

Long-term maize straw substituted for chemical fertilizers promoted rice yield due to the altered soil properties in the red paddy soil

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Abstract

Despite straw application within rice agriculture being widely practiced, both in China and globally, there remain few studies on the maize straw substituted for chemical fertilizers. In this study, maize straw substituted for chemical fertilizers to a double-cropping rice field and compared the effects of medium (MS 9,600 kg·ha⁻¹·year⁻¹) and high (HS 19,200 kg·ha⁻¹·year⁻¹) application on rice yield and soil characteristics with that of the application of single chemical fertilizers (CF) over a period of 1982 to present. The yields of late and early rice increased by 42.66 and 25.04% in 2019 and 2020, respectively. The soil bulk density of MS and HS decreased significantly by 15.94 and 33.35% compared with that of CF, whereas total soil porosity increased significantly by 9.46 and 20.17%, respectively. Long-term straw application significantly improved the soil stable aggregates content (> 0.25 mm). Straw application increased soil urease, protease, alkaline phosphatase (ALP), acid phosphatase (ACP) and catalase activities, microbial biomass carbon (C), microbial biomass nitrogen (N), and soil nutrients content compared with CF, especially HS. Correlation analysis showed that double-cropping rice yield was highly significantly correlated with soil bulk density, total porosity, catalase, microbial biomass C, microbial biomass N, and available P. In conclusion, maize straw substituted for chemical fertilizers not only makes rational use of straw resources, but also improves soil characteristics to improve crop yield.

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Abstract

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Keywords: Maize straw substituted; Double-cropping rice; Yield; Soil microbial biomass; Soil physico-chemical properties

Introduction

Agricultural production results in a considerable quantity of straw that include maize, rice, wheat and so on. In fact, China produced 1.04 billion tons of total crops straw in 2015, approximately one-third of global output (Lal, 2005; Medhn, et al., 2017; Li et al., 2018). While the burning of straw is widely practiced in developing countries (Yao et al., 2017; Zhou et al., 2017), it has resulted in a serious waste of resources and environmental pollution, including the loss of almost all C and N and the emissions of various greenhouse gases (Sun et al., 2016). Consequently, the Chinese government has strictly prohibited the direct burning of straw, promoting instead the return of straw to agricultural fields as the most environmentally-friendly option (Zhao et al., 2018).

The crops straw is rich in N, phosphorus (P), potassium (K), and other nutrient elements. The decomposition of straw can improve soil fertility by supplementing available soil nutrients such as N or K as well as soil enzyme activities, which in turn increase the efficiency of N use and crop yields (Zhao et al., 2016a; Yang et al., 2017; Akhtar et al., 2018; Gao et al., 2020; Yang et al., 2020a). Moreover, straw application can promote the accumulation of soil organic matter and improved soil structure by decreasing soil bulk density and increasing porosity (Zhang et al., 2016). Soil microorganisms play a key role in soil nutrient conversion, energy transformation, the formation of humus, and the mediation of straw decomposition (Chen et al., 2014; Guo et al., 2014; Cong et al., 2020). Straw application can promote the growth and activity of soil microorganisms and enhance soil microbial biomass (Xia et al., 2019). Long-term straw application can increase soil microbial diversity and change the microbial community structure (Peng et al., 2016; Maarastawi et al., 2018). However, the effect of straw incorporation is affected by many factors. Wang et al. (2018a) determined that straw application amount more than 9,000 kg·ha⁻¹ year⁻¹ to achieve significant differences in soil physical properties and soil available nutrients. The CH₄ annual emission of ditch-buried wheat straw application was significantly lower than that of wheat straw application with rotary tillage, and the N₂O annual emission was significantly lower than wheat straw application with plowing (Hu et al., 2016). Chen et al. (2017) showed that total phospholipid fatty acid (PLFA), bacterial biomass, and actinomycetes biomass of Luvisols soil were significantly increased through the return of straw, whereas no significant difference was identified in Anthrosols soil. In addition, Su et al. (2020) showed that lower fungal community diversity and higher abundance of fungal pathogen were observed with maize straw application, especially at high application rates, compared with wheat straw application. In summary, it implied that the effects of straw application to the field are related to the amounts of straw application, the methods of straw application, soil types, straw types and so on.

