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Integrated Straw Return with Less Power Puddling Improves Soil Fertility and Rice Yield in China's Cold Regions

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Abstract: The rice production system in China is facing challenges, including declining soil fertility and a stagnant rice yield. This study aimed to test whether integrating the return of straw to fields with less power puddling could simultaneously enhance soil fertility and rice yields. Therefore, field experiments were conducted in Heilongjiang Province, a key rice-growing region in China, from 2017 to 2021, using three different planting methods: control group (CK), straw return (SR) and straw return integrated with less power puddling (SR + LP). The results showed that small soil aggregates (particle diameter < 0.25 mm) and soil bulk density were significantly decreased when straw return was integrated with less power puddling. These changes contributed to the preservation of soil structure. Simultaneously, this approach significantly increased soil ammonium nitrogen content from 9.9 to 10.9 mg kg^{-1}, organic matter content from 35.0 to 36.2 g kg^{-1}, available nitrogen content from 140.5 to 147.0 mg kg^{-1} and available potassium content from 128.6 to 136.8 mg kg^{-1} at mature stage on average. Consequently, the post-heading stored assimilates accumulation of rice was increased from 6.12 to 6.43 t ha^{-1}, and the nitrogen, phosphorus and potassium accumulation of rice were increased by 7.85 kg ha^{-1}, 1.13 kg ha^{-1} and 5.68 kg ha^{-1}, respectively. These changes ultimately resulted in a higher 1000 g weight and filled grain rate, providing the foundation for higher yields (an increase from 9.31 t ha^{-1} to 9.55 t ha^{-1}). Furthermore, this approach also increased the net income for farmers by USD 14 t ha^{-1}. In summary, this study demonstrates that integrating straw return with less power puddling can enhance soil's nutrient supply and retention capacity. This enhancement may boost the absorption and transportation of nutrients, ultimately establishing the groundwork for higher yields and economic benefits by enhancing the 1000 g weight and filled grain rate. Future research should delve deeper into its applicability across different ecosystems and investigate the yield-increasing mechanisms.

Keywords: nutrient accumulation; soil aggregates; assimilates accumulation; yield components; soil fertility

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1. Introduction

The sustainability and security of food production have been global concerns for a long time. Rice, as a major cereal crop, provides sustenance for a half of the world's population and plays a vital role in meeting the increasing food demands worldwide [1,2]. Therefore, ensuring stable growth in the rice yield is crucial for global food security. China stands as the world's largest producer and consumer of rice. In 2022, its rice production and plant area reached 2.08 × 10^8 t and 2.95 × 10^7 ha respectively. However, in recent 10 years, rice production has fluctuated between 2.06 × 10^8 ton and 2.12 × 10^8 ton [3]. Consequently,

with the rise in global population and escalating food requirements [4], the improvement of sustainable rice cultivation has emerged as a common objective among agricultural scientists and farmers alike.

For years, the agricultural sector has been engaged in a quest to find effective strategies for enhancing rice yields. Traditional practices have heavily relied on the extensive use of chemical fertilizers as a primary method to boost rice production [5,6]. However, the excessive application of fertilizers has led to limited improvement in yield and has precipitated numerous environmental issues, including soil pollution and acidification, which in turn diminish soil fertility [7–9]. Consequently, there is a pressing need to discover sustainable approaches that can simultaneously augment soil fertility and rice yields, addressing the evolving challenges of modern agriculture.

Extensive research has been conducted on returning straw to fields as a method to enhance soil fertility and increase crop yield [10,11]. Returning straw into fields can enrich soil nutrients, improve soil structure, reduce erosion and foster rice growth [12,13]. Straw contains abundant elements such as carbon, nitrogen, phosphorus and potassium [14]. Directly returning straw to fields effectively supplements the readily available nutrients, leading to an increase in soil fertility. Additionally, straw incorporation can enhance soil aeration and water retention [15], and can help plants to absorb nutrients [16]. This not only enhances crop resilience but also reduces the risks of soil erosion and water runoff [17]. Long-term field experiments have demonstrated that straw return can significant boost rice yields from 5% to 10% [18–20].

Despite straw return having some benefits, it also comes with certain drawbacks. For example, it requires more powerful agricultural machinery for mechanized operations, leading to increased production costs. Moreover, straw return reduces conditions in waterlogged soil, potentially leading to the production of excessive H_2S, which can cause black root disease and even premature death of rice [21]. Higher straw incorporation rates may more strongly reduce conditions in soils, negatively affecting rice yields [22–25]. Therefore, it is necessary for researchers to delve deeper into optimizing the process of straw return to maximize its positive effects on rice yield and soil fertility.

Prior to rice transplantation, many farmers employ a technique known as power puddling to fragment and even out the soil, creating a soft, flat terrain ideal for planting rice seedlings, thereby enhancing the success rate of rice transplantation [26,27]. However, this practice often disrupts soil's pore structure and soil aggregates, which can increase soil bulk density and amplify the negative effects on returned straw [28,29]. To mitigate these issues, there has been a recent trend towards reducing and minimizing excessive soil agitation. This approach involves simplifying the stirring process and utilizing only a scraper to level the cropland, which can preserve soil structure, enhance the growing environment of rice and reduce costs. Nonetheless, there is a scarcity of studies examining the integrated effect of straw return with less power puddling on soil fertility and rice yields, and whether this measure can effectively improve soil fertility and rice yield still needs to be verified.

Heilongjiang province, one of the globe's key rice-producing regions in China, contributes approximately one-eighth of the rice harvest in China. In recent times, however, this region has encountered challenges, including declining soil quality and stagnant rice yields [30]. Consequently, we selected this region as the focal point for our study to examine the impact of integrated straw return with less power puddling on soil fertility and rice production. Our hypothesis posits that integrating straw return with less power puddling could simultaneously enhance both soil fertility and rice yields. To verify this, we conducted a comprehensive five-year field experiment to assess the impacts of this integrated approach on soil's physical and chemical properties, rice nutrient accumulation, yield and economic benefits. This research aims to offer a fresh empirical perspective and a theoretical foundation for an agricultural management model that could simultaneously improve soil fertility and rice yield, thereby contributing an empirical case study and a theoretical basis to the sustainable practices in rice cultivation.

2. Materials and Methods

2.1. Experimental Site Description

The experimental site was situated in Jiansanjiang Qixing farm, China (47°14′56.93″ N, 132°49′33.02″ E), with a cold-temperate continental monsoon climate. The annual mean air temperature ranges from 1 °C to 2 °C, with an effective cumulative temperature between 20 °C and 24 °C. This region receives approximately 2260 to 2449 h sunshine and 550 mm to 600 mm precipitation annually. The frost-free period lasts about 110 to 135 days. The average temperature from May to September was relatively close during the period 2017 to 2021. However, there were more days in 2021 when average temperature exceeded 25 °C, and the precipitation in 2019 was more than other years (Figure 1). Prior to rice fertilization in 2017, albic paddy soil samples were collected from the 0–20 cm layer for physicochemical analysis. The analysis revealed soil bulk density of 1.24 g cm^{-3}, soil pH of 6.40, soil organic matter (SOM) content of 39.2 g kg^{-1}, alkali-hydrolyzable nitrogen (AN) content of 146 mg kg^{-1}, available phosphorus (AP) content of 17.7 mg kg^{-1} and available potassium (AK) content of 123 mg kg^{-1}.

