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EFFECTS OF PLASTIC MULCHING AND STRAW INCORPORATION ON RICE YIELD AND NITROGEN USE EFFICIENCY IN A COLD REGION

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KEYWORDS

paddy soil nutrients, net photosynthetic rate, dry matter production, crop growth rate, nitrogen use efficiency.

ABSTRACT

For the synergistic improvement of soil fertility and rice yields in a cold region, we investigated the effects of plastic mulching with different straw incorporation rates on the rice yield and nitrogen use efficiency in a rice growing area of a cold region. The field experiment was conducted using the Jijing 88 rice cultivar, and set up four straw incorporated treatment: 20% (S1), 40% (S2), 60% (S3) and 100% (S4) under two conditions: mulching (M) and without mulching (NM). The results showed that under the same straw incorporation rates: (1) Plastic mulching increased the total soil nitrogen and organic matter contents while improving the grain yield; the yield increases were 2.8–14.9% in 2016 and 1.4–12.3% in 2017. (2) The mulched treatment improved the net photosynthetic rate, the maximum tiller number, the crop growth rate of the later growth stages, and the shoot dry weight. (3) The recovery efficiency, agronomic efficiency, and partial factor productivity of the nitrogen applications were all higher under the mulched treatment than under the non-mulched treatment. In a comparison of the different straw incorporation treatments, above three indicators consistently increased before they decreased, and significantly higher levels were reached under the 40% straw incorporation treatment with mulching than under the other treatments.

INTRODUCTION

Rice is one of the major grain crops, serving as a staple food for more than 50% of the global population. Therefore, it has always been the primary task of rice breeders and farmers to improve rice yields. In the face of a larger population and less land with scarce resources, it is particularly important to exploit the yield potential of existing rice cultivars through cultivation management practices. The massive application of chemical fertilizers has long been an important practice for ensuring high and stable rice yields, the amount of nitrogen fertilizer is no longer a limiting factor in rice yield. However, these applications have resulted in problems, such as a decline in paddy soil fertility, a stagnation in rice yields, the lowering of the fertilizer use efficiency, and the constantly increasing pollution of agricultural resources, which have become increasingly prominent. Hence, making synergistic improvements to soil fertility and rice yields is currently an urgent problem to address in rice production.

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To date, straw incorporation has been actively promoted owing to its advantages such as effects related to nutrition, soil improvement, and the farmland ecological environment (Akhtar et al., 2020; Chen et al., 2021; Dossou-Yovo et al., 2016b; Huo et al., 2017; Wang et al., 2019). Straw incorporation can improve soil fertility, increase the soil organic matter content, and modify the soil structure; this practice can also promote crop root development as well as improve the crop yield (Akhtar et al., 2018; Li et al., 2016; Ma et al., 2021) and resource use efficiency (Hu et al., 2020; Qu et al., 2020; Totin et al., 2013; Yang et al., 2020), and it also reduces the environmental pollution caused by burning or stacking straw (Jiang et al., 2014). However, in the rice growing area of the cold region, the decomposition of the applied straw is slow as limited by a low temperature, which limits the promotion and application of the straw incorporation technique.

The plastic mulching cultivation system used on rice has been shown to increase the soil temperature (Liu et al., 2013; Tao et al., 2015). In the rice growing area of the cold region, the plastic mulching cultivation system compensates for the shortcomings associated with a severe shortage of light and heat, attenuating low-temperature limitations during the early growth stages of rice. Its warming effect is most prominent from transplantation to the maximum tillering stage of rice, which considerably increases the rice grain yield (Zhang et al., 2020; Zhang et al., 2017b). However, in the plastic mulching cultivation system, higher soil temperatures promote the mineralization of soil organic matter (Fang et al., 2005) and may thus lead to a decrease in the soil organic matter stocks, further causing soil fertility declines in the long run (Fan et al., 2012; Ma et al., 2018; Pan et al., 2004; Steinmetz et al., 2016; Wang et al., 2020).

Straw incorporation and plastic mulching each have specific advantages and disadvantages. Combining these two practices can help achieve the goals of increasing the yields and efficiency of crops (Fang et al., 2021), such as sunflowers (Zhao et al., 2016). However, the effects of this combination on rice production in cold regions have not been reported. To this end, a field experiment was conducted using the Jijing 88 rice cultivar at the experimental field of Jilin Agricultural University. A combination of straw incorporation and plastic mulching was applied to investigate the effects on dry matter accumulation, photosynthesis, yields, and nitrogen use efficiency in rice. This study provides useful data for the high-yield, high-efficiency cultivation of rice and the rational utilization of straw resources in the rice growing area of the cold region.