Double-cropping rice and maize agriculture is widely implemented in Hunan province, China, the sown area

of double-cropping rice was 2,254,000 hectares and that of maize was 387,000 hectares, which were the first and second largest of sown area in 2019 (Hunan Statistics Yearbook, 2020). The disposal of the large quantities of straw produced through maize agriculture has been a perpetual challenge. At present, maize straw can be used to make feed, industrial raw materials and fuel in addition to returning to the field. However, the above uses have higher production cost, greater technical difficulty, lower economic benefits and easier to cause environmental pollution, compared with maize straw application to the field. Chemical fertilizers partly replaced by maize straw has many advantages, such as reducing the amount of fertilizer can reduce the production cost, reduce the risk of agricultural non-point source pollution and so on. However, it is not clear how maize straw substituted for chemical fertilizers affects crop yield. In this study, the crushed maize straw replaced part of chemical fertilizers was applied in double-cropping rice field to examine the effects of maize straw application on the yield of double-cropping rice and soil characteristics. The purpose of this study is to have a relatively comprehensive understanding of the effects of long-term maize straw replaced part of chemical fertilizers on the yield and soil characteristics of double-cropping rice. The present study would make rational use of straw resources, reduce agricultural production costs and reduce agricultural non-point source pollution caused by excessive application of chemical fertilizer. It is hoped to provide a scientific basis for building a resource-saving and environment-friendly agricultural production environment.

Materials and methods

Site description

The experimental site is hosted by the experimental farm of Hunan Agricultural University in Changsha City, Hunan Province, China (28deg 18' N, 113deg 08' E, 50 m above sea level). The paddy soil of the site is dryland soil developed from Quaternary red clay and is classified as an Oxisol according to the United States Department of Agriculture (USDA) Soil Taxonomy (Yang et al., 2020b).

Experimental design

The present study shows the results of a long-term double-cropping winter fallow rotation rice cultivation experiment that was initiated in 1982 and contained 36 experimental plots. The experiment involved three experimental treatments: (1) application of chemical fertilizers only (CF); (2) medium maize straw replaced 1/3 of N fertilizer, and straw application amount was 9,600 kg*ha⁻¹*year⁻¹ (MS); (3) high maize straw replaced 2/3 of N fertilizer, and straw application amount was 19,200 kg*ha⁻¹*year⁻¹ (HS), fertilizers (urea, superphosphate and potassium chloride) were used in both the MS and HS treatments to supplement deficiencies in N, P and K within straw application and to ensure their uniform content among three treatments. The present study randomly selected 9 replicates under the same environmental conditions for each treatment. The fertilizer rates applied during both the early and late rice seasons were 150 kg N ha⁻¹, 75 kg P₂O₅ha⁻¹, and 150 kg K₂O ha⁻¹. Maize straw was chopped and incorporated into the approximately 0–20 cm soil depth. And maize straw was used in the treatments characterized by average contents of N, P, and K of 10.4 g kg⁻¹, 5.93 g kg⁻¹, and 12.6 g kg⁻¹, respectively. In the past five years, the Xiangzaoxian15 was selected for early rice varieties, which was transplanted in late April and harvested in early July, while VY46 was selected for late rice varieties, transplanting in mid-July and harvested in late October.

Sampling

Rice was harvested to calculate yield, during which rice plants were randomly selected from each plot for the analysis of yield components. Soil samples (depth of 0–20 cm) were collected at different points in each plot in 2019 in the late and early rice harvest periods according to the S path method, labeled as 2019LR and 2020ER, respectively. Each soil sample was divided into two parts. The first part was air-dried for the determination of soil water-stable aggregates, pH, soil organic matter, and soil nutrition content. The second part was stored at 4 degC for the determination of soil microbial biomass C and N and soil enzyme activities (Lu et al., 2018). In addition, within each plot, a steel support was used to push a uniform volume ring knife (5 cm in diameter; 100 cm³ in volume) into the soil for the collection of three soil samples in 2020ER for determining the soil bulk density and porosity (Secco et al. 2021).