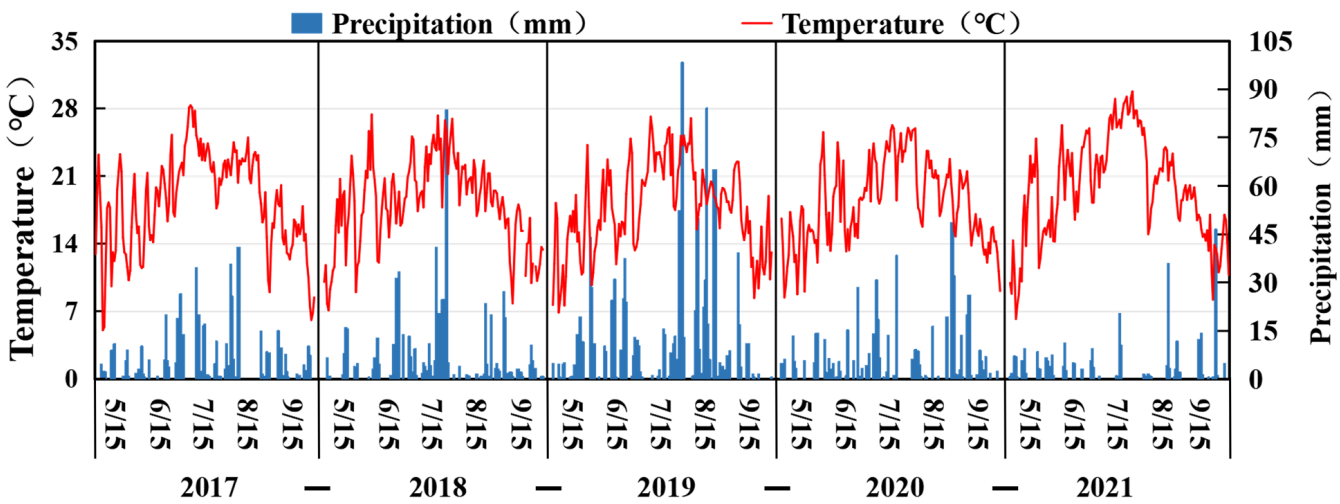

Figure 1. Average daily temperature and precipitation in Qixing farm for May to September from 2017 to 2021. Note: The red lines represent average daily temperature, while the blue line segments represent average daily precipitation.

The variety of rice cultivated in 2017 was Long Japonica 46, and it was subsequently replaced with Long Japonica 31 from 2018 to 2021 due to Long Japonica 46′s susceptibility to diseases. Both rice varieties are local staple rice cultivars, characterized by 11 leaves on the main stem and a time from transplanting to maturity stage of approximately 120 days. Due to the different rice varieties, we did not present the nutrient accumulation and yield results of rice in 2017.

2.2. Experimental Design

For this experiment, a randomized complete block design was used with three treatments and replicated three times (Figure 2). Each cropland area was 700 m^2. The experimental setup and details are presented in Table 1.

For the control treatment (CK, no straw return), rice straw was removed from cropland after harvesting rice. We applied 75 kg N, 45 kg P_2O_5 and 30 kg K_2O using side-deep techniques per hm^2 of cropland when transplanting rice seedlings. When the main rice panicle reached approximately 1.0 cm in length, 30 kg N and 30 kg K_2O were broadcast applied per hm^2 of cropland. N fertilizers were urea and diammonium, while phosphorus and potassium fertilizers were diammonium phosphate and potassium chloride, respectively. Cropland was plowed in autumn, and before transplanting rice seedlings, we soaked the cropland with water for 15 to 30 days. Further, a power puddling churn and scraper were

used for puddling and leveling cropland, maintaining a cropland surface height gap of 3–5 cm. After puddling and leveling process, the cropland was naturally settled for more than one week.

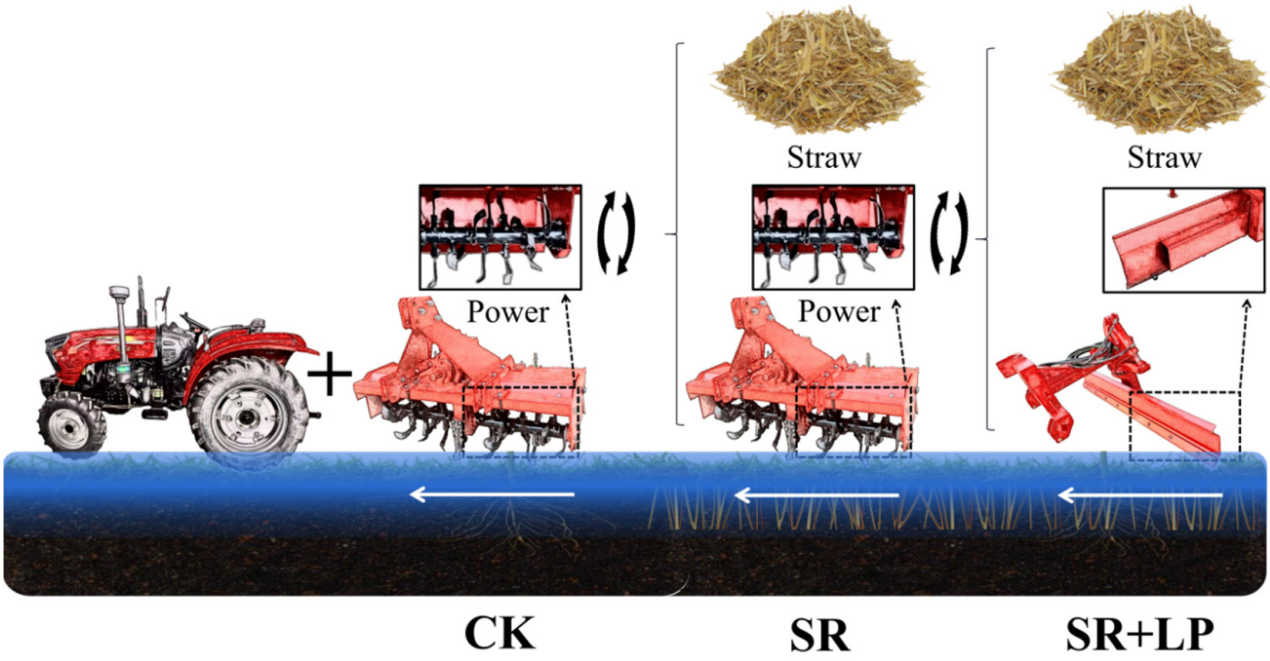

Figure 2. Comparison among control (CK), straw return (SR) and integrated straw return with less power puddling (SR + LP) treatments. Note: a power puddling machine was used to break up soil; returned straw was crushed and buried into cropland, the white arrow indicates the moving direction of tractor, and the black arrow indicates the rotating direction of power puddling machine.

