ORIGINAL RESEARCH

The combination of different nitrogen fertilizer types could promote rice growth by alleviating the inhibition of straw decomposition

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Abstract
Straw return plays an important role in the improvement of farmland ecological environments, increasing soil fertility, crop quality, and yield. However, in the early growth of rice (Oryza sativa L.), straw decomposition and rice growth may be inhibited by suboptimal carbon/nitrogen (C/N) ratios. We, therefore, explored methods that could alleviate the inhibition of straw decomposition using different combinations of ammonium bicarbonate and compound fertilizer. No fertilizer (CK) and compound fertilizer (S0) were used as the control. The ratios of added ammonium bicarbonate were 10% (S1), 20% (S2), 30% (S3), and 40% (S4), respectively. Compared with the S0 treatment, the S2 treatment accelerated straw decomposition, promoted the early growth of tillers and roots, and improved the leaf area index, dry matter accumulation, and N use efficiency (apparent N utilization, agronomic N utilization, and partial factor productivity increased by 4.05–19.48% in two years). Moreover, panicle number, filled-grain percentage, and 1000-grain weight were significantly higher in the S2 treatment than other treatments. The grain yield of S2 treatment was significantly higher than that of S0 treatment by 4.06% (2019) and 5.66% (2020). Regression analysis revealed that the optimal ratios of ammonium bicarbonate for increasing straw decomposition and grain yield were relatively close, 16.27% and 14.60%, respectively. These results suggest that compared with conventional fertilization method (S0), the 20% treatment is a more effective fertilization method that prevents inhibition of straw decomposition, promoting rice growth and yield, and improving nitrogen (N) use efficiency.

KEYWORDS
grain yield, N fertilizer, rice, root growth, straw return
1 | INTRODUCTION

Rice–wheat rotation is the main agricultural farming form in the Yangtze River agricultural regions, which covers a total area of 13 million ha and produces grain yield accounting for 72% of total cereal yield in China (Timsina & Connor, 2001; Yang et al., 2020). Nowadays, crop residues are often integrated into soil in rice–wheat rotation system. Returning straw to the field can bring several benefits. For example, long-term straw return can increase soil organic matter content and carbon sequestration (Lal, 2004; Zhao et al., 2018); nutrient released from straw decomposition can promote crop growth (Shan et al., 2008); and crop straw return also can improve soil structure through reducing soil bulk density, increasing soil porosity, and facilitating soil aggregation (Lenka & Lal, 2013).

However, straw return also causes some negative impacts on crop growth. The high carbonate content in crop straw promotes the absorption of N by microorganisms (Dejian et al., 2014; Yadavinder-Singh et al., 2004). Large amounts of N nutrients are used to support the decomposition of crop straw instead of crop growth (Eiland et al., 2001; Verma & Bhagat, 1992), which results in nitrogen deficiency and plant growth inhibition (Blanco-Canqui & Lal, 2009; Yan et al., 2018). Therefore, more inorganic N supply is necessary for the rapid growth of crops after returning straw to the field. Insufficient N will not only cause slow growth of crops and inhibit the formation of crop yields, but also slow down the decomposition of straw, overstock of crop straw, deterioration of field soil structure in the short term, and the increased loss of fertilizer and water (Kanal, 1995; Yan, Sun, Hui, et al., 2018).

To adjust the appropriate C/N, the common method is to add the total N application rate in previous studies (Aminah et al., 2019; Guan et al., 2020; Yan, Sun, Xu, et al., 2018). However, the previous research showed that the rapid decay period of straw is the early stage after straw returned to the field (Guo et al., 2018). This result indicates that it could be more effective to adjust the supply rate and velocity of nitrogen at the early stage of plant growth. Ammonium N fertilizer is dissolved in water to generate ammonium ions, which can be directly absorbed by crops, while amide N fertilizers need to be converted into ammonium ions by urease before they can be used by crops (Cai et al., 1986). Therefore, the fertilizer effect of ammonium N fertilizer is faster than that of amide N fertilizers. This characteristic indicates that ammonium N fertilizer as a base fertilizer may be able to quickly provide N nutrients for the decomposition of straw and the early growth of plants. To solve these problems, ammonium N fertilizer and compound fertilizer were used as the base fertilizer after returning straw to field (Tang et al., 2020), so as to promote the decomposition rate of straw, improve the tillering and dry matter accumulation of rice during early growth period. However, the combined application method may also lead to a later nutrient deficiency and a decline in grain yield, probably because the high ratio of ammonium N fertilizer in the base fertilizer could cause rapid nutrients loss. Therefore, it may be critical to determine an appropriate ratio of ammonium N fertilizer and compound fertilizer in the base fertilizer.

