

## Effects of Straw Pellet Incorporation on Soil Nutrients and Winter Wheat Yield Postprint

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### Abstract

To clarify the feasibility of promoting and applying straw pellet incorporation in agricultural production, a field microplot experiment was conducted in the winter wheat-summer maize double-cropping region of Shandong Province to investigate the effects of no straw incorporation (CK), conventional crushed straw incorporation (CCSI), and straw pellet incorporation (GSI) on topsoil nutrient content, winter wheat population tiller number, flag leaf net photosynthetic rate, chlorophyll content, dry matter accumulation and distribution, and wheat yield. The results showed that, compared with CK and CCSI treatments, GSI treatment significantly increased soil organic matter, alkaline-hydrolyzable nitrogen, and available phosphorus contents; increased basic seedling number and tiller-to-ear rate, and significantly increased effective ear number by 13.23% and 16.64%. Meanwhile, GSI treatment significantly increased leaf area index, flag leaf chlorophyll content, and net photosynthetic rate at the grain-filling stage, improved flag leaf photosynthetic performance after anthesis, and promoted aboveground dry matter accumulation and its translocation to grain. Compared with CK and CCSI treatments, GSI treatment significantly increased post-anthesis dry matter translocation to grain by 19.65% and 14.75%, and significantly increased grain yield by 9.69% and 10.71%.

Correlation analysis indicated that grains per ear and thousand-grain weight had no significant effect on yield, and the increase in effective ear number was the main reason for the yield increase from straw pellet incorporation. Therefore, straw pellet incorporation can be used as a safe and effective incorporation method and promoted in agricultural production.

## Full Text

### Abstract

To clarify the feasibility of incorporating granulated straw into soil in the Huang-Huai-Hai region, a micro-plot field experiment was conducted in a winter wheat/summer maize rotation cropping system at Dezhou Agricultural Research Academy of Shandong Province. The effects of granulated straw incorporation on soil nutrient contents, wheat growth, and yield components were investigated. Three treatments were included in the experiment: no straw incorporation (CK), conventional chopped straw incorporation into the 0-15 cm soil layer (CCSI), and granulated straw incorporation into the 0-15 cm soil layer (GSI). All treatments were arranged in a completely randomized design with three replicates. Indices determined during the winter wheat season included wheat tiller number, chlorophyll content and net photosynthetic rate of flag leaf, dry matter accumulation and its contribution to yield, soil nutrient contents, and wheat yield after harvest.

The results showed that compared with CK, both CCSI and GSI treatments significantly increased soil nutrient contents. The contents of soil organic matter, available nitrogen, and available phosphorus under GSI treatment were higher than those under CCSI treatment by 8.54%, 6.12%, and 6.25%, respectively. GSI treatment also improved seedling emergence and increased tiller number. Compared with CK and CCSI treatments, GSI treatment increased the number of basic seedlings by 1.63% and 19.39%, tiller number by 3.16%-13.23% and 11.28%-16.64%, fertile tiller rate by 9.88% and 4.92%, and spike number by 13.23% and 16.64%, respectively. Meanwhile, GSI treatment delayed leaf senescence and increased leaf area index at filling stage by 21.79% and 16.97%, increased chlorophyll content by 7.56%-47.24% and 0.53%-12.88%, and increased net photosynthetic rate of flag leaf at grain-filling stage by 15.76% and 3.33% compared with CK and CCSI treatments, respectively. Improvement in leaf photosynthetic characteristics contributed to the increase in aboveground dry matter production and translocation from vegetative organs to grain. Compared with CK and CCSI treatments, GSI treatment increased aboveground biomass at flowering stage by 17.09% and 6.33%, aboveground biomass at maturity stage by 9.85% and 18.91%, and translocation of accumulated dry matter after flowering stage to grain-filling stage by 19.65% and 14.75%, respectively. Finally, GSI treatment achieved the highest grain yield, which was 9.69% and 10.71% higher than those under CK and CCSI treatments.

Further analysis showed that grain yield had no significant correlation with kernel number per spike and thousand-kernel weight, but it had significant positive correlation with effective spike number. This indicated that spike amount was the main reason for the grain yield increase. Therefore, granulated straw incorporation was an effective option for straw return to the soil in agricultural production in the Huang-Huai-Hai region.