Table 1. Comparison of CK, SR and SR + LP treatments.

Treatment	Straw Return	Soaked Time before Transplanting Rice Seedlings	Power Puddling Measure	N-P_2O_5-K_2O ($kg \cdot ha^{-1}$)		
CK	No	15 to 30 days	Yes	105	45	90
SR	Yes	15 to 30 days	Yes	105	45	90
SR + LP	Yes	5 to 7 days	No	105	45	90

Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment.

For the straw return treatment (SR), all straw was crushed into approximately 10 cm pieces and evenly distributed into cropland after harvesting rice. The amounts of fertilizer and fertilization times were the same as for the CK treatment. Cropland was also plowed, soaked, puddled and leveled in the same manner as for the CK treatment.

For the integrated straw return with less power puddling treatment (SR + LP), the returned straw, amounts of fertilizer and fertilization times were the same as for the SR treatment. However, before transplanting rice seedlings, we soaked the cropland with water only for 5 to 7 days, and power puddling was omitted; cropland was leveled directly using a scraper, and cropland was naturally settled after the leveling process.

Between mid-April 2017 and 2021, 3 to 5 seeds were sown in each seeding tray. The germinated seedlings were cultured in a greenhouse for 30 to 40 days, transplanted between 10 May and 18 May during 2017 to 2021, and harvested between 15 September and 30 September each year when rice exhibited physiological maturity. The spacing in rows and spacing between rows were 30 cm and 14 cm, with 4 to 6 plants per hole. All cropland was irrigated with groundwater to a depth of approximately 3 cm. Throughout the experiment's duration, weed infestation was effectively managed using herbicides and

manual weeding practices. Pests and diseases were controlled through the application of appropriate insecticides and fungicides. Notably, there were no significant instances of moisture-related stress, weed proliferation, pest or disease during the cultivation of rice.

2.3. Sampling and Measurements

2.3.1. Soil Samples

After harvesting rice, three soil bulk density samples were collected using the ring knife method from the 0–10 cm soil layer in each treatment. Three soil nutrients samples were collected using a soil sampler of 5 cm diameter at four stages: before rice transplanting, jointing, heading and maturity stages from 2017 to 2021. Prior to sampling, each repeated treatment cropland was divided into five transect zones randomly; soil samples were collected in these zones and composited as one soil sample. Visible impurities such as stones and plant residues were removed. The composited soil samples were divided into three parts. One part of the soil sample was placed into sterilized self-sealing bags in an incubator with low temperature for preservation before being promptly storing in a refrigerator, and for the quantification of soil ammonium nitrogen (NH_4^+-N). A second part of the soil sample was air-dried and finely ground for the quantification of soil organic matter (SOM), soil alkali-hydrolyzable nitrogen (AN), soil available phosphorus (AP) and soil available potassium (AK). The remaining part of the soil sample was passed through 0.5 mm and 0.25 mm sieves sequentially to obtain large soil aggregates (particle diameter more than 0.5 mm), middle soil aggregates (particle diameter between 0.25 mm and 0.5 mm) and small soil aggregates (particle diameter less than 0.25 mm).

To determine soil NH_4^+-N content, soil samples were soaked in potassium chloride solution, and determined using a continuous-flow analyzer (AA3, Bran and Luebbe, Norderstedt, Germany). SOM content was determined using the potassium dichromate titrimetric method, soil AN content was determined using micro Kjeldahl digestion, soil AP content was determined using the molybdenum antimony colorimetric method, and soil AK content was determined using the flame photometric method. The reagents used in this paper were all analytical reagent (Sinopharm, Hebi, China).

2.3.2. Plant Samples

Plant samples were collected at the same time as soil nutrient samples. Thirty rice tillers were counted to determine the average tiller number, and four plant samples with the closest tiller number to average tiller number were selected and brought back to the laboratory for analysis. Due to the impact of the COVID-19 pandemic, no plant samples were collected during jointing to heading stages in 2020. Two plant samples were separated into three parts: stem, leaf and panicle. All samples were dried in an oven at 80 °C to obtain their dry weight. Plant nitrogen (N) concentration was measured using hydrogen peroxide-sulfuric acid digestion and a continuous-flow analyzer (AA3, Bran and Luebbe, Norderstedt, Germany). Plant phosphorus (P) and potassium (K) concentrations were measured using inductively coupled plasma mass spectrometry (ICP-MS, Agilent, Santa Clara, CA, USA). The following formula was used to calculated nutrient accumulations:

$$CA_{NPK} = Con_{NPK} \times DW_{Rice} \times 1000$$

where CA_{NPK} are the nitrogen, phosphorus and potassium accumulations of the plant (kg ha^{-1}), Con_{NPK} are the nitrogen, phosphorus and potassium concentration of the plant (mg kg^{-1}), DW_{Rice} is the dry weight of the plant (t ha^{-1}). The post-heading stored assimilates accumulation of the rice (PAA) (t ha^{-1}) was calculated by the following formula:

$$PAA = TDW_{Maturity} - TDW_{Heading}$$

where $TDW_{Maturity}$ is the dry weight of rice at maturity (t ha^{-1}) and $TDW_{Heading}$ is the dry weight of rice at heading (t ha^{-1}). The contribution of post-heading stored assimilates to grain yield (CPA) (%) was calculated by the following formula:

$$CPA = PAA/GDW_{Maturity} \times 100\%$$

where $GDW_{Maturity}$ is the grain dry weight of rice at maturity (t ha^{-1}).

Another two plant samples were used to determine yield components: filled grain rate (%, the ratio of filled grain to unfilled grain after winnowing by wind selector); 1000 g weight (g, the dry weight of 1000 filled grains); harvest index (%, the ratio of grain dry weight to total plant dry weight); spikelets (10^2 per m^2, the number of spikelets per m^2). Additionally, at maturity stage, approximately 100 m^2 grain was threshed from the central area of each treatment cropland to determine rice yield, 2% impurity rate was deducted from grain, and grain weight was converted into the weight at 14.5% moisture content. Grain moisture content was measured using a digital water meter (SANJIU TD-6, Shenzhen, China).