MATERIAL AND METHODS

Description of Research Site

Field experiments were conducted at Jilin Agricultural University (43°05′ N, 125°38′ E), Changchun City, Jilin Province, China, during the 2016 and 2017 growing seasons. The average annual rainfall is 522 and 615 mm. The mean annual temperature is 6.2 °C, with the average frost-free period 138 days. The values of organic matter, total nitrogen and pH of topsoil were 3.92 g kg^{-1}, 0.3 g kg^{-1} and 6.73, respectively.

Experimental Design

The experimental cultivar was Jijing 88. The experiment was laid out in a randomized complete block design. Two cultivation patterns, mulching (M) and non-mulching (NM), were assigned to main plots. Four straw incorporation rates, 20% (S1), 40% (S2), 60% (S3), and 100% (S4) of the total incorporation rate (the total rate was calculated from the grain-straw ratio of Jijing 88, which was 8000 kg ha^{-1}) were kept in subplots. A total of eight treatments were included, with three replications per treatment. To determine the nitrogen use efficiency of the rice, a no-nitrogen control group was included. The plot areas were 15 m^2 each. The plots were isolated by ridge construction, and a thin plastic film was buried in the topsoil to prevent the lateral infiltration of nutrients and water between plots. After the stubble was removed from the experimental field, the rice straw was cut into 5–7 cm lengths, evenly applied to the plot, and manually mixed with the topsoil. The mulched area was covered with plastic mulch while making borders and furrows. The mulch was a black, single-layer, simple, and ultra-degradable film. The furrow between the borders was 20 cm deep and 15 cm wide. Mulching was conducted on the ground that had been leveled between the borders. The mulch and the soil were kept in close contact, leaving no gaps.

The cultivation pattern is the traditional transplanting mode, after the water prepares the ground, falls the water to transplant. To ensure more accurate and effective transplanting, a special puncher was used to punch holes in the mulch before the transplanting. The row spacing was 30 cm, the plant spacing was 16.5 cm, and three basic seedlings were transplanted into each hill. In the non-mulching system, the irrigation management was continuously flooded. Except drainage at the mid-season, the continuously flooded regime maintained a continuous flood with 2–3 cm water depth until one week before the final harvest. The soil water content was maintained at saturation in the mulched system within a week of transplanting. A week later, the soil water content was kept at approximately 80–90% of the maximum field capacity. For the mulched treatment, water was kept in the furrow, with no water on the ground surface. Fertilizers were applied to all the plots at rates of 220 kg ha^{-1} N, 50 kg ha^{-1} P_2O_5, and 75 kg ha^{-1} K_2O. For the no-nitrogen group, the application of phosphate and potassium fertilizers was consistent with that applied to other plots. No top dressing was conducted following the single-dose application of all the fertilizers. The remaining management methods were performed in accordance with conventional field management methods.

Determination and Methods

Soil temperature. After transplanting to the maximum tilling stage of rice, the temperatures of 5 , 10 , 15 and 20 cm depth soil were recorded at 8：00, 11：00, 14：00, 17：00 and 20：00, respectively, using ZDR-41 temperature recorder.

Soil total nitrogen and organic matter contents. At the rice maturity stage, soil samples were taken from a depth of 0–20 cm and used to determine the total soil nitrogen and organic matter contents. After collection, soil samples were immediately air-dried, passed through a 1-mm sieve for later analysis. The total soil nitrogen content was determined by the Kjeldahl method, and soil organic matter by the procedure of Bremner and Jenkinson (K. SHAW.,1959). All analyses were duplicated.

Tiller dynamics. The number of tillers was surveyed every 7 days from the rice reviving stage. In each plot, the tiller number was continuously counted for 10 hills until it decreased in two consecutive surveys. The maximum tiller number was recorded.

Dry matter weight and nitrogen use efficiency. Based on the mean tiller number in each plot, 10 hill representative sample plants were collected at the heading, jointing, grain filling and maturity stages. These plants were separated into leaves, stems (culm and sheath), and panicles (at the heading stage, filling stage and maturity stage). The sampled plants were deactivated at 105 °C for 30 min and then oven-dried at 70 °C for 72 h, weighed, and maturity stage sub samples were ground and treated with 0.25 mm sieveand and then taken for N determination. N content in the vegetative parts and grains was determined by micro Kjeldahl digestion, distillation and titration to calculate aboveground N uptake.

