reduce nitrogen loss. It showed its advantages in reducing ammonia volatilization loss in paddy system. Figure 9(b) shows the ammonia volatilization accumulation. The ammonia volatilization accumulation of G1, G2, and G3 were 2.01 kg·N/hm^2, 16.89 kg·N/hm^2, and 9.93 kg·N/hm^2, respectively. The results showed that the ammonia volatilization cumulative loss of G2 was the largest, followed by G3, and the smallest in G1 treatment. At the same N application rate, the artificial fertilizer spreading treatment had a substantially higher cumulative ammonia volatilization loss than the MSDF treatment. This suggested that the MSDF treatment had a higher effect on nitrogen retention, which could lower nitrogen loss and increase the rate at which NF is used, hence lessening the environmental impact.

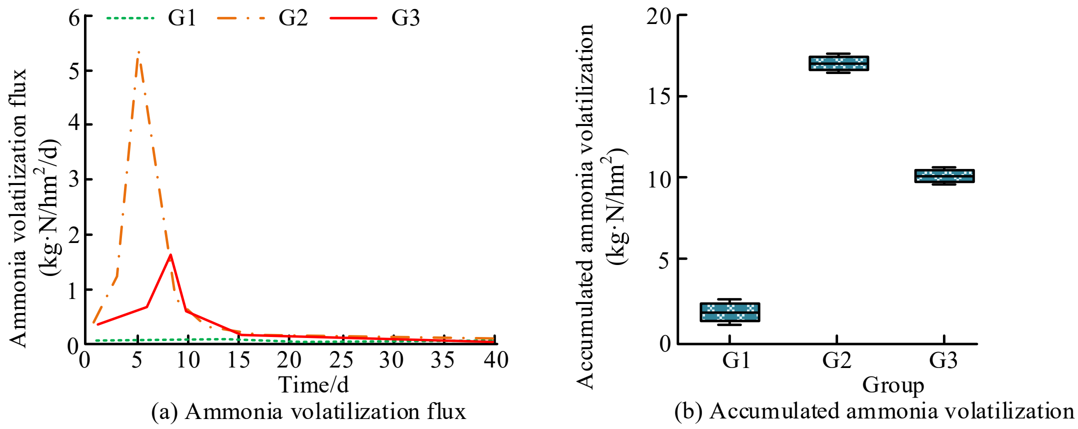

Fig. 9 - Results of ammonia volatilization flux in paddy fields

Figure 10 illustrates the change in the amount of nutrients in the stem flow water of a paddy field.

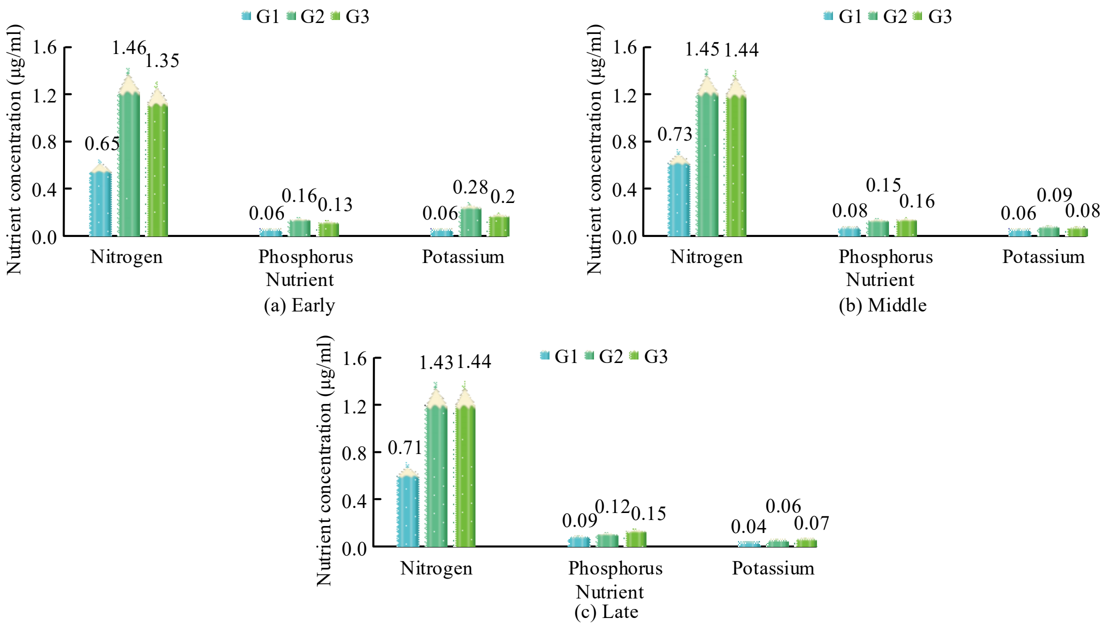

Fig. 10 - Changes in nutrient content of paddy field stem flowing water

Figure 10(a) displays the early drainage sampling. The nitrogen content of G1, G2, and G3 was 0.65, 1.46, and 1.35 μg/ml. The phosphorus content of G1, G2, and G3 was 0.06, 0.16, and 0.13 μg/ml. The potassium content of G1, G2, and G3 was 0.06, 0.28, and 0.20 μ g/ml. Figure 10(b) shows the mid-term drainage sampling.