2.3.3. Economic Benefit

The cost and income of each treatment were recorded from 2018 to 2021. The farmer's net benefit ($Benefit_{net}$) (USD ha^{-1}) in the rice production system was calculated by the following formula:

$$Benefit_{net} = Cost_{Rice} - Income_{Rice}$$

where $Cost_{Rice}$ is the cost in the rice production system (USD ha^{-1}) and $Income_{Rice}$ is the income in the rice production system (USD ha^{-1}), calculated by the following formulas:

$$Cost_{Rice} = Cost_{AI} + Cost_{MO} + Cost_{Labor} + Cost_{Profit\ tax}$$

$$Income_{Rice} = AY \times Price_{Rice} \times 1000$$

where $Cost_{AI}$ is the agricultural materials cost, including fertilizers, pesticides and irrigated water (USD ha^{-1}); $Cost_{MO}$ is the mechanization operation cost, including diesel, electricity and machinery leasing (USD ha^{-1}); $Cost_{Labor}$ is the long-term and short-term labor cost (USD ha^{-1}); $Cost_{Profit\ tax}$ is the annual tax cost (USD ha^{-1}); AY is the yield of rice (t ha^{-1}); $Price_{Rice}$ is the price of rice (USD·kg^{-1}) based on the average rice price from 2017 to 2021.

2.4. Data Analysis

Data were processed and analyzed using Microsoft Excel 2019 (Microsoft, Redmond, WA, USA) and Statistical Package for the Social Sciences 22.0 (IBM, Armonk, NY, USA) software, employing the Tukey's test and the two-way ANOVA test. Figures were created using Origin 2021 (OriginLab, Northampton, MA, USA) software.

3. Results

3.1. Soil Aggregates Proportion

There were significant variations among crop treatments in different soil aggregate proportions ($p < 0.05$) (Figure 3). SR and SR + LP treatments protected the large soil aggregates in varying degrees. As a result, the proportion of large soil aggregates in the CK treatment was lowest (11.0%), which was 0.9% and 8.4% lower than that in the SR and SR + LP treatments, respectively. Similar to this result, the proportion of middle soil aggregates in the CK treatment was also lowest (9.5%), which was 3.0% and 5.2% lower than that in SR and SR + LP treatments, respectively. In contrast, the proportion of small soil aggregates in the CK treatments was highest (79.5%), and was 3.9% and 13.6% higher than that in SR and SR + LP treatments, respectively.

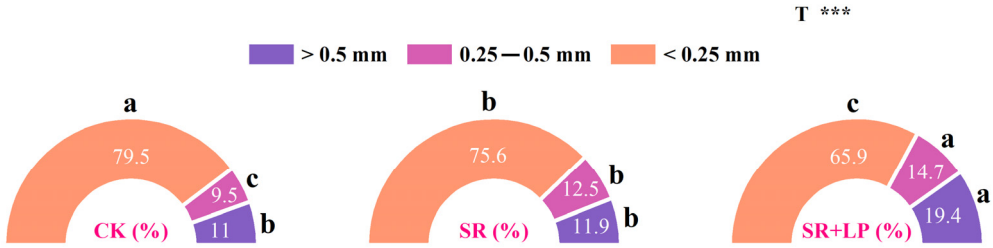

Figure 3. Proportion of soil aggregates in different particle sizes. Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. Arcs represent means of replicates. Arcs with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$). T, cropping treatment. *** represent significant results of one-way analysis of variance (ANOVA) for cropping treatment at 0.1% ($p < 0.001$) level.

3.2. Soil Ammonia Nitrogen Content

Soil NH_4^+-N content at transplanting, jointing, heading and maturity stages exhibited significant interannual variations ($p < 0.05$). The highest soil NH_4^+-N content at transplanting stage was 7.95 mg kg^{-1} in 2021 (Figure 4), and the highest soil NH_4^+-N content at jointing, heading and maturity stages was 12.14, 10.28 and 11.88 mg kg^{-1} in 2018, respectively. The lowest soil NH_4^+-N content at transplanting, jointing, heading and maturity stages was 2.07, 5.37, 5.82 and 7.58 mg kg^{-1} in 2017, respectively. From transplanting to jointing stages, soil NH_4^+-N content increased by 65.6% on average. However, from jointing to maturity stages, there was little variation in soil NH_4^+-N content.

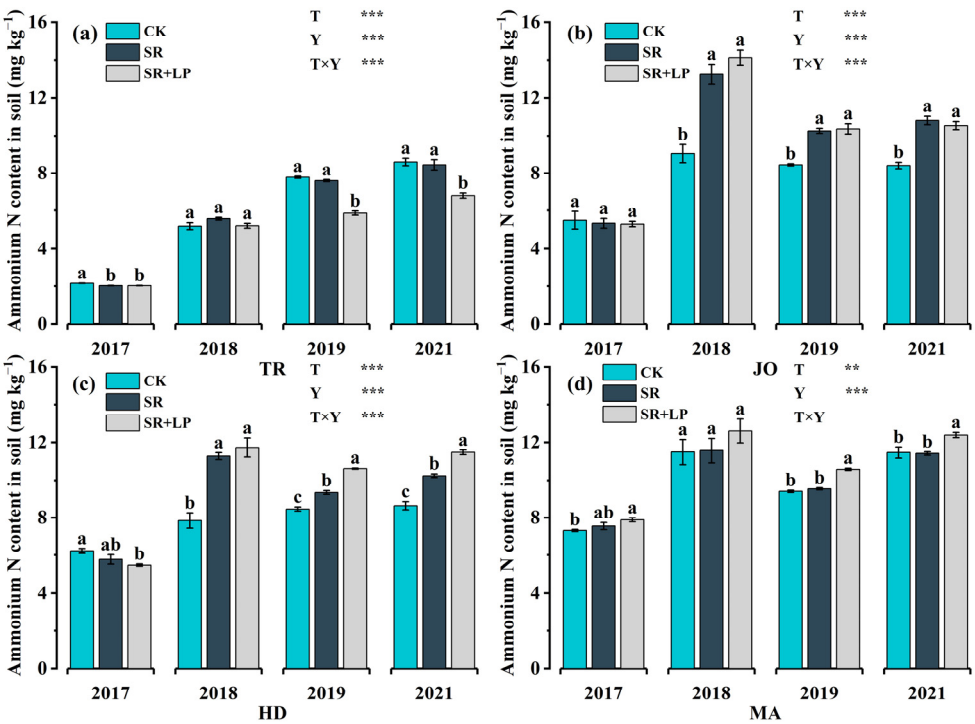

Figure 4. Soil ammonium N content at rice transplanting (**a**), jointing (**b**), heading (**c**) and maturity (**d**) stages in 2017, 2018, 2019 and 2021. Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. TR, transplanting stage, JO, jointing stage, HD, heading stage, MA, maturity stage. Bars represent means of replicates; error bars represent the standard error. Bars with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$). T, cropping treatment, Y, cropping year, T × Y, the interaction between cropping treatment and cropping year. **, and *** represent significant results of two-way analysis of variance (ANOVA) for cropping treatment and cropping year at 1% ($p < 0.01$) and 0.1% ($p < 0.001$) levels, respectively.