Analytical methods

Rice yield and yield components

1 x 1m was selected from each experimental area to determine the yield of rice. Rice yield components were measured according to Zhong (2021). Five plants were randomly sampled from each plot at harvest season in each year, and the yield components were calculated about the plant individual level.

Soil physical properties

The soil samples were placed in a water bath for 48 h, following which the volumetric water content at saturation was taken as the total porosity. Soil samples were then dried and the ratio of dry soil mass to the volume of the cylinder was taken as a measure of soil bulk density (Awe et al., 2020). Determination of soil water-stable aggregates was as according to Lu et al. (2018).

Soil organic matter, pH, and nutrient levels

The analytical methods used to determine soil organic matter, pH, and nutrient levels are described in Zhang et al (2021). Soil organic matter (SOM; g kg⁻¹) was determined by the potassium dichromate external heating method; pH by the use of deionized water to remove CO₂ (1:1 soil/water, w/v); TN (g kg⁻¹) by the Kjeldahl N method; TP (g kg⁻¹) by the NaOH fusion molybdate blue colorimetric method; total K (TK, g kg⁻¹) by flame photometry after NaOH fusion; available N (AN, mg kg⁻¹) by alkaline hydrolysis diffusion; available P (AP, mg kg⁻¹) by colorimetry following extraction with 0.5 mol L⁻¹ NaHCO₃ (pH = 8.5); available K (AK, mg kg⁻¹) by flame photometry following extraction with 1 mol L⁻¹CH₃COONH₄ (pH = 7.0).

Soil enzyme activity

Sodium phenate-sodium hypochlorite colorimetry was used to determine urease activity (Yu et al., 2019); protease activity by the Folin-Ciocalteu colorimetry method using casein as a substrate and culturing in tris-hydrochloric acid buffer (Borase et al., 2020); acid phosphatase (ACP) and alkaline phosphatase (ALP) activities by the colorimetric method with *p*-nitrophenyl phosphate as substrate (Xie et al., 2017); catalase activity by potassium permanganate titration (Liu et al., 2020). All samples were analyzed without a matrix control and all enzyme activities were measured without a soil control.

Soil microbial biomass

Soil microbial biomass C and N (MBC & MBN) were determined by the chloroform fumigation-K₂SO₄ extraction method, following which extract C and N were measured using the same methods as that for soil organic C and soil TN, respectively (Zhao et al., 2016b).

Computational formula that the rice yield and soil characteristics rate of changes

The rice yield and soil characteristics rate of changes after long-term maize straw substituted for chemical fertilizers was calculated by the following formula:

$$R = (S - CF) / CF \times 100\%$$

where *R* is the rate of changes, *S* is the rice yield and soil characteristics under maize straw substituted for chemical fertilizers treatments, and *CF* is the rice yield and soil characteristics under single chemical fertilizers treatment.

Statistical analyses

All data were collated using Microsoft Office Excel 2016. One-way analysis of variance (ANOVA) was applied to all data in SPSS19.0 (IBM), followed by Duncan's multiple range test (*P* < 0.05). GraphPad Prism 7.0 was used for plotting. Principal component analysis (PCA) was conducted and visualized in Origin 2018. Mantel tests were also performed between rice yield and soil characteristics in R with the mantel function in the "vegan" package (version 4.0.4) (Yuan et al., 2021)

Results

Effect of maize straw substituted for chemical fertilizers on double-cropping rice yield and its components

There was no significant difference in rice yield between the CF and MS treatments in 2019LR (Fig. 1), whereas the yield of the HS treatment exceeded that of CF by 42.66% (Fig. 5a). The same trend was observed in 2020ER, with the yield of HS exceeding that of CF by 25.04% (Fig. 5b).