Flag leaf photosynthetic rate. The photosynthesis rate in the rice flag leaves was measured using a LI-6400XT portable photosynthetic apparatus at 10 a.m. on sunny days during the later growth stages (after full heading). Measurements were performed on 10 representative flag leaves in each plot, with three replications each.

Yield and yield component. Plants were hand-harvested on 28 September in 2016 and 3 October in 2017. Twenty plants were selected from each plot to determine yield components. Panicles per m^2, spikelets per panicle, grain filling percentage (100 × filled spikelets number/total spikelets number), 1000-grain weight and harvest index (100 × filled spikelets weight/aboveground total biomass) were calculated. Grain yield was determined from a 2-m^2 area in each plot and adjusted to the standard moisture content of 0.14 g H_2O g^{-1} fresh weight, with three replications each.

Calculations and Statistical Analysis

The crop growth rate (CGR, $gm^{-2}d^{-1}$) were calculated as the daily increase in dry matter accumulation (DrM) from panicle initiation to maturity (PI-MA). The formula were as:

$$\text{Crop growth rate (CGR)} = DrM^{t2} - DrM^{t1} / \text{day of } (t2 - t1)$$

where,

DrM^{t1} and DrM^{t2} being the crop dry weights per unit land area at the beginning and end of intervals,

t1 and t2 being corresponding days.

Nitrogen recovery efficiency (NRE) is defined as the quantity of nutrient uptake per unit of nutrient applied. It can be calculated by:

$$NRE (\%) = 100 \times (TN_{+N} - TN_{-N}) / FN$$

where,

TN_{+N} is total aboveground plant N accumulation in the plot received N fertilizer,

TN_{-N} is total aboveground plant N accumulation in the zero-N control,

FN is the amount of N fertilizer applied.

Partial factor productivity of applied N（PFP_N）is an important indicator to reflect the comprehensive effect of soil basic nutrient level and fertilizer application rate. It can be calculated by:

$$PFP_N \text{ (Grain kg kg}^{-1} \text{ N)} = GY_{+N} / FN$$

Where,

GY_{+N} is grain yield in the plot received N fertilizer,

FN is the amount of N fertilizer applied.

Nitrogen agronomic efficiency (AE_N): The agronomic efficiency is defined as the economic production obtained per unit of N applied. It can be calculated by:

$$AE_N \text{ (mg mg}^{-1}) = Gf–Gu / Na$$

Where,

Gf is the grain yield of the fertilized plot (mg),

Gu is the grain yield of the unfertilized plot (mg), and

Na is the quantity of N applied (mg).

Statistical Analyses

Data were analyzed following analysis of variance SPSS 16.0 and means were compared based on the least significant difference (LSD) test at the 0.05 probability level.

RESULTS AND DISCUSSION

Soil Temperature and Nutrient Changes

After the maximum tilling stage, the effect of film warming is weakened due to the increase in plant cover density. To this end, the soil average temperatures at different depths of 8:00, 11:00, 14:00, 17:00, and 20:00 per day at the maximum tilling stage are listed in Table 1. When the rice was transplanted to the maximum tilling stage, the mulching system had a great influence on the soil temperature of 5 cm and 10 cm depth, which was 0.2 °C~1.6 °C and 0.3 °C~1.3 °C higher than the non-mulching system; and the soil temperature at the depth of 15 cm and 20 cm was less affected by the mulching film.

TABLE 1 Effect of plastic film on soil temperature in different depth in 2017. (°C)

Treatment		8:00	11:00	14:00	17:00	20:00
5cm	M	18.8	25.9	28.6	25.1	20.8
	NM	18.6	25.6	27.0	24.4	20.0
	M-NM Increment	0.2	0.3	1.6	0.7	0.8
10cm	M	17.4	20.8	21.8	20.6	19.3
	NM	17.1	19.5	21.1	20.3	18.5
	M-NM Increment	0.3	1.3	0.7	0.3	0.8
15cm	M	15.4	17.5	18.0	17.7	16.6
	NM	15.4	17.3	17.8	17.5	16.4
	N-NM Increment	0.0	0.2	0.2	0.2	0.2
20cm	M	14.6	15.2	16.0	15.8	15.1
	NM	14.5	15.0	16.0	15.7	14.9
	M-NM Increment	0.1	0.2	0.0	0.1	0.2

M: mulching, NM: non-mulching.