There were significant variations among crop treatments in soil NH_4^+-N content at transplanting, jointing, heading and maturity stages ($p < 0.05$). At transplanting stage, soil NH_4^+-N content in CK and SR treatments was similar (average 5.92 mg kg^{-1}), which was 19.1% higher than that in the SR + LP treatment (Figure 4a). At jointing stage, soil NH_4^+-N content in SR and SR + LP treatments was similar (average 9.99 mg kg^{-1}), which was 27.3% higher than that in the CK treatment (Figure 4b). At heading stage, the highest soil NH_4^+-N content from 2018 to 2021 was observed in the SR + LP treatment (average 9.81 mg kg^{-1}), which was 25.9% and 7.2% higher than that in CK and SR treatments, respectively (Figure 4c). At maturity stage, the highest soil NH_4^+-N content was 10.87 mg kg^{-1} in the SR + LP treatment, which was 9.7% and 8.5% higher than that in the CK and SR treatments, respectively (Figure 4d).

3.3. Soil Nutrient Content

SOM, soil AN, AP, AK contents and soil bulk density exhibited significant interannual variations ($p < 0.05$) (Figure 5). SOM content exhibited an increasing trend over time, with the lowest and highest values at 35.27 and 36.34 g kg^{-1} in 2017 and 2021, respectively. Soil AN content increased at first, and then decreased, with the highest and lowest values at 151.07 and 134.13 mg kg^{-1} in 2019 and 2017, respectively. Soil AP content exhibited a decreasing trend over time, with the highest and lowest values at 20.77 and 18.47 mg kg^{-1} in 2017 and 2021, respectively. Conversely, soil AK content exhibited an increasing trend over time, with the lowest and highest values at 116.08 and 159.15 mg kg^{-1} in 2017 and 2021, respectively. Soil bulk density exhibited a fluctuating increasing trend, ranging from 1.22 to 1.27 g cm^{-3} from 2017 to 2021.

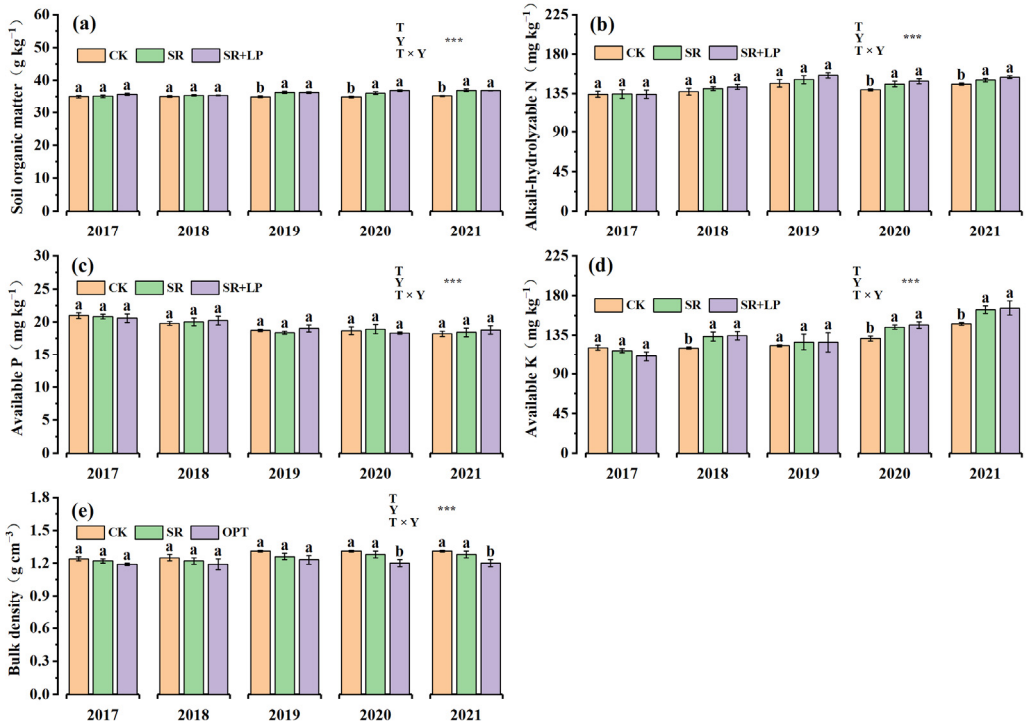

Figure 5. Soil organic matter content (**a**), alkali-hydrolyzable N content (**b**), available P content (**c**), available K content (**d**) and soil bulk density (**e**) from 2017 to 2021. Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. Bars represent means of replicates; error bars represent the standard error. Bars with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$). T, cropping treatment, Y, cropping year, T × Y, the interaction between cropping treatment and cropping year. *** represent significant result of two-way analysis of variance (ANOVA) for cropping treatment and cropping year at 0.1% ($p < 0.001$) levels.

There were no significant variations among cropping treatments in SOM, soil AN, AP, AK content and soil bulk density ($p < 0.05$). However, from 2019 to 2021, straw return significantly increased SOM content, and from 2020 to 2021, it significantly increased soil AN content and reduced soil bulk density. Additionally, in 2018, 2020 and 2021, straw return significantly increased soil AK content. SR + LP treatment had the highest SOM content (36.21 g kg^{-1}), which was similar to that of the SR treatment but 3.4% higher than that of the CK treatment (Figure 5a). SR + LP treatment also had the highest soil AN content (146.97 mg kg^{-1}), which was 4.6% and 1.8% higher than that of CK and SR treatments, respectively (Figure 5b). Soil AP content in all treatments was similar, ranging from 19.27 to 19.38 mg kg^{-1} (Figure 5c). Soil AK content in SR and SR + LP treatments was similar (average 137.01 mg kg^{-1}), which was 6.6% higher than that of the CK treatment (Figure 5d). SR + LP treatment exhibited the lowest soil bulk density (1.20 g cm^{-3}), which was 6.3% and 4.0% lower than that of CK and SR treatments, respectively (Figure 5e).

3.4. Biomass Dry Weight and Nutrient Accumulations

The biomass dry weight of rice exhibited significant interannual variations at jointing, heading and maturity stages ($p < 0.05$) (Table 2). The highest dry weight at jointing and maturity stages was 3.48 and 16.54 t ha^{-1} in 2021, respectively. The highest dry weight at heading stage was 9.58 t ha^{-1} in 2018. At the same time, PAA and CPA of rice displayed significant interannual variations ($p < 0.05$), and the highest PAA and CPA values were 7.59 t ha^{-1} and 94.98% in 2021 and 2019, respectively.

Table 2. Biomass dry weight at jointing, heading and maturity stages, the post-heading stored assimilates accumulation of rice and the contribution of post-heading stored assimilates to grain yield from 2018 to 2021.