In this study, the effects were investigated of different proportions of ammonium bicarbonate and compound fertilizer in the base fertilizer on straw decomposition and rice growth. Application of the appropriate proportion of the two kinds of fertilizers could be conducive to alleviate the inhibition of straw decomposition on rice growth and improve nitrogen utilization and grain yield, which is beneficial to agricultural production practice.

2 | MATERIALS AND METHODS

2.1 | Experimental materials

The rice variety of Quanliangyou 681 was used in this study, which was obtained from Hubei Quanyin High-tech Seed Industry Co. Ltd. Three fertilizer including ammonium bicarbonate, compound fertilizer, and urea were provided by Hubei Xinshengyuan Biological Engineering Co. Ltd., Xinyangfeng Agricultural Technology Co. Ltd., and Hubei Qianjiang Jinhua Run Chemical Fertilizer Co. Ltd., respectively.

2.2 | Field site and experimental design

The field experiment was conducted in the Agriculture Science and Technology Industrial Park of Yangtze University, Huazhong Agricultural High-tech Industrial Development Zone, Jingzhou City, Hubei Province, China (30°22′N, 112°4′E). The type of soil was light loam (Kakingski soil texture classification system). The properties of the soil and materials tested were shown in Table S1. The sowing dates were May 10, 2019 and May 13, 2020; the transplanting dates were June 1, 2019 and June 3, 2020; and the harvesting dates were September 20, 2019 and September 23, 2020. The rainfall and temperature over two years were shown in Figure 1. Seedlings were cultivated in seedling trays and transplanted by a rice transplanter (Kubota Agricultural Machinery Co., Ltd., SPW-28C). The planting density was 30 cm × 16 cm.

The N fertilizer was comprised of ammonium bicarbonate fertilizer (ammonium bicarbonate is an available N fertilizer, which can provide fast-acting nutrients for plant growth faster than compound fertilizer; the N content of ammonium bicarbonate is 17.1%), compound fertilizer (N: P2O5: K2O=15: 15: 15), and urea (46% N). The dosage of nitrogen fertilizer was 195 kg/ha. It was applied at the basal, tillering (7 days after transplantation, 7 DAT), and panicle initiation stage with the
ratio of 5: 3: 2, and the detailed information was shown in Table 1. The contents of P$_2$O$_5$ and K$_2$O in each treatment were adjusted to 97.5 kg/ha by using calcium superphosphate (16% P$_2$O$_5$) and potassium chloride (60% K$_2$O). Both calcium superphosphate and potassium chloride were applied during transplanting. Each treatment was 90 m$^2$ in area with 30-cm-wide and 30-cm-high ridge, covered with plastic film to prevent water and nutrient penetration between contiguous plots. In this experiment, a random block design was adopted, and a total of 18 plots were used.

2.3 | Measurement indices

2.3.1 | Rice stem and tiller number

The number of seedlings was recorded after transplantation; ten representative plants were selected to calculate the average number of stems and tillers in each plot. The number of stems and tillers was investigated every four days until the number of tillers stabilized.

2.3.2 | Root growth

Ten representative plants were selected to measure the indicators of root growth, including total number of roots, total root length, and average root diameter. The root length and the middle root diameter were measured using a Vernier Caliper. Root vitality was measured three times using 2, 3, 5-Triphenyltetrazolium chloride (TTC) method (Baozhang et al., 1994; Clemensson-Lindell, 1994). Specifically, 0.5 g fresh root tips were immersed in 0.1 mol/L phosphate buffer (pH = 7.0) containing 0.4% TTC and incubated at 37°C in dark for 4 h, and 1 mol/L H$_2$SO$_4$ solution was added to terminate the reaction. Then ethyl acetate and a small amount of quartz sand were added to grind together, and the red TTF was repeatedly extracted with ethyl acetate, the extract was filtered into a graduated test tube, and diluted to 10ml with ethyl acetate. The optical density of the extract was measured by using a Backman DU-640 spectrophotometer at a wavelength of 485 nm, and the TTC reduction (TTF) calculated according to the standard curve. Root vitality is expressed by the amount of TTF generated per fresh root per unit time (ug g$^{-1}$ h$^{-1}$). All indicators of root growth were measured every 3 days from 3 to 30 days after transplantation.