The increase in rice yield was due to the increases in panicle number and grain filling rate (Table 1). The panicle numbers of MS and HS in 2019LR exceeded those of CF by 19.59 and 31.96%, respectively. In contrast, the panicle number of only HS was significantly higher than that of CF by 15.16% in 2020ER, whereas there was no significant difference between MS and CF.

The same trends were observed in the grain filling rate in 2019LR and 2020ER, with no significant difference between CF and MS, while the grain filling rate of HS exceeded those of CF and MS by 11.29 and 17.73%, respectively. There were no significant differences in plant height and panicle length between the three treatments.

Effect of maize straw substituted for chemical fertilizers on soil physical properties

The soil bulk densities of MS and HS were significantly reduced by 15.94 and 33.35%, respectively compared to that of CF (Fig. 2a, Fig. 5b), whereas soil total porosity significantly increased by 9.46 and 20.17%, respectively (Fig. 2b, Fig. 5b).

The diameters of soil aggregates among the three treatments were mainly within 0.25–2 mm, followed by 0.053–0.25 mm, <0.053 mm, and >2 mm, and there were no significant differences between the three treatment in the dominance of the >2 mm and <0.053 mm diameter categories (Fig. 2c). The proportions of soil aggregates with a diameter of 0.25–2mm were significantly higher in MS and HS compared to that in CF, whereas the proportions of soil aggregates with a diameter of 0.053–0.25mm were significantly lower in MS and HS. There were no significant differences in the proportions of soil aggregates with diameters of 0.25–2mm and 0.053–0.25mm between MS with HS.

Long-term straw application significantly increased the proportion of stable aggregate content (SAC; > 0.25 mm) in soil (Fig. 2d), with SAC in MS and HS exceeding that in CF by 11.79 and 14.07%, respectively (Fig. 5b), whereas there was no significant difference between MS with HS.

Effect of maize straw substituted for chemical fertilizers on soil enzyme activities and microbial biomass

Urease activity in HS significantly exceeded that in CF by 52.42 and 36.43% in 2019LR and 2020ER, respectively (Fig. 3a, Fig. 5), whereas there was no significant difference between CF and MS.

The activity of soil protease in HS significantly exceeded that in CF by 58.55 and 122.91% in 2019LR and 2020ER, respectively (Fig. 3b, Fig. 5), whereas there was no significant difference between MS with CF.

The ALP activities in MS and HS exceeded that of CF by 39.25 and 77.47% in 2019LR and by 28.13 and 59.09% in 2020ER (Fig. 3c, Fig. 5), respectively, whereas there was no significant difference between MS and HS.

The ACP activities of MS and HS significantly exceeded that of CF by 43.62 and 98.30% in 2019LR and by 64.81 and 89.02% in 2020ER (Fig. 3d, Fig. 5), respectively.

Soil catalase activity among the three treatments increased with increasing straw application (Fig. 3e), with soil catalase activity in MS and HS significantly exceeding that in CF by 45.93 and 108.50% (Fig. 5a) and by 28.33 and 68.94% (Fig. 5b) in 2019LR and 202ER, respectively.

The MBC contents of MS and HS significantly exceeded that of CF by 72.25 and 129.49% in 2019LR, respectively, whereas only MBC contents of HS significantly exceeded that of CF by 85.11% in 2020ER (Fig.

4a, Fig. 5), with no other significant differences between treatments.

The MBN contents of MS and HS significantly exceeded that of CF by 154.29 and 250.53% and by 50.71 and 108.21% in 2019LR and 2020ER, respectively. Fig. 4b and Fig. 5 shown the significant differences among the treatments in 2019LR and 2020ER.

Effect of maize straw substituted for chemical fertilizers on soil pH and nutrients

The highest SOM content was observed in HS, exceeding that in CF by 41.66 and 44.49% in 2019LR and 2020ER, respectively (Table 2, Fig. 5). There was no significant difference in SOM between MS and CF in 2019LR, whereas the SOM of MS exceeded that of CF by 22.34% in 2020ER.