Year	Treatment	Biomass Dry Weight of Rice (t ha^{-1})				Contribution Rate (%)
		JO	HD	MA	PAA	CPA
2018	CK	2.93 a	9.48 a	14.07 a	4.59 a	59.3 a
	SR	3.06 a	9.74 a	14.38 a	4.64 a	59.7 a
	SR + LP	3.08 a	9.53 a	14.07 a	4.54 a	59.5 a
2019	CK	2.15 a	8.19 a	14.64 b	6.44 b	95.5 a
	SR	2.35 a	8.25 a	14.61 b	6.36 b	94.8 a
	SR + LP	2.13 a	8.33 a	15.37 a	7.05 a	94.6 a
2020	CK	-	-	16.11 b	-	-
	SR	-	-	16.18 b	-	-
	SR + LP	-	-	16.89 a	-	-
2021	CK	3.50 a	8.88 a	16.39 b	7.52 b	85.9 a
	SR	3.40 a	8.86 a	16.18 b	7.32 b	85.2 a
	SR + LP	3.53 a	9.12 a	17.06 a	7.93 a	87.3 a
Two-way ANOVA results						
Y		***	***	***	***	***
T		NS	NS	NS	NS	NS
Y × T		NS	NS	NS	NS	NS

Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling measure treatment. JO, jointing stage, HD, heading stage, MA, maturity stage. PAA, the post-heading stored assimilates accumulation of rice. CPA, the contribution of post-heading stored assimilates to grain yield. Numbers in the same year and item with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$). T, cropping treatment, Y, cropping year, T × Y, the interaction between cropping treatment and cropping year. *** represent significant results of two-way analysis of variance (ANOVA) for cropping treatment and cropping year at 5% ($p < 0.05$), 1% ($p < 0.01$) and 0.1% ($p < 0.001$) levels, respectively. NS, non-significant at 5% level. "-", there is no data.

The variations among cropping treatments in rice biomass dry weight at jointing, heading and maturity stages, and PAA and CAT were all not significant ($p < 0.05$). However, in 2019, 2020 and 2021, the biomass dry weight at heading stage was 15.37 t ha^{-1}, 16.89 t ha^{-1}

and 17.06 t ha^{-1}, which was significantly higher than that in CK and SR treatments; besides that, the PAA in the SR + LP treatment in 2019 and 2021 was 7.05 t ha^{-1} and 7.93 t ha^{-1}, which was also significantly higher than that in the CK and SR treatments.

The N, P and K accumulations of rice exhibited significant interannual variations at jointing, heading and maturity stages ($p < 0.05$) (Table 3). At jointing stage, the highest N accumulation was in 2018 (78.71 kg·ha^{-1}). The highest P and K accumulations were in 2021 (14.60 kg·ha^{-1} and 101.05 kg·ha^{-1}). At heading stage, the highest N and K accumulations were in 2021 (140.72 kg·ha^{-1} and 186.80 kg·ha^{-1}); the highest P accumulation was in 2018 (34.22 kg·ha^{-1}). At maturity stage, the highest N, P and K accumulations were all in 2021 (138.20 kg·ha^{-1}, 49.68 kg·ha^{-1} and 186.80 kg·ha^{-1}).

Table 3. Nutrient accumulations at jointing, heading and maturity stages from 2018 to 2021.

Year	Treatment	Nutrient Accumulations of Rice (kg ha^{-1})								
		N			P			K		
		JO	HD	MA	JO	HD	MA	JO	HD	MA
2018	CK	77.7 a	129.2 a	132.5 a	12.2 a	33.9 a	41.9 a	91.5 a	175.8 a	159.4 a
	SR	78.2 a	134.9 a	148.3 a	12.6 a	34.2 a	42.3 a	97.1 a	171.9 a	163.9 a
	SR + LP	80.3 a	131.8 a	138.2 a	12.5 a	34.6 a	42.3 a	97.0 a	172.7 a	163.6 a
2019	CK	62.6 a	133.3 a	141.4 b	8.5 a	30.4 a	40.6 b	55.5 a	164.9 a	157.2 b
	SR	65.9 a	131.4 a	141.8 b	9.4 a	29.9 a	40.3 b	63.1 a	170.5 a	159.0 b
	SR + LP	62.3 a	133.3 a	153.1 a	8.7 a	30.8 a	44.4 a	55.9 a	171.4 a	168.1 a
2020	CK	-	-	141.3 b	-	-	34.4 a	-	-	182.2 b
	SR	-	-	144.3 b	-	-	32.8 a	-	-	181.6 b
	SR + LP	-	-	154.1 a	-	-	33.8 a	-	-	187.7 a
2021	CK	77.4 a	135.8 b	157.2 b	14.7 a	31.3 a	48.9 b	101.9 a	181.8 b	177.1 b
	SR	75.6 a	139.5 b	160.9 b	14.6 a	30.9 a	49.1 b	98.6 a	185.9 b	179.2 b
	SR + LP	80.8 a	146.9 a	170.0 a	14.6 a	31.5 a	51.1 a	102.8 a	192.7 a	185.5 a
Two-way ANOVA results										
Y		***	NS	**	***	***	***	***	***	***
T		NS	NS	*	NS	NS	NS	NS	NS	NS
Y × T		NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. JO, jointing stage, HD, heading stage, MA, maturity stage. Numbers in the same year and item with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$). T, cropping treatment, Y, cropping year, T × Y, the interaction between cropping treatment and cropping year. *, **, and *** represent significant results of two-way analysis of variance (ANOVA) for cropping treatment and cropping year at 5% ($p < 0.05$), 1% ($p < 0.01$), and 0.1% ($p < 0.001$) levels, respectively. NS, non-significant at 5% level. "-", there is no data.

In maturity stages, the variation among cropping treatments in N accumulation was significant ($p < 0.05$), while those in P and K accumulation were not significant. In jointing and heading stages, the variations among cropping treatments in N, P and K were all not significant. In 2019, N, P and K accumulations in the SR + LP treatment were 153.1 kg ha^{-1}, 44.4 kg ha^{-1} and 168.1 kg ha^{-1} at maturity stage, which were significantly higher than those of CK and SR treatments. In 2020, N and K accumulations in the SR + LP treatment were 154.1 kg ha^{-1} and 187.7 kg ha^{-1} at maturity stage, which were also significantly higher than those of CK and SR treatments. In 2021, N and P accumulations in the SR + LP treatment were 146.9 kg ha^{-1} and 192.7 kg ha^{-1} at heading stage; N, P and K accumulations were 170.0 kg ha^{-1}, 51.1 kg ha^{-1} and 185.5 kg ha^{-1} at maturity stage, which were all significantly higher than those of CK and SR treatments. Apart from the above time, there were no significant differences among treatments.

3.5. Yield and Yield Components

Rice yield components and harvest index and yield exhibited significant interannual variations (Table 4) ($p < 0.05$). The highest spikelets and harvest index were 338.6 × 10^2

per m^2 and 54.4% on average in 2018; the highest filled grain rate, 1000 g weight and yield were 82.8%, 26.8 g and 10.31 t ha^{-1} on average in 2021.

Table 4. Yield and yield components of rice from 2018 to 2021.