**Keywords:** Granulated straw incorporation; Soil nutrient content; Winter

wheat; Tiller number; Dry matter accumulation; Grain yield

## Introduction

Crop straw is an important agricultural byproduct. According to statistics, China's annual crop straw production reaches 840 million tons [?]. In recent years, with improvements in agricultural production levels and changes in farmers' lifestyles, large amounts of straw have been randomly discarded or burned in the field, causing resource waste and environmental pollution [?]. Straw incorporation can increase soil organic matter content, improve soil structure, enhance soil water content and microbial activity, and promote crop yield increase [?]. It is the main approach for efficient straw resource utilization and an important measure for achieving combined cultivation and conservation of farmland. However, in production practice, large amounts of straw directly returned to the field through mulching or shallow tillage often affect straw decomposition, sowing and emergence of subsequent crops, leading to low emergence rates, difficult root establishment, and yield reduction [?], which greatly reduces farmers' enthusiasm for straw incorporation. Only about 20% of the total straw produced is returned to the field annually [?]. As the saying goes, "straw is beneficial when used, but harmful when abandoned" [?].

Previous studies have shown that straw properties and physical form can affect straw decomposition rate and crop yield [?]. Shortening straw length or increasing the degree of mixing between straw and soil can significantly improve straw decomposition rate [?], reduce soil bulk density, enhance soil water-holding capacity [?], and improve water use efficiency [?]. To solve the negative problems caused by seasonal concentrated straw incorporation, Wang et al. [?] proposed a new straw return method—granulated straw incorporation—which transforms lightweight, fluffy straw into dense, small-volume solid particles applied to soil. Granulated straw incorporation can not only increase the soil's capacity to accommodate straw, improve incorporation performance, and accelerate straw decomposition rate for rapid soil fertility improvement, but also increase deep soil water content and optimize crop growth environment [?]. However, current research on granulated straw incorporation remains limited, and its effects on soil fertility conditions and crop growth and development are still unclear.

The Huang-Huai-Hai region is China's main wheat production area, with wheat (*Triticum aestivum*) production accounting for 56% of the national total [?]. In recent years, after summer maize (*Zea mays*) harvest, large amounts of straw directly returned to the field through crushing and rotary tillage often cause problems such as seedling deficiency, poor seedling quality, and insufficient population size [?]. Therefore, there is an urgent need to seek more effective straw incorporation methods. In view of this, this study conducted a micro-plot field experiment in the winter wheat-summer maize double cropping system in Shandong Province to investigate the effects of granulated straw incorporation on soil nutrient content and winter wheat yield formation, aiming to optimize straw incorporation methods and provide theoretical basis and technical support for

safe straw incorporation in the Huang-Huai-Hai region.

### 1.1 Experimental Site

The experiment was conducted from 2013 to 2014 at the experimental farm of Dezhou Agricultural Science Research Institute in Huangheya Town, Decheng District, Dezhou City, Shandong Province (116°18 E, 37°27 N). This region is a typical winter wheat-summer maize double cropping area with a warm temperate continental monsoon climate. The annual mean temperature is 13.4°C, the annual accumulated temperature  $\geq 10^{\circ}\text{C}$  is 4,621°C, the frost-free period is 205 days, and the annual rainfall is 510 mm, mainly concentrated from July to September. Daily mean aquic soil with uniform fertility. The basic physicochemical properties of the 0–20 cm soil layer before the experiment:  $\text{pH} 7.76$ , organic matter  $12.96 \text{ g} \cdot \text{kg}^{-1}$ , alkaline hydrolyzable nitrogen  $40.65 \text{ mg} \cdot \text{kg}^{-1}$ , available phosphorus  $3.68 \text{ mg} \cdot \text{kg}^{-1}$ , total nitrogen  $0.78 \text{ g} \cdot \text{kg}^{-1}$ , and available potassium  $128.38 \text{ mg} \cdot \text{kg}^{-1}$ .

[Figure 1: see original paper]

### 1.2 Experimental Materials

The tested straw was collected from the aboveground part of summer maize ('Zhengdan 958') after harvest in 2013. After natural air-drying, part of the straw was crushed to 6–10 cm using a 9CFZ-680 crusher and stored in a drying room as chopped straw. The other part of air-dried straw was first ground through a 2 mm sieve using an HC-2000 grinder, then 30%–35% distilled water was added and mixed evenly. The mixture was extruded at room temperature using an FTHBCX 350 feed pellet machine to produce rod-shaped cylinders with a diameter of 4 mm and length of 4–6 cm. After cooling and air-drying, these were stored in a drying room as straw pellets. The bulk densities of chopped straw and straw pellets were  $26.44 \text{ kg} \cdot \text{m}^{-3}$  and  $242.93 \text{ kg} \cdot \text{m}^{-3}$ , respectively.