The soil TN contents of MS and HS significantly exceeded that of CF by 25.04 and 44.94% and by 35.82 and 45.83% in 2019LR and 2020ER respectively, whereas there was no significant difference between MS with HS.

The soil AN contents of MS and HS significantly exceeded that of CF by 29.40 and 42.62% and by 21.57 and 42.87 in 2019LR and 2020ER, respectively. There was no significant difference in AN between MS and HS in 2019LR, whereas there were significant differences among the three treatments in 2020ER.

The soil AK content of HS significantly exceeded that of CF by 106.58% in 2019LR, whereas there was no significant difference between CF and MS. The AK contents of MS and HS significantly exceeded that of CF in 2020ER by 87.30 and 185.41%, respectively.

The soil pH values of MS and HS were significantly lower than that of CF by 4.63 and 6.00%, respectively in 2019LR, although there was no significant difference between MS and HS. In 2020ER, the pH values of MS and HS were significantly lower than that of CF by 4.11 and 6.63%, respectively, and the pH of HS significantly decreased by 2.78% in comparison to that of MS.

The soil TP of HS significantly reduced by 31.54 and 29.29% compared to that of CF in 2019LR and 2020ER, respectively, whereas there was no significant difference between CF and MS.

The soil AP of HS was significantly lower than that of CF by 43.96% in 2019LR, whereas there was no significant difference between MS and HS. The AP values of MS and HS were significantly reduced by 19.48 and 56.57% compared with that of CF in 2020ER, respectively, and there were significant differences among all treatments.

There was no significant difference in soil TK contents among all treatments.

Correlations between double-cropping rice yield and soil characteristics

The results of principal component analysis (PCA) showed that correlations between double-cropping rice yield and soil characteristics differed among the different treatments (Fig. 6). The first two principal components, PC1 and PC2, of 2019LR explained 77.1 and 7.6% of observed variation, respectively (Fig. 6a), whereas that of 2020ER explained 81.5 and 7.9%, respectively (Fig. 6b). There were significant differences in rice yield and soil characteristics among all three treatments.

The Mantel test showed that yield was highly significantly correlated with soil TP, AP, MBC, and MBN and with the activities of urease, ALP, and catalase. Yield was significantly correlated with AK and the activities of protease and ACP. There were no significant correlations between yield and TN, TK, SOM, AN, and pH in 2019LR (Fig. 7a).

However, yield was highly significantly correlated with soil AN, AP, AK, MBC, and MBN as well as with catalase activity, soil bulk density, and total porosity. Yield was significantly correlated with TN, SOM, pH, and SAC as well as with ACP and ALP activities. There was no significant correlation between yield and TP and TK and between urease and protease activities in 2020ER (Fig. 7b).

Pearson's correlation analysis showed that there were no significant correlations between TK and all soil characteristics. TN was significantly positively correlated with SOM, AN, AK, MBC, and MBN and with

activities of urease, protease, ALP, and catalase in 2019LR, whereas TN was significantly negatively correlated with TP, AP, and pH, and not significantly correlated with ACP (Fig. 7a).

SOM was significantly positively correlated with AN, AK, MBC, and MBN and the activities of protease and catalase, whereas it was significantly negatively correlated with TP, AP, and pH. However, there was no significant correlation between SOM and the activities of urease, ACP, and ALP. ACP had a significantly positive correlation with AN, a significantly negative correlation with pH, and no significant correlation with TP, TK, AP, and AK. There was a significant positive correlation between microbial biomass and soil enzyme activities, with only the relationships between microbial biomass and ACP and protease not reaching a significant level.

TN was positively correlated with SOM, AN, AK, MBC, MBN, ACP, ALP, catalase, total porosity, and SAC in 2020ER, whereas it was negatively correlated with pH, AP, and soil bulk density, and not significantly correlated with TP and protease. TP was significantly positively correlated with pH, AP, and bulk density, whereas it was significantly negatively correlated with SOM, AK, MBN, urease, ALP, catalase, and total porosity, but not significantly correlated with AN, MBC, protease, and ACP.