The nitrogen content of G1, G2, and G3 was 0.73, 1.45, and 1.44 μg/ml, respectively. The phosphorus content of G1, G2, and G3 was 0.08, 0.15, and 0.16 μg/ml, respectively. The potassium content of G1, G2, and G3 was 0.06 μg/ml, 0.09 μg/ml, and 0.08 μ g/ml. Figure 10(c) shows the late drainage sampling. The nitrogen content of G1, G2, and G3 was 0.71, 1.43, and 1.44 μg/ml. The phosphorus content of G1, G2, and G3 was 0.09, 0.12, and 0.15 μg/ml, respectively. The potassium content of G1, G2, and G3 was 0.04, 0.06, and 0.07 μ g/ml.

Figure 11 illustrates the total amount of nutrient stem loss in paddy fields. Figure 11 (a) shows the cumulative loss of nitrogen, which was 1.79 kg/hm^2, 4.23 kg/hm^2, and 4.01 kg/hm^2 for G1, G2, and G3, respectively. Figure 11 (b) shows the cumulative loss of phosphorus, which was 0.18 kg/hm^2, 0.51 kg/hm^2, and 0.47 kg/hm^2 for G1, G2, and G3, respectively. Figure 11(c) shows the cumulative loss of potassium, which was 0.19 kg/hm^2, 0.59 kg/hm^2, and 0.41 kg/hm^2 for G1, G2, and G3, respectively. The findings demonstrated that nitrogen, phosphate, and potash losses in paddy fields were more likely to occur when fertilizer was applied, but the cumulative losses of these components in runoff water were effectively reduced by weight loss treatments. At the same fertilizer application rate, the cumulative loss in runoff from paddy field was reduced by MSDF treatment compared to manual fertilization.

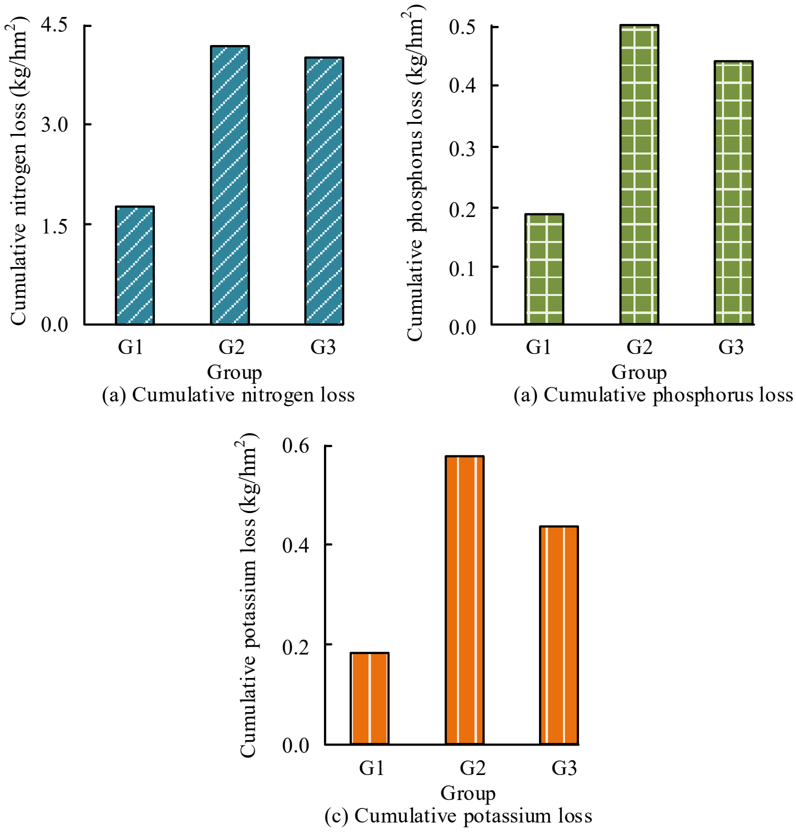

Fig. 11 - Accumulation of nutrient stem loss in paddy fields

CONCLUSIONS AND DISCUSSIONS

The study was conducted in a trial at Jiansanjiang Qixing Farm, Company 36, Jiamusi City, Heilongjiang Province. Nutrient changes in rice and fields were analyzed in combination with different fertilizer application methods and application rates. The outcomes indicated that the number of tillers was 311×104/hm^2 in G1, 502×104/hm^2 in G2, and 566×104/hm^2 in G3. Compared to G1, the rice LAI was improved by 2.39 in G2 and 3.12 for G3 at the tasseling stage. At the tasseling stage, the SPAD of rice leaves was 37.1, 40.9, 44.1, 43.3, 40.9, 40.1 for G1, G2, G3, G4, G5, and G6, respectively. At the maturity stage, G1, G2, G3, G4, and G5, G6 were 5.58 t/hm^2, 9.93 t/hm^2, 11.72 t/hm^2, 10.97 t/hm^2, 10.29 t/hm^2, and 9.11 t/hm^2, respectively. The cumulative loss of nitrogen in the paddy field of G1, G2, and G3 was 1.79 kg/hm^2, 4.23 kg/hm^2, and 4.01 kg/hm^2, respectively. Studies indicated that MSDF could significantly increase the number of stem tillers and plant height, increase the LAI, improve the chlorophyll content and photosynthetic capacity of rice, and create conditions for high yield and high quality. The MSDF treatment could effectively promote rice growth and improve nutrient absorption efficiency.

Compared with manual fertilization, MSDF significantly increased the nitrogen content of stems and leaves, and decreased the phosphorus and potassium content. It was found that the use of MSDF in paddy fields can effectively reduce ammonia volatilization and nutrient runoff losses. This can improve nitrogen utilization efficiency, which is important for environmental protection and sustainable agricultural development. Nevertheless, the study still had certain flaws and neglected to take into account how different rice cultivars affect nutrient uptake and loss. To improve fertilization methods, future research might examine how various rice cultivars and phases of growth affect nutrient uptake and loss.

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