### 1.3 Experimental Design

The experiment consisted of three treatments: no straw incorporation (CK), conventional chopped straw incorporation (CCSI), and granulated straw incorporation (GSI), with three replicates for each treatment arranged in a completely randomized design. Micro-plots were constructed starting on October 5, 2013. After the previous maize harvest, all aboveground straw and stubble were removed. Trenches 40 cm deep and 10 cm wide were dug around each micro-plot, and cement boards (300 cm  $\times$  6 cm  $\times$  55 cm, length  $\times$  width  $\times$  height) were placed in them. Two layers of plastic film were laid on the inner side of the cement boards and fixed with "U" nails. The spacing between plots was 50 cm to prevent interaction between plots. Each micro-plot area was 9 m<sup>2</sup> (3 m  $\times$  3 m).

For CCSI and GSI treatments, the prepared chopped straw and straw pellets were evenly applied at  $6 \text{ t} \cdot \text{hm}^{-2}$ , respectively. For CK treatment, only chemical fertilizer was applied as base fertilizer at rates of  $105 \text{ kg} \cdot \text{hm}^{-2}$  N,  $120 \text{ kg} \cdot \text{hm}^{-2}$

$P_2O_5$ , and  $105 \text{ kg} \cdot \text{hm}^{-2} \text{ K}_2\text{O}$ . The tested wheat variety was 'Jimai 22'. Seeds were manually dibbled on November 7, 2013, with row spacing of 20 cm and seeding rate of  $225 \text{ kg} \cdot \text{hm}^{-2}$ . All plots were irrigated with  $750 \text{ m}^3 \cdot \text{hm}^{-2}$ . At jointing stage,  $69 \text{ kg} \cdot \text{hm}^{-2} \text{ N}$  was top-dressed and  $750 \text{ m}^3 \cdot \text{hm}^{-2}$  water was applied. Other management practices followed local conventional cultivation.

#### 1.4 Measurement Items and Methods

**1.4.1 Soil Nutrient Content** At winter wheat maturity, soil samples from the 0–20 cm layer were collected using a stainless steel auger following the diagonal method. After removing visible litter and roots, samples were air-dried and sieved for physicochemical analysis. Soil organic matter was determined by the potassium dichromate oxidation-external heating method, total nitrogen by the semi-micro Kjeldahl method, alkaline hydrolyzable nitrogen by the diffusion method, available phosphorus by the molybdenum-antimony colorimetric method, and available potassium by flame photometry [?].

**1.4.2 Population Tiller Number** At seedling stage, pre-wintering stage, initial jointing stage, jointing stage, flowering stage, and maturity stage of winter wheat, basic seedling number and tiller number in 1 m double rows were measured at fixed points, with three replicates per treatment. Fertile tiller rate was calculated using the formula: Fertile tiller rate = (Population tiller number at maturity stage / Population tiller number at initial jointing stage)  $\times$  100.

**1.4.3 Leaf Area Index** At flowering stage and filling stage (21 days after anthesis), 30 stems that headed on the same day were selected. Flag leaf area and leaf area per stem were measured using the weighing method, and leaf area index was calculated based on population tiller number.

**1.4.4 Flag Leaf Chlorophyll Content** At heading stage, 90 uniform single stems per treatment were labeled. After anthesis, nine labeled plants were selected every 7 days, and flag leaf chlorophyll content was measured using a SPAD-502 chlorophyll meter. Each leaf was measured three times and the average value was taken.

**1.4.5 Flag Leaf Net Photosynthetic Rate** At flowering stage and filling stage (21 days after anthesis) between 9:00–11:00 AM, flag leaf net photosynthetic rate was measured using a Li-6400XT portable photosynthesis system (LI-COR, USA) with an artificial light source at photosynthetic photon flux density of  $1,200 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ .

**1.4.6 Dry Matter Accumulation and Translocation** At flowering stage and maturity stage, 30 stems that headed on the same day were selected and divided into grain and other parts. Samples were killed at  $105^\circ\text{C}$  for 15 minutes, then dried at  $75^\circ\text{C}$  to constant weight. Grain and aboveground dry matter

weights were recorded, and dry matter accumulation and translocation patterns were calculated according to Duan et al. [?].