SOM was significantly positively correlated with AN, AK, MBC, MBN, urease, ACP, ALP, catalase, total porosity, and SAC, whereas it was significantly negatively correlated with pH, AP, and soil bulk density. However, there was no significant correlation between MBC and protease activity and the correlation between microbial biomass and enzyme activity was basically consistent with the results of 2019LR (Fig. 7b).

Bulk density was significantly positively correlated with TP, AP, and pH, whereas it was significantly negatively correlated with other soil characteristics. The correlations between total soil porosity and other soil properties were completely opposite to that for soil bulk density. SAC was positively correlated with TN, SOM, AN, AK, MBC, MBN, ACP, and catalase, whereas it was negatively correlated with AP and not significantly correlated with TP, pH, urease, protease, ALP, bulk density, and total porosity.

Discussion

Rice yield

Wang et al.(2018a) showed that straw application under equal amount of chemical fertilizers increased the maize yield, and the maize yield increased with straw application amount increased. It might be that straw application provided a lot of nutrients, promoted crop growth and increased yield. The results of the present study also showed that straw substituted for chemical fertilizers increased rice yield (Fig.1), but it might be that chemical fertilizers partly replaced by maize straw increased rice yield by improving soil characteristics. Meanwhile, straw substituted for chemical fertilizers can reduce non-point source pollution while rationally using straw resources, which has a positive effect on the agricultural environment.

The number of panicles and grain filling rate are influenced by fertilizers input, water management, and rice variety, and reasonable fertilization model can increase crop yield by increasing panicles number, grain filling rate and so on (Zhong et al., 2021).The results of the present study showed that long-term straw substituted for chemical fertilizers improved rice yield by increasing the panicles number and grain filling rate (Table 1), moreover, HS treatment had a better yield-increasing effect compare with MS treatment, consistent with the results of Xia et al. (2018).

Maize straw application significantly increased 1,000-grain weight in 2019LR, whereas there was no significant difference in 2020ER (Table 1), which could be attributed to differences in rice varieties and climatic conditions. In this study, maize straw substituted for chemical fertilizers increased rice yield by improving soil physical properties, increasing soil enzyme activity, microbial biomass, and soil nutrients compared with CF.

Soil physical properties

Straw forms humus under the action of soil microorganisms, which effectively increases SOM content, changes the overall soil properties, reduces soil bulk density and increases soil total porosity. Soil bulk density is an

important physical parameter of soil that is commonly used to quantify soil compactness. Soil compactness reflects the tightness of soil and directly affects soil aeration and the development of plant roots (Silva et al., 1997). Soil total porosity contributes to soil structure and positively contributes to the conduction of soil water and air and plant root growth (Luo et al., 2010). Straw application reduced soil bulk density and increased soil total porosity (Fig. 2a; Fig. 2b), thereby promoting the growth of rice roots and increasing rice yield, consistent with the results of Yang et al. (2020a).

There were highly significant correlations between yield and soil bulk density, total porosity (Fig. 7b), indicating that long-term straw application improved soil physical structure and promoted the growth of rice roots and nutrient uptake, thereby partly explaining the increase in rice yield.

Soil aggregates are the structural units of soil and their physical stability is considered a key parameter of soil quality (Menon et al., 2020). Soil aggregates, particularly water-stable aggregates, have a great influence on soil structure and are very important for the migration and maintenance of soil moisture and nutrients (Bailey et al., 2013; Merino-Martín et al., 2020). The diameters of soil aggregates in the present study mainly fell within the range of 0.053–2 mm (Fig. 2c), consistent with the results of Zhang et al. (2021). At the same time, long-term straw application increased the proportion of SAC (> 0.25 mm) (Fig. 2d), indicating that nutrients released by straw degradation directly or indirectly promote the growth of soil aggregates, but also improve the stability of soil aggregates, consistent with the results of Huang et al. (2020). The present study found that SAC benefitted rice yield and noted a significant correlation between soil stability aggregates and yield (Fig. 7b). This might be that maize straw substituted for chemical fertilizers has improved SAC, maintained soil nutrients, improved soil quality, and thereby increased crop yields.