Year	Treatment	Spikelets 10^2 per m^2	Filled Grain Rate %	1000 g Weight g	Harvest Index %	Yield t ha^{-1}
2018	CK	339.5 a	70.2 a	25.28 a	55.0 a	9.02 a
	SR	336.7 a	72.5 a	24.91 b	54.1 a	9.11 a
	SR + LP	339.6 a	72.2 a	24.28 c	54.2 a	8.93 a
2019	CK	333.8 ab	58.9 a	26.83 a	46.2 a	7.89 b
	SR	323.8 b	61.0 a	26.43 a	47.1 a	7.83 b
	SR + LP	356.8 a	61.4 a	26.42 a	48.4 a	8.68 a
2020	CK	367.6 a	78.1 b	23.22 b	53.0 a	9.98 b
	SR	332.9 b	81.7 b	24.48 a	52.8 a	9.98 b
	SR + LP	342.0 ab	85.0 a	24.11 a	53.3 a	10.51 a
2021	CK	320.1 a	81.6 b	26.10 c	53.3 a	10.22 b
	SR	305.3 a	81.4 b	27.00 b	53.2 a	10.06 b
	SR + LP	303.7 a	85.5 a	27.32 a	53.4 a	10.64 a
Two-way ANOVA results						
Y		***	***	***	***	***
T		**	***	**	NS	**
Y × T		*	NS	***	NS	***

Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. Numbers in the same year and items with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$). T, cropping treatment, Y, cropping year, T × Y, the interaction between cropping treatment and cropping year. *, **, and *** represent significant results of two-way analysis of variance (ANOVA) for cropping treatment and cropping year at 5% ($p < 0.05$), 1% ($p < 0.01$) and 0.1% ($p < 0.001$) levels, respectively. NS, non-significant at 5% level.

There were significant variations among crop treatments in the number of spikelets, filled grain rate, 1000 g weight and rice yield. In 2019 and 2020, SR + LP and CK treatments exhibited a significantly higher number of spikelets than SR treatment. In 2020 and 2021, the filled grain rate in the SR + LP treatment was 85.0% and 85.5%, respectively, which was significantly higher than that of CK and SR treatments. In 2018, the 1000 g weight was significant lower in the SR + LP treatment (24.28 g), while in 2021, the highest 1000 g weight in the SR + LP treatment (27.32 g) was significantly higher than that in CK and SR treatments. From 2017 to 2021, no significant variations were observed in harvest index among cropping treatments. From 2019 to 2021, the yield was significantly higher in the SR + LP treatment (average 9.94 t ha^{-1}), which was 6.2% and 7.0% higher than that in CK and SR treatments on average, respectively.

Filled grain rate and harvest index were significant correlated with rice yield (correlation coefficients were 84% and 42%, respectively) (Figure 6a,b). In contrast, the correlation among the 1000 g weight, spikelets and rice yield were not significant correlated (Figure 6c,d).

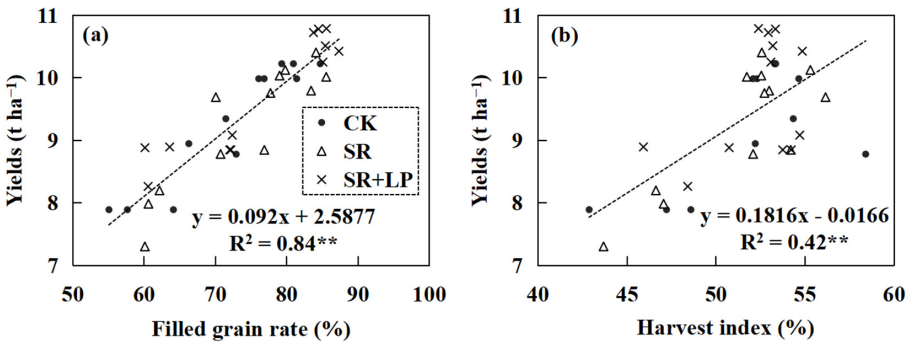

Figure 6. *Cont.*

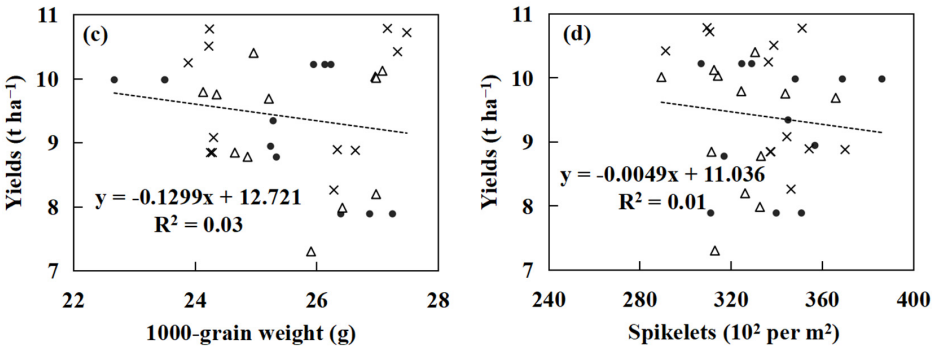

Figure 6. Relationship with yield and filled grain rate (**a**), harvest index (**b**), 1000 g weight (**c**) and spikelets per m^2 (**d**). Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. ** represent the correlation coefficient was significant at 1% level ($p < 0.1$) (n = 36).

3.6. Economic Benefit

The total cost, income and net benefit in each cropping treatment were different (Table 5). The total cost in CK and SR treatments was USD 238 ha^{-1} and USD 239 ha^{-1}, respectively. However, the total cost in the SR + LP treatment was USD 223 ha^{-1}. On the other hand, the total income and net benefit were both higher in the SR + LP treatment at USD 3207 ha^{-1} and USD 418 ha^{-1}, respectively. In the CK treatment, the total income and net benefit were USD 3127 ha^{-1} and USD 404 ha^{-1}, respectively. As for SR treatment, the total income and net benefit were USD 3107 ha^{-1} and USD 402 ha^{-1}, respectively.

Table 5. Average cost, income and net benefit of each treatment from 2017 to 2021.

Items	CK	SR	SR + LP
$Cost_{AI}$ (USD ha^{-1})	466 a	466 a	451 b
$Cost_{MO}$ (USD ha^{-1})	487 a	494 a	452 b
$Cost_{Labor}$ (USD ha^{-1})	691 a	691 a	635 b
$Cost_{Profit\ tax}$ (USD ha^{-1})	53 a	53 a	53 a
$Cost_{Rice}$ (USD ha^{-1})	238 a	239 a	223 b
Average yield of rice (t ha^{-1})	9.31 b	9.25 b	9.55 a
Average price of rice (USD kg^{-1})	0.34 a	0.34 a	0.34 a
$Income_{Rice}$ (USD ha^{-1})	3127 b	3107 b	3207 a
$Benefit_{Net}$ (USD ha^{-1})	404 b	402 b	418 a

Note: CK, control treatment, SR, straw return treatment, SR + LP, integrated straw return with less power puddling treatment. Numbers in the same item with different lowercase letters indicate a significant difference among treatments according to Tukey's test ($p < 0.05$) (n = 5).