**1.4.7 Wheat Yield Measurement** At maturity stage, effective spike number was recorded in 1 m double rows randomly selected in each plot. Thirty consecutive spikes were taken to determine thousand-kernel weight and kernels per spike. Each plot was manually harvested, threshed, and air-dried. Yield and grain water content were recorded, and actual yield was calculated using the formula: Actual yield ( $\text{kg} \cdot \text{hm}^{-2}$ ) = Actual harvested yield ( $\text{kg} \cdot \text{hm}^{-2}$ )  $\times$  (1 - grain water content) / (1 - 13%) / harvested area ( $\text{hm}^2$ )  $\times 10^4$ .

## 1.5 Data Analysis

Variance analysis was performed using Microsoft Excel 2007 and SPSS 23.0 software, and multiple comparisons were conducted using the LSD method ( $P < 0.05$ ).

## Results

### 2.1 Effects of Granulated Straw Incorporation on Soil Nutrient Content

As shown in Table 1, compared with CK, CCSI treatment significantly increased the contents of soil organic matter, total nitrogen, alkaline hydrolyzable nitrogen, available phosphorus, and available potassium in the topsoil. GSI treatment further increased soil organic matter, alkaline hydrolyzable nitrogen, and available phosphorus contents by 8.54%, 6.12%, and 6.25% compared with CCSI treatment, respectively, while its total nitrogen and available potassium contents showed no significant difference from CCSI treatment. These results indicated that granulated straw incorporation could improve soil nutrient status to some extent.

### 2.2 Effects of Granulated Straw Incorporation on Winter Wheat Population Tiller Number

As shown in Table 2, winter wheat population tiller number increased with growth progression, peaked at the initial jointing stage, and then gradually decreased. At all growth stages, population tiller number followed the order: GSI > CK > CCSI. At early growth stages (seedling, pre-wintering, and initial jointing), GSI treatment increased tiller number by 19.39%, 12.79%, and 11.28% compared with CCSI treatment, respectively, and by 1.63%, 4.06%, and 3.16% compared with CK, though the differences with CK were not significant. At middle and late growth stages (jointing, flowering, and maturity), GSI treatment had significantly higher tiller numbers than both CK and CCSI. Compared with CK and CCSI treatments, GSI treatment significantly increased mature tiller number by 13.23% and 16.64%, and increased fertile tiller rate by 9.88% and 4.92%, respectively. These results indicated that granulated straw incorporation

was beneficial for wheat emergence and tillering, increased mature tiller number, and thus constructed a higher population size.

### **2.3 Effects of Granulated Straw Incorporation on Winter Wheat Leaf Area Index**

As shown in Table 3, there were no significant differences in flag leaf area among treatments at flowering and filling stages. However, GSI treatment significantly increased green leaf area per stem by 6.27% and 8.66% at flowering and filling stages compared with CK, while CCSI treatment increased it by 8.21% and 9.72% compared with CK. Leaf area index followed the order: GSI > CCSI > CK. Compared with CCSI treatment, GSI treatment increased leaf area index by 8.31% and 16.97% at flowering and filling stages, respectively, with significant differences, indicating that granulated straw incorporation could increase winter wheat population leaf area and benefit light interception.

### **2.4 Effects of Granulated Straw Incorporation on Flag Leaf Chlorophyll Content**

As shown in Figure 2 [Figure 2: see original paper], flag leaf SPAD values of all treatments gradually decreased from anthesis to 28 days after anthesis. At anthesis and 7 days after anthesis, SPAD values of GSI and CCSI treatments were higher than CK, but no significant differences were observed among the three treatments. At 14 and 21 days after anthesis, GSI treatment significantly increased flag leaf SPAD values by 9.41% and 38.08% compared with CK, and by 0.53% and 3.05% compared with CCSI treatment, though the latter differences were not significant. At 28 days after anthesis, GSI treatment significantly increased SPAD values by 47.24% and 12.88% compared with CK and CCSI treatments, respectively. These results indicated that straw incorporation could delay chlorophyll content decline, with granulated straw incorporation showing a superior delaying effect compared with conventional chopped straw incorporation.

[Figure 2: see original paper]

### **2.5 Effects of Granulated Straw Incorporation on Flag Leaf Photosynthetic Characteristics**

As shown in Figure 3 [Figure 3: see original paper], GSI treatment significantly increased flag leaf net photosynthetic rate at flowering stage by 2.76% compared with CK and by 1.18% compared with CCSI treatment, though the latter difference was not significant. At filling stage, GSI treatment had significantly higher flag leaf net photosynthetic rate than other treatments, increasing by 15.76% and 3.33% compared with CK and CCSI treatments, respectively. These results indicated that granulated straw incorporation could maintain strong light energy conversion capacity of flag leaves at late growth stages.