Soil enzyme activities

Soil urease, protease, ACP, and ALP play an important role in the cycle of soil N and P, and their products are easy to be absorbed and utilized by crops (Li et al., 2017). Wu et al. (2020) showed that straw application significantly increased activities of soil enzymes, and Zhang et al. (2016) found that soil urease, phosphatase, and invertase activities increased with increasing amount of straw application, consistent with the results of the present study. There were significantly increased activities of soil urease, protease, ACP, and ALP in HS as compared to that in CF (Fig. 3), which could possibly be attributed to increased soil microbial metabolism resulting from straw application (Yang et al., 2021). The increase of soil urease, protease, ACP, and ALP activities indicated the increase of nutrients that can be absorbed and utilized by rice, which might be one of the reasons for increasing rice yield.

Catalase enables the decomposition of peroxide during metabolism, thereby preventing its toxic effects on crops (Liu et al., 2017). The present study found chemical fertilizers partly replaced by maize straw increased catalase activity, especially HS treatment. And a highly significant correlation between rice yield and catalase and a positive correlation between soil porosity and catalase. (Fig. 7). This result could be indicated that straw application improved the soil environment and increased rice yield.

Soil microbial biomass

Soil microbial biomass is not only a storage of soil nutrients, but also an important source of nutrients available for plant growth, which plays an important role in increasing the number and activity of soil microorganisms, accelerating soil nutrient cycling, improving soil bioavailability and increasing rice nutrient absorption, so as to increase rice yield (Lundquist et al., 1999). MBC and MBN both reflect the growth and activities of soil microorganisms and generally increase through the incorporation of straw (Shahbaz et al., 2017). Straw application has also significantly increased soil MBC and MBN in paddy fields (Wang et al., 2018b). Maize straw application significantly increased MBC and MBN, especially HS treatment (Fig. 4), it might be straw input increase the C source. MBC and MBN were highly significantly correlated with rice yield (Fig. 7).

SOM, soil nutrients and pH

SOM is a major determinant of soil ecosystem quality and includes a complex mixture of organic matter

from litter, root turnover, and microorganisms. These components are important sources of plant nutrients and play a key role in the global C cycle and climate warming (Li et al., 2019). Numerous studies have demonstrated that the amount of maize straw application showed a positive correlation with SOM (Ren et al., 2018; Hao et al., 2019; Wu et al., 2019; Yan et al. al., 2020), it might be that straw application increased soil microbial biomass, this study showed a same result (Fig.4). At the same time, SOM increased crop yield (Liu et al., 2021). The present study showed that maize straw application improved SOM content, and HS treatment had a better effect than MS treatment (Table 2). Meanwhile, this is one of the reasons for increasing yield.

The maize straw application in the present study improved all soil nutrients, except TP, AP, and TK (Table 2), consistent with the results of Zhao et al. (2014) and Guan et al. (2020), but contradicting those of Dong et al. (2012), who found no significant difference in AN and AK between straw application treatments and CF. These conflicting different results depend on soil type, straw type, fertilization quantity, and planting system.

The present study showed that straw application reduced soil pH (Table 2), consistent with the findings of Zhao et al. (2009) and Wang et al. (2018a). However, Zhao et al. (2020) showed that straw incorporation increased soil pH. This difference might be caused by soil type, straw type and so on. Maize straw application also significantly reduced TP and AP (Table 2), which may be attributed to differences in straw decomposition rates between MS and HS due to differences in the amount of straw application. Meanwhile, the decomposition of straw released organic P, and loss of organic P by runoff significantly exceeded that of inorganic P (Wang et al., 2014). In addition, the increase in soil organic matter reduced adsorption of P to soil, thereby facilitating the transfer soil P to the liquid phase and increasing soil P loss through runoff (Nobile et al., 2020).

In addition, only two straw replacement amounts were set in this study, so it is necessary to further study the effects of different straw replacement amounts on soil quality and rice yield in order to confirm an optimal straw replacement amount.