Under the same straw incorporation rates, the plastic mulching increased both the total soil nitrogen and the organic matter contents (Table 2). Under the mulched condition, the soil organic matter did not differ significantly between the straw incorporation treatments, whereas the soil total nitrogen content changed as follows. In 2016, 40% straw incorporation resulted in a significantly higher total soil nitrogen content than under 60% and 100% straw incorporation, while there was no significant difference compared with 20% straw incorporation. In 2017, the total soil nitrogen content under 40% straw incorporation was significantly higher than that under 20% and 100% straw incorporation, but no significant difference was found compared with the 60% straw incorporation treatment. Under the non-mulched condition, there were no significant differences in the soil total nitrogen or organic matter contents between the straw incorporation treatments in 2016 and 2017.

TABLE 2 Soil total nitrogen and organic matter contents of different treatment.

Treatment		Soil total nitrogen (g kg^{-1})		Organic matter (g kg^{-1})	
		2016	2017	2016	2017
M	S1	0.47ab	0.47b	4.35a	4.38a
	S2	0.55a	0.64a	4.48a	4.53a
	S3	0.42b	0.58a	4.41a	4.49a
	S4	0.45b	0.48b	4.33a	4.42a
NM	S1	0.41b	0.40b	3.85b	3.87b
	S2	0.41b	0.47b	3.83b	3.94b
	S3	0.41b	0.47b	3.87b	3.96b
	S4	0.44b	0.45b	4.01b	4.03b

[a]S1: 20% straw incorporation treatment, S2: 40% straw incorporation treatment, S3: 60% straw incorporation treatment, S4: 100% straw incorporation treatment.

[b]Within a column means followed by the different letters are significantly from each other at LSD (0.05).

Yield and Yield Component Factors

Both plastic mulching and straw incorporation significantly affected the yield (Table 3). Under the same rates of straw incorporation, the mulched treatment increased the grain yield by 2.8–14.9% (2016) and 1.4–12.3% (2017) compared with the non-mulched treatment. With the increasing straw incorporation rate, the yield initially increased and then decreased. Under the mulched condition, the highest yield was obtained under 40% straw incorporation treatment, at 11624 kg ha^{-1} (2016) and 11934 kg ha^{-1} (2017); these values were significantly higher than the values for the other treatments. Under the non-mulched condition, the yield resulting from the 40% straw incorporation treatment still ranked highest in both 2016 and 2017. The yield from the optimal straw incorporation treatment (40%) under the mulched condition was significantly higher than that from the optimal straw incorporation treatment (40%) under the non-mulched condition, indicating that plastic mulching combined with an appropriate rate of straw incorporation was more favorable for improving the rice yield.

With regard to the yield component factors under different treatments, straw incorporation significantly affected effective panicles per m^{-2}, spikelets per panicle, grain filling percentage, and 1000-grain weight (Table 3). Plastic mulching had no significant effects on spikelets per panicle, grain filling percentage, and 1000-grain weight; nonetheless, it significantly increased the effective panicles per m^{-2}. In 2016 and 2017, both effective panicles per m^{-2} and spikelets per panicle first increased and then decreased with the increasing straw incorporation rate, irrespective of whether mulching treatment was performed. In 2016, the effective panicles per m^{-2} under the 40% straw incorporation treatment with mulching was significantly higher than that of other treatments. In 2017, the highest effective panicles per m^{-2} was also obtained under the 40% straw incorporation treatment with mulching; this was significantly higher than the results of the 20% and 100% straw incorporation treatments with mulching but not different from the 60% straw incorporation treatment with mulching. The spikelets per panicle ranked highest under 60% straw incorporation with mulching in both 2016 and 2017, while the highest grain filling percentage was obtained using a lower straw incorporation rate (20%) during those two years.

TABLE 3. Effects of plastic mulching and straw incorporation on yield and yield components.