[Figure 3: see original paper]

## 2.6 Effects of Granulated Straw Incorporation on Dry Matter Accumulation and Translocation

As shown in Table 4 , compared with CK, both GSI and CCSI treatments significantly increased dry weight per stem and population dry weight at flowering and filling stages. Compared with CCSI treatment, GSI treatment significantly decreased dry weight per stem by 4.91% and 5.83% at flowering and maturity stages, respectively, but significantly increased population dry weight by 6.33% and 9.85%, indicating that granulated straw incorporation was more beneficial for increasing winter wheat population biomass.

As shown in Table 5 , the translocation amount, translocation ratio, and contribution to grain of pre-flowering assimilates in GSI and CCSI treatments were lower than those in CK, with GSI treatment showing more pronounced reductions of 2.32% and 8.64% compared with CCSI treatment, respectively. Post-flowering dry matter translocation amount and its contribution to grain followed the order: GSI > CCSI > CK. Specifically, GSI treatment significantly increased post-flowering translocation amount to grain by 14.75% compared with CCSI treatment, and increased the contribution ratio of post-flowering dry matter to grain by 3.76%, though this difference was not significant. These results indicated that granulated straw incorporation could optimize photosynthate allocation and facilitate photosynthate translocation to grain.

## 2.7 Effects of Granulated Straw Incorporation on Winter Wheat Yield and Its Components

As shown in Table 6 , GSI treatment significantly increased winter wheat yield by 9.69% and 10.71% compared with CK and CCSI treatments, respectively. In terms of yield components, GSI treatment significantly increased effective spike number by 13.23% and 16.64% compared with CK and CCSI treatments, respectively. GSI treatment increased thousand-kernel weight by 2.35% compared with CK and by 0.71% compared with CCSI treatment, with the latter difference not being significant. GSI treatment had lower kernels per spike than CK and CCSI treatments, but no significant differences were observed among the three treatments.

Correlation analysis showed that wheat yield was extremely significantly positively correlated with effective spike number ( $R = 0.832$ ,  $P < 0.01$ ), but had no significant correlation with kernels per spike ( $R = 0.331$ ,  $P > 0.05$ ) or thousand-kernel weight ( $R = 0.125$ ,  $P > 0.05$ ). These results indicated that granulated straw incorporation had a greater effect on wheat tillering and spike formation, and the substantial increase in effective spike number was the main reason for yield increase.

## Discussion

### 3.1 Effects of Granulated Straw Incorporation on Soil Nutrients

This study showed that both GSI and CCSI treatments significantly increased the contents of soil organic matter, total nitrogen, alkaline hydrolyzable nitrogen, available phosphorus, and available potassium in the topsoil, with GSI treatment showing greater increases. This should be related to the different decomposition rates of straw in different physical forms. Wang et al. [?] reported that the average decomposition rate of straw pellets was 31.68% higher than that of chopped straw, and their carbon, nitrogen, and phosphorus release rates were 1.8, 2.5, and 1.8 times those of chopped straw, respectively, which was conducive to rapid increase in soil nutrients. Additionally, during pellet production, the crushing degree was increased and the epidermal tissue of maize straw was destroyed, reducing the physical protection of lignified palisade tissue [?]. This could enhance the decomposition activity of soil microorganisms on straw fiber materials and promote the conversion of straw recalcitrant substances into soil nutrients [?]. Furthermore, rapid decomposition of straw pellets could provide more energy sources for soil microorganisms, enhance soil microbial activity [?], facilitate microbial reproduction, increase microbial quantity [?], and promote the conversion of organic nutrients to inorganic forms in soil, thereby increasing the content of soil available nutrients.

### 3.2 Effects of Granulated Straw Incorporation on Winter Wheat Yield Formation

Seedling quality is a major factor affecting winter wheat population size and largely influences crop growth and yield [?]. Yin et al. [?] reported that increasing the contact degree between straw and soil could improve emergence rate and seedling uniformity, thereby increasing wheat yield. In this study, GSI treatment had significantly higher basic seedling number than CCSI treatment, with no significant difference from CK. At late growth stages, GSI treatment had significantly higher population tiller number than both CK and CCSI treatments. This might be because straw pellets, with their high density and small volume, could mix uniformly with soil after incorporation, effectively avoiding problems such as seedling deficiency and difficult root establishment caused by large amounts of straw accumulation in the topsoil [?, ?], thus ensuring normal seed germination and improving basic seedling number. Additionally, as straw decomposed, nutrients were gradually released into the soil, greatly improving soil fertility conditions, promoting seedling growth, significantly increasing fertile tiller rate, and ultimately resulting in higher effective spike number at maturity. Although CCSI treatment had relatively high soil nutrient content that promoted tillering and spike formation, its poor sowing quality and insufficient basic seedling number resulted in lower population tiller number than CK. Therefore, granulated straw incorporation could improve incorporation quality, ensure normal wheat emergence, promote wheat tillering, increase fertile tiller rate, and facilitate the construction of high-level population size.