Conclusions

This study showed that the maize straw substituted for chemical fertilizers significantly improved double-cropping rice yield by promoting soil quality, including soil physical properties, soil enzyme activities, microbial biomass, and soil nutrients, especially in HS treatment. The yield of double-cropping rice was highly significantly correlated with soil bulk density, total porosity, catalase, MBC, MBN, and AP, and was significantly correlated with SAC and ACP, whereas there was no significant correlation with TK. In summary, straw substituted for chemical fertilizers is a high-yield, resource-saving and soil improvement operation mode.

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table1 Effects of different fertilization treatments on the rice yield components in the 2019LR (2019 late rice) and 2020ER (2020 early rice).

	Treatment	Plant height(cm)	Panicle length (cm)	Panicle no.($\times 10^4/\text{hm}^2$)	Grain filling rate (%)	1000-grain weight (g)
2019LR	CF	115.03±2.11a	23.50±0.50a	261.96±16.87c	67.67±3.21b	23.30±0.36c
	MS	118.67±1.62a	23.90±1.47a	313.27±12.38b	72.00±1.00b	24.41±0.41b
	HS	113.83±4.16a	23.27±1.70a	345.68±16.87a	79.67±3.21a	25.45±0.43a
2020ER	CF	71.68±3.06a	18.52±0.64a	202.33±10.41b	75.31±2.37b	24.08±0.45a
	MS	72.30±2.72a	17.98±0.46a	220.00±19.31ab	76.81±1.75b	24.01±0.78a
	HS	74.55±2.34a	18.59±0.49a	233.00±5.00a	83.81±0.36a	23.97±0.85a

Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.	Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.	Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.	Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.	Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.	Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.	Note: The above data represent mean \pm standard deviations. Different lowercase letters mean significant difference at 5% level. The data and the lowercase letters share the same meaning in Table 2.
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Table2 Soil pH and nutrients in 2019LR and 2020ER

	Treatment	pH	SOM (g/kg)	TN (g/kg)	TP (g/kg)	TK (g/kg)	AN (mg/kg)	AP (mg/kg)	AF (mg/kg)
2019LR	CF	5.12 \pm 0.10a	25.03 \pm 3.23b	1.42 \pm 0.08c	1.15 \pm 0.10a	12.21 \pm 0.45a	119.20 \pm 4.07b	16.22 \pm 2.02a	56.12 \pm 1.10b
	MS	4.88 \pm 0.03b	33.14 \pm 2.99ab	1.77 \pm 0.10b	1.06 \pm 0.14a	12.10 \pm 0.05a	154.24 \pm 6.50a	13.28 \pm 1.89a	71.12 \pm 1.10b
	HS	4.82 \pm 0.05b	35.48 \pm 4.77a	2.05 \pm 0.15a	0.79 \pm 0.05b	12.27 \pm 0.11a	170.09 \pm 10.71b	13.32 \pm 1.10b	114.12 \pm 1.10b
2020ER	CF	5.21 \pm 0.10a	24.62 \pm 2.53c	1.42 \pm 0.02b	0.97 \pm 0.07a	11.85 \pm 1.15a	129.47 \pm 0.35c	29.54 \pm 1.88a	77.12 \pm 1.10b
	MS	4.99 \pm 0.05b	30.00 \pm 1.33b	1.92 \pm 0.14a	0.89 \pm 0.15a	11.61 \pm 0.59a	157.43 \pm 12.75b	23.78 \pm 1.52b	144.12 \pm 1.10b
	HS	4.86 \pm 0.13c	35.41 \pm 1.76a	2.06 \pm 0.13a	0.69 \pm 0.12b	12.35 \pm 0.22a	184.99 \pm 7.16a	12.87 \pm 1.87c	219.12 \pm 1.10b

Note: SOM: soil organic matter; TN: total nitro- gen; TP: total phos- phorus; TK: total potas- sium; AN: alkali- hydrolyzale nitro- gen; AP: avail- able phos- phorus; AK: avail- able potassium.									
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