Treatment		Grain yield (kg ha^{-1})	Panicles (m^{-2})	Spikelets per panicle	Grain filling (%)	1000-grain weight (g)
2016						
M	S1	10302.9bc	380bc	133.4cd	95.7a	22.3bc
	S2	11624.3a	416a	148.8b	90.9b	21.4c
	S3	10615.0b	392b	163.4a	84.9c	22.1bc
	S4	7291.4d	312d	131.4cd	84.9c	23.7ab
NM	S1	9606.9c	368c	135.8c	93.6a	23.2ab
	S2	10088.3bc	388bc	146.6b	90.2b	22.2bc
	S3	9782.8bc	380bc	159.8a	84.9c	22.1bc
	S4	7067.5d	300d	127.2d	85.5c	24.0a
2017						
M	S1	10720.9bc	380bc	134.2cd	96.1a	22.3bc
	S2	11934.2a	420a	160.1b	91.6b	21.3c
	S3	11091.1b	405a	167.5a	85.3c	22.5bc
	S4	7540.5d	318d	139.7cd	85.5c	23.5ab
NM	S1	10138.8c	368c	138.4c	94.5a	23.3ab
	S2	10613.6bc	388bc	149.4b	90.9b	22.2bc
	S3	10092.8bc	380bc	171.2a	85.5c	22.3bc
	S4	7437.6d	300d	137.1c	86.2c	24.3a

Within a column in 1 year, means followed by the different letters are significantly from each other at LSD (0.05).

Maximum Tiller Number, Shoot Dry Matter Accumulation, and Growth Rate at Later Growth Stages

An analysis of variance showed that (Table 4) plastic mulching significantly affected the maximum tiller number of the rice, but no effects were observed for the shoot dry weight and growth rate during the later growth stages (the reproductive growth phase). Straw incorporation significantly affected the shoot dry weight of the heading stage and the growth rate of the reproductive growth phase.

Under the same straw incorporation rates, the maximum tiller number significantly increased in the mulching cultivation system. Under the mulched condition, the maximum tiller number first increased and then decreased with the increasing straw incorporation rate, and significant differences were observed between the different straw incorporation treatments. Under the non-mulched condition, 40% straw incorporation resulted in a significantly higher maximum tiller number than under 20, 60, and 100% straw incorporation, while no significant difference was detected between the 60 and 100% straw incorporation rates.

Under the same straw incorporation rates, the shoot dry weight of the heading stage, filling stage, and maturity stages increased in the mulching cultivation system. In particular, the shoot dry weight under the 40% straw incorporation treatment with mulching was significantly higher than that of other treatments. Regardless of whether mulching was performed or not, the 100% straw incorporation rate was not conducive to shoot dry matter accumulation. Under both mulched and non-mulched conditions, the highest dry weight was always obtained under 40% and 60% straw incorporation treatments, respectively. The dry weight of the maturity stage under the optimal straw incorporation treatment with mulching (40%) was significantly higher than the optimal straw incorporation treatment without mulching (60%).

During the later growth stages (jointing-maturity), a higher growth rate was obtained in the mulching cultivation system compared with the non-mulching system under the same rates of straw incorporation. Under the mulched condition, the growth rate of rice first increased and then decreased with the increasing straw incorporation rate, and significant differences were found between the different straw incorporation treatments. Under the non-mulched condition, 100% straw incorporation resulted in a significantly lower growth rate compared with 20, 40, and 60% straw incorporation, while no significant differences were found between the latter three treatments.

TABLE 4. Effects of plastic mulching and straw incorporation on maximum tiller number, aboveground dry matter weight and growth rate of late reproductive period.

Treatment		Maximum tiller number (m^{-2})	Dry matter weight ($g\ m^{-2}$)			Growth rate ($g\ m^{-2}\ d$)
			heading stage	filling stage	maturity	
2016						
M	S1	620c	1042.7d	1217.0cd	2301.1bc	25.8c
	S2	660b	1403.0a	1805.1a	2976.8a	32.7a
	S3	680a	1251.2b	1370.5b	2481.4b	27.8b
	S4	540e	672.7e	954.6e	1635.3d	18.4d
NM	S1	610d	953.7d	1138.4d	2244.1c	24.3c
	S2	620c	1030.5d	1265.2bc	2196.0c	22.9c
	S3	540ef	1119.1c	1231.8cd	2283.8bc	23.6c
	S4	520f	589.0f	846.8e	1399.3d	15.8e
2017						
M	S1	620c	1030.2d	1232.6cd	2371.0bc	26.2c
	S2	667b	1409.0a	1880.4a	3006.2a	32.7a
	S3	686a	1287.6b	1402.0b	2601.4b	29.5b
	S4	545e	674.7e	989.6e	1720.3d	19.5d
NM	S1	610d	947.1d	1144.2d	2249.0c	24.5c
	S2	620c	1056.4d	1270.4bc	2201.2c	22.9c
	S3	535ef	1127.2c	1273.2cd	2216.9bc	23.6c
	S4	520f	594.0f	842.2e	1402.6d	15.9e

Within a column in 1 year, means followed by the different letters are significantly from each other at LSD (0.05).