Approximately 70-85% of carbohydrates in wheat grains come from post-flowering photosynthetic products. Therefore, leaf photosynthetic performance after flowering directly affects grain filling and determines kernel weight [?]. Previous studies have shown that straw incorporation could improve flag leaf photosynthetic performance at middle and late growth stages and increase crop yield [?]. This study was consistent with previous results, showing that straw incorporation could increase flag leaf chlorophyll content and net photosynthetic rate at filling stage, significantly increase aboveground dry matter accumulation, and GSI treatment had significantly higher net photosynthetic rate than CCSI treatment. This pattern was similar to the changes in soil nutrients, indicating that improved soil fertility could delay leaf senescence, enhance leaf photosynthetic performance at filling stage, and strengthen light energy interception and conversion capacity, enabling GSI treatment to achieve higher population biomass. Zheng et al. [?] reported that dry matter accumulation is the basis of crop yield formation, and the allocation and translocation of post-flowering photosynthates to grain directly determine grain yield. This study showed that GSI treatment could significantly increase post-flowering dry matter translocation amount to grain and its contribution to grain, thereby increasing kernel weight. The reasons might be: first, rapid decomposition of straw pellets improved fertilizer efficiency in the current season [?], benefiting crop growth and increasing aboveground biomass at flowering stage, which promoted translocation of pre-flowering photosynthates to grain; second, GSI treatment improved flag leaf photosynthetic characteristics at filling stage, facilitating the synthesis of more carbohydrates, increasing post-flowering dry matter translocation to grain, and enhancing kernel weight. Additionally, this study found no significant differences in kernels per spike between GSI, CCSI, and CK treatments, which differed from the results of Han et al. [?], possibly due to differences in straw incorporation amount and method.

Most studies have shown that straw incorporation could significantly increase spike number, kernels per spike, and thousand-kernel weight, thereby increasing crop yield [?]. However, some researchers believe that straw incorporation has no significant effect on thousand-kernel weight but can significantly increase effective spike number and kernels per spike [?, ?]. Liu et al. [?] reported that straw incorporation had no significant effect on kernels per spike, and the substantial increase in thousand-kernel weight and spike number was the main reason for wheat yield increase. This study showed that GSI treatment significantly increased winter wheat yield, while CCSI treatment showed no significant difference from CK. Correlation analysis revealed that grain yield was extremely significantly positively correlated with effective spike number, but not significantly correlated with kernels per spike or thousand-kernel weight, indicating that GSI treatment mainly increased yield by improving seedbed quality, ensuring wheat emergence, promoting wheat tillering, increasing fertile tiller rate, and thereby significantly increasing effective spike number and wheat yield.

In summary, GSI treatment could improve incorporation quality, effectively solv-

ing the problems of insufficient basic seedling number and fertile tiller number caused by CCSI treatment. It could also improve soil fertility conditions, increase flag leaf net photosynthetic rate, chlorophyll content, and leaf area index at filling stage, promote post-flowering dry matter accumulation and its translocation to grain, and thereby significantly increase grain yield. This effectively avoided the problem of premature senescence caused by insufficient fertilizer supply at late growth stages in the no straw incorporation treatment. However, whether the yield-increasing effect of granulated straw incorporation varies with climate change and tillage methods requires further in-depth research.

## Conclusion

Compared with no straw incorporation and conventional chopped straw incorporation, granulated straw incorporation could maintain higher basic seedling number and increase mature tiller number by 13.23% and 16.64%, respectively. It also improved soil fertility conditions, increased flag leaf chlorophyll content and net photosynthetic rate after flowering, significantly increased aboveground dry matter accumulation at flowering and maturity stages and post-flowering dry matter translocation to grain, and increased wheat yield by 9.69% and 10.71%, respectively. Therefore, granulated straw incorporation is a safe and efficient straw return method.

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*Note: Figure translations are in progress. See original paper for figures.*

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