4. Discussion

4.1. The Effect of Integrated Straw Return with Less Power Puddling on Soil Aggregates

We observed that integrated straw return with less power puddling could effectively safeguard soil structure. Compared to control treatment, when straw was returned alone, there was no significant difference in the proportion of large soil aggregates (diameter > 0.5 mm) and soil bulk density. However, when straw was returned with less power puddling, there was a significant increase in the proportion of large soil aggregates and a decrease in soil bulk density (Figure 3). The presence of large soil aggregates generated pores and channels that could enhance soil aeration and contribute to the maintenance of soil structure stability [31], ultimately resulting in a reduced soil bulk density [32,33]. Furthermore, it mitigated the obstruction of soil pores by sedimentation during repeated settling of mud and water, effectively preserving gas exchange pathways within the soil [34]. Therefore, the adoption of the less power puddling significantly contributed to the preservation of soil structure and served as a form of conservation tillage practice.

4.2. The Effect of Integrated Straw Return with Less Power Puddling on Soil Fertility

We noted a positive impact on the storage and release of soil nutrients in the integrated straw return with less power puddling treatment, especially after the jointing stage (Figure 4). This change can be primarily attributed to the implementation of less power puddling. Prior to rice transplanting, the absence of power puddling safeguarded large soil aggregates, thereby preventing the loss of stored ammonium nitrogen [35]. Consequently, soil ammonium nitrogen content was lower when transplanting rice. However, after jointing stage, the protected soil aeration conditions facilitated the decomposition of straw [36,37], leading to a significant increase in soil ammonium nitrogen content from jointing to maturity stages. It can be inferred that less power puddling played a role in adjusting the timing of nutrient release.

Additionally, we observed that regardless of whether less power puddling was implemented or not, there were no significant differences in soil organic matter, alkali-hydrolyzed nitrogen, available phosphorus and available potassium content (Figure 5). However, whenever straw was returned, soil organic matter, alkali-hydrolyzed nitrogen and available potassium content all significantly increased in the short term. It was evident that the enhancement of soil fertility relied on the contribution of straw return [38], while less power puddling only served as an auxiliary measure to create favorable physical conditions for soil, rather than being a primary measure to increase soil fertility. Meanwhile, we found that the content of available phosphorus in soil did not significantly increase, which may be related to its propensity to readily transform into other forms of phosphorus and become fixed in the soil [39,40]. Therefore, in the future, if straw returning is maintained, it may be advisable to consider appropriately reducing the application of nitrogen and potassium fertilizers while maintaining the application of phosphorus fertilizers. In summary, integrated straw return with less power puddling measure represents an efficient management scheme that not only safeguards soil structure but also amplifies the positive effects of straw return.

4.3. The Effect of Integrated Straw Return with Less Power Puddling on Rice Biomass Dry Weight and Nutrient Accumulation

The results indicate that during jointing and heading stages, integrated straw return with less power puddling had no significant effect on rice biomass dry weight, nitrogen, phosphorus and potassium accumulations of rice. This suggests that the impact of less power puddling on rice nutrient accumulations was limited during the early growth stages, and it may be necessary to regulate other influencing factors, such as control the depth of irrigation, adjust the treatment method of straw, adjust the formula and dosage of fertilizers, etc. [41–43], to achieve better effects on biomass dry weight and nutrient accumulation during the earth growth stages.

However, after integrated straw return with less power puddling for three years, we found rice dry biomass and nutrient accumulations were significantly higher than in the straw return treatment at maturity stage (Tables 2 and 3). This indicates that less power puddling can enhance the positive effects from returned straw, and it may relate to the improved nutrient supply capacity of soil. Previous research also indicated that when the soil's fertility was supplemented and enhanced, rice nutrient uptake and accumulation was notably improved [44–46], especially from heading stage to maturity stage, and less power puddling improved nutrient supply and retention capabilities by protecting soil structure [36,47]. Nutrients were released gradually as rice grew, ensuring a continuous nutrient supply for rice to uptake [48–50]. In summary, the implementation of integrated straw return with less power puddling had a positive impact on nutrient accumulations.

4.4. The Effect of Integrated Straw Return with Less Power Puddling on Rice Yield

The results also demonstrate that integrated straw return with less power puddling significantly increased rice yield. This improvement can be primarily attributed to increased nutrient accumulations and improved post-heading stored assimilates accumulation of

rice resulting from these practices, ultimately leading to a higher 1000 g weight and filled grain rate (Figure 6), which, in turn, resulted in higher rice yields (Tables 2 and 4). This provides a new approach to increasing rice yield. Previous strategies mainly focused on increasing materials input, such as fertilizer and soil amendments, or changes in rice genetics [51]. While these methods can contribute to increasing rice yield, the former may lead to the waste of resource and an environmental impact, while the latter requires a significant amount of time and may affect rice quality [52,53]. In contrast, integrated straw return with less power puddling not only improves soil physical and chemical properties to a certain extent, but also simplifies field management, benefiting both farmers and the environment. In conclusion, integrated straw return with less power puddling is beneficial for increasing rice biomass dry weight and nutrient accumulations at the maturity stage, ultimately providing a foundation and new approach to increasing rice yield. However, the results of this study were insufficient to explain the mechanism for increased rice yield. Therefore, future studies need to further explore its effects on soil microbial communities, nutrient cycling and greenhouse gas emissions.

4.5. The Effect of Integrated Straw Return with Less Power Puddling on Economic Benefit and Its Implications for Sustainable Agriculture

The results indicate that integrated straw return with less power puddling could increase economic benefits (Table 5, with an average increase of 18.2% compared with control treatment). This boost in economic benefits can be attributed to the higher rice yields and lower costs resulting from less power puddling, which reduced the utilization of machinery and water resources. Previous research has shown that the integrated economic benefit of straw return was lower [54]; our study results also indicate that the economic benefit of straw return was indeed lower than that of no straw return. However, although the initial investment to implement integrated straw return with less power puddling may be slightly higher than that of not returning straw, this investment pays off in the medium to long term. It could increase yield and reduce production costs, leading to higher economic benefits for farmers. In conclusion, integrated straw return with less power puddling not only increased rice yields but also significantly increased farmers' economic benefits, offering substantial support for the sustainable development of agriculture.

5. Conclusions

Our findings highlight that integrated straw return with less power puddling represents a promising strategy for enhancing both soil fertility and rice yield synergistically. Nevertheless, while our study offers valuable insights, future research should perform more verification in other regions and delve deeper into understanding the specific mechanisms underlying the improvements in soil fertility and crop yields. This should encompass investigations into its impacts on microbial communities, nutrient cycling and greenhouse gas emissions, requiring further refinement of our understanding. Furthermore, due to the diverse regional climates and soil types, it is essential to validate the stability of the effects of integrated straw return with less power puddling in various agro-ecosystems. These comprehensive studies will enable us to more fully uncover the role of integrated straw return with less power puddling in advancing sustainable agricultural development.

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