Net Photosynthetic Rate

A higher photosynthetic rate after heading plays a critical role in maintaining the function of the flag leaves, which effectively ensures high assimilate accumulation and promotes increased plant dry weights in rice. Table 5 shows that both plastic mulching and straw incorporation significantly affected the net photosynthetic rate in rice from days 5 to 20 of the full heading stage. At day 25 of the full heading stage, plastic mulching had no significant effect on the net photosynthetic rate whereas straw incorporation exhibited a significant effect.

The peak net photosynthetic rate was reached under all treatments at day 10 of the full heading stage. Plastic mulching increased the net photosynthetic rate of the rice under the same straw incorporation rate. For example, at day 10 of full heading, the net photosynthetic rates under the 20, 40, 60, and 100% straw incorporation treatments with mulching were higher than those of the corresponding treatments without mulching by 7.4, 17.6, 11.2, and 0.7%, respectively; the relative increases changed to 0.7, 2.8, 16.9, 17.5, and 4.3%, respectively, at day 20 of full heading.

TABLE 5. Effects of plastic mulching and straw incorporation on photosynthetic rate in 2016. （μmol·m²·s⁻¹）

Treatment		Days after heading				
		5d	10d	15d	20d	25d
M	S1	18.2ab	19.9b	17.3b	15.2b	13.5a
	S2	19.1a	22.2a	18.9a	16.4a	13.7a
	S3	18.0ab	20.5b	18.0b	16.5a	13.8a
	S4	15.0de	17.7d	15.4cd	13.8cd	11.8b
NM	S1	16.3cd	18.5cd	15.6cd	14.8bc	13.4a
	S2	15.8d	18.8c	16.1c	14.0cd	13.0a
	S3	17.4bc	18.4cd	16.3c	14.0cd	13.0a
	S4	14.3e	17.5d	15.1d	13.3d	11.9b

Within a column in 1 year, means followed by the different letters are significantly from each other at LSD (0.05).

Nitrogen Use Efficiency of Rice

Table 6 shows that plastic mulching improved the recovery efficiency, agronomic efficiency, and partial factor productivity of nitrogen applied under the same straw incorporation rates in 2016 and 2017. Under the mulched conditions, all three indicators consistently increased first and then decreased with the increasing straw incorporation rate, and they all reached significantly higher levels under the 40% straw incorporation treatment with mulching compared with other treatments. Regardless of whether mulching was performed or not, 100% straw incorporation resulted in significantly lower recovery efficiency, agronomic efficiency, and partial factor productivity compared with those for the other straw incorporation rates.

TABLE 6. Effects of plastic mulching and straw incorporation on nitrogen use efficiency.

Treatment		Nitrogen recovery efficiency (RE_N) (%)	Nitrogen agronomic efficiency (AE_N) (Grain kg kg^{-1} N)	Partial factor productivity of applied N（PFP_N） (Grain kg kg^{-1} N)
2016				
M	S1	64.8b	18.3bc	46.8bc
	S2	79.9a	24.3a	52.8a
	S3	69.4b	19.7b	48.3b
	S4	31.5d	4.6d	33.1d
NM	S1	63.3b	15.4c	43.9c
	S2	46.6c	17.3bc	45.9bc
	S3	42.1c	15.7c	44.3c
	S4	28.5d	3.6d	32.1d
2017				
M	S1	65.3b	20.6bc	48.6bc
	S2	80.7a	25.5a	54.1a
	S3	71.3b	21.8b	50.5b
	S4	36.5d	5.4d	33.6d
NM	S1	64.2b	17.3c	45.9c
	S2	50.6c	19.5bc	48.2bc
	S3	44.4c	17.3c	45.9c
	S4	30.7d	5.0d	32.1d

Within a column in 1 year, means followed by the different letters aresignificantly from each other at LSD (0.05).

This study applied a combination of straw incorporation and plastic mulching for rice cultivation in the rice growing area of the cold region. Under this practice, plastic mulching was used to control the ground temperature and accelerate straw decomposition, while straw incorporation was used to compensate for the soil organic matter loss caused by mulching. The results show that the cultivation method that combined plastic mulching and straw incorporation could improve the plant growth rate during the later growth stages and ultimately improve the rice grain yield. This study provides evidence for solving problems related to the slow decomposition of rice straw after straw incorporation in rice growing areas in cold regions under low soil temperatures.

Straw incorporation is an important method for straw utilization, and it is compatible with the future direction of rice cultivation and production, that is, to achieve synergistic improvements in soil fertility and rice yields on the premise of reducing pollution and agricultural resource waste. Many studies have reported that straw incorporation increased rice yields (Dossou-Yovo et al., 2016b; Zhang et al., 2017b). However, straw incorporation also faces some problems under real production conditions. For example, because of the high C/N ratio of straw, microorganisms tend to take up more nitrogen during straw decomposition, which in turn causes competition for nitrogen between crops and microorganisms. Therefore, it is necessary to apply nitrogen fertilizer during straw incorporation (Akhtar et al., 2019; Dossou-Yovo et al., 2016a; Xie et al., 2017; Zhang et al., 2013). In addition, straw is decomposed slowly after incorporation into rice fields in the cold region because of the low temperature in the early spring and the short growth period. Therefore, improving the soil temperature conditions and exploring the appropriate straw incorporation rate in rice growing areas in cold regions are of great significance to the promotion and application of straw incorporation.

The mulching cultivation technique has high promotional and applicable value in the rice growing area of the cold region, with its low temperatures in early spring and short growth period. Under conventional mulching cultivation, the soil surface is covered by impermeable plastic mulch, making it impossible to top application. Hence, farmers generally apply a single dose of basal fertilizer before transplanting into a mulched area. This approach causes the overgrowth of rice plants during the early growth stages (Qu et al., 2012), while the growth rate decreases at the later stages and the crop may suffer from nitrogen deficiency (Liu et al., 2014). However, in the present study, plastic mulching did not reduce rice growth during the later stages (Table 4) but did improve the rice yield (Table 3) under an appropriate rate of straw incorporation. The possible reasons are as follows. (1) The mulching cultivation system increased the soil temperature from rice transplanting to tilling stage; a higher soil temperature during the early growth stages is essential for improving the rice grain yield (Liu et al., 2014; Liu et al., 2013). (2) Higher ground temperatures facilitated straw decomposition, while the single-dose application of basal fertilizer before transplanting ensured the nitrogen supply; this action could reduce the “nitrogen competition” between straw decomposition and rice growth and promote the early emergence of tillers and the formation of tiller peaks, which are beneficial to the formation of effective panicles in rice. (3) When an appropriate rate of straw incorporation was applied, plastic mulching accelerated the decomposition of straw and increased the soil organic matter (Table 2); additionally, it improved the soil structure and increased the soil permeability. Furthermore, it facilitated crop root development and overcame the decreased growth rate problem during the later rice growth stages due to insufficient nutrients (Huo et al., 2017; Liu et al., 2014). However, the quantity and structure of soil organic matter, the characteristics of soil microorganism, the mechanism of soil carbon sequestration and the mechanism of soil fertility conservation under the conditions of straw returning and film mulching are still not clear, so it is necessary to do further research.

Photosynthetic material production as well as dry matter distribution and translocation after flowering are crucial for yield formation in rice. In the present study, plastic mulching with an appropriate straw incorporation rate markedly delayed the decline in the flag leaf photosynthetic rate of the rice and maintained this rate at relatively high levels during the later growth stages (Table 5), which greatly improved the sink-source relationship. It is plausible that under the mulched condition and an appropriate straw incorporation rate, the straw was decomposed effectively, while soil nutrients such as nitrogen, phosphorus, and potassium were supplemented (Fang et al., 2021; Gupta et al., 2007; Huang et al., 2013; Surekha et al., 2003; Yadvinder-Singh et al., 2004), effectively providing the nutrients needed for photosynthetic metabolism in rice and thus assisting in the accumulation of photosynthetic products at the filling stage (Table 4). However, straw incorporation improved the soil structure, increased the soil permeability, and promoted rice root development, which is of great significance for rice yield increases.

The grain yield of rice depends on having an effective panicles per m^{-2}, spikelets per panicle, grain filling percentage, and 1000-grain weight (Yang & Zhang, 2010). The effective panicles per m^{-2} is determined by a combination of the maximum tiller number before booting stage and the nutritional level after booting stage. Both spikelets per panicle and grain filling percentage are determined after jointing-booting stage (Zhang et al., 2017a). Plastic mulching can increase the soil temperature during the early growth stages of rice and promote rice tilling, which is essential for improving the rice grain yield (Liu et al., 2013; Zhang et al., 2020; Zhang et al., 2017a). Here, our results showed that plastic mulching considerably increased the effective panicles per m^{-2} and improved the average rice yield (Table 3). Additionally, an appropriate rate of straw incorporation increased the crop growth rate and the shoot dry matter accumulation during the later rice growth stages (Table 4), which is conducive to dry matter translocation from stems and leaves to grains (Zhang et al., 2009; Zhang et al., 2019). The yields under both mulched and non-mulched treatments initially increased and then decreased with the increasing rate of straw incorporation, and the highest yield was found under the 40% straw incorporation treatment with mulching. Additionally, the effective panicles per m^{-2} and spikelets per panicle of both mulched and non-mulched treatments initially increased and then decreased with the increasing rate of straw incorporation, whereas the grain filling percentage decreased steadily. Treating with plastic mulching markedly increased the effective panicles per m^{-2}, while incorporating straw increased the effective panicles per m^{-2} and spikelets per panicle in the rice. Taken together, the above results indicate that the combination of plastic mulching with an appropriate rate of straw incorporation likely improved the rice yield by increasing the effective panicles per m^{-2} and the spikelets per panicle. However, an overdose of straw incorporation led to a decline in the grain filling percentage of the rice. This result might be due to the fact that when an increased rate of straw was incorporated, the decomposition of straw consumed many of the nutrients required for rice growth. This consumption resulted in a phenomenon of a large sink with an insufficient source, causing a decline in the grain filling percentage. In summary, to stabilize rice yield, a high rate should not be used during the early stage of straw incorporation in rice growing areas in cold regions. With the increasing duration (years) of straw incorporation, soil nutrients such as total nitrogen and organic matter accumulate while the microbial activity is enhanced; as such, the determination of the optimal straw incorporation rate requires further investigation.

A rice production system should address not only whether the system can improve the yield but also whether the system can improve the nitrogen use efficiency. Previous studies have shown that straw incorporation (Baruah & Baruah, 2015; Puttaso et al., 2011; Zhang et al., 2017b) and plastic mulching (Qu et al., 2012; Tao et al., 2014) can improve the nitrogen use efficiency in rice. In the current study, both plastic mulching and straw incorporation had significant effects on the recovery efficiency, agronomic efficiency, and partial factor productivity of nitrogen (Table 6). Under the same rates of straw incorporation, the mulched treatment increased the recovery efficiency, agronomic efficiency, and partial factor productivity of nitrogen, whereas the non-mulched treatment resulted in a slightly higher physiological nitrogen use efficiency. Incorporating straw at an appropriate rate was beneficial in terms of improving the nitrogen use efficiency in rice, while an excessively high rate could reduce it. This finding may be attributable to the following reasons. (1) Plastic mulching reduced ammonia volatilization within the rice growth stage (Hayashi & Yan, 2010; Li et al., 2021; Xu et al., 2013). (2) The soil water content was maintained at saturation under the mulched condition and thus reduced the potential leaching of nitrate. (3) An appropriate rate of straw incorporation increased the paddy soil available nutrients, enhanced the rice sink strength, and promoted nutrient transport, thereby promoting the uptake, transformation, and accumulation of nitrogen by rice plants. However, an excessively high rate of straw incorporation would compete with rice for nitrogen so that a considerable quantity of nutrients was supplied for straw decomposition, causing a decline in the nitrogen use efficiency of the rice.

CONCLUSIONS

The combination of plastic mulching with an appropriate rate of straw incorporation can lead to a higher yield while improving the nitrogen use efficiency and increasing the soil total nitrogen and organic matter contents in rice growing areas in cold regions. In the present context of promoting sustainable agricultural development, the combination of plastic mulching with straw incorporation may become a new rice cultivation pattern in rice growing areas in cold regions. Given the differences in cultivars, soils, and climates, the appropriate rate of straw incorporation may vary across different regions. To ensure high and stable rice yields, it is necessary to quantify the straw incorporation rate of different regions for the future promotion and application of this technique.

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