2.3.3 | Straw decomposition rate

The straw decomposition rate was measured by using the nylon mesh bag method. Briefly, 40.00 g of dried wheat straw was cut into 5 cm segments and then packed into a nylon mesh bag (120 mesh, 35 cm x 25 cm) and buried (5–10 cm)
into each plot in the field before transplantation. The mesh bag was removed from the plots, washed with water, dried, and weighted at 5 d, 10 d, 20 d, 35 d, 55 d, 80 d, and 110 d after transplanting, and each treatment was repeated three times (Cui et al., 2017).

2.3.4 | Leaf area index

The representative plants were selected at tillering (35 DAT), booting (60 DAT), full heading (80 DAT), and mature stages (110 DAT). The leaf of representative plants was tilled on white paper, took photograph, and the leaf area was calculated by ImageJ 1.51j8 (Wayne Rasband, NIH, USA), and then, the leaf area index was obtained. Each treatment had three biological repeats.

2.3.5 | Dry matter accumulation and total N content

The representative plants were selected at tillering (35 DAT), booting (60 DAT), full heading (80 DAT), and mature stages (110 DAT), killed at 105 °C, and dried to constant weight at 80°C. Then, the samples were crushed and the N content of rice was measured by the ECS 4024 CHNSO Classic Analyzer (Costech, Italy). Each treatment had three biological repeats.

2.3.6 | Yield and yield components

After rice matured, an area of about 5 m² was selected from the central part of each plot for grain yield measurement. Ten representative plants were selected to record the average number of effective panicles. At the same time, five plants were selected to determine the number of grains per panicle, filled-grain percentage, and 1000-grain weight. Each treatment had three biological repeats.

2.4 | Statistical analysis

The data analysis was performed by using Data Processing System 7.05 (Qiyi Tang, China) and ORIGIN 2020 (OriginLab Corp., Northampton, MA, USA). Statistical analyses were performed by one-way ANOVA combined with the least significant difference (LSD) test, and means were separated at a significant level of $p \leq 0.05$ or extremely significant level of $p \leq 0.01$.

The decomposition rate of straw was calculated as follows: (dry weight of initial straw—dry weight of remaining straw)/dry weight of initial straw × 100%.

The leaf area index was calculated as follows: leaf area of plants/ground area of plants.

The apparent N use efficiency (ANUE, %) was calculated as follows: (total N content of plants in application plots with N—total N content of plants in application plots without N)/N application rate × 100%.

The agronomic N use efficiency (AE, kg/kg) was calculated as follows: (grain yield in application plots with N—grain yield in application plots without N)/N application rate.

The physiological N use efficiency (PNUE, kg/kg) was calculated as follows: (grain yield in application plots with N—grain yield in application plots without N)/(total N content of plants in application plots with N—total N content of plants in application plots without N).

The N partial factor productivity (PFP-N, kg/kg) was calculated as follows: grain yield/N application rate.

3 | RESULTS

3.1 | Effect of ammonium bicarbonate combined with compound fertilizer on straw decomposition rate

As shown in Figure 2(a), the decomposition rate of straw displayed an increasing trend with the growth. The period of fast
decomposition occurred before day 35; the decay rate tended to be slow after day 55. After fertilization, the decomposition rate of S2 treatment was the fastest one in each growth period. Within 0–35 days, the decay speed of S2 treatment was significantly ($p < 0.05$) higher versus S0, S1, S3, and S4 by 7.44, 4.06, 6.12, and 17.90%, respectively. In addition, within 55–110 days, the decomposition speed of S2 treatment was higher than that of S0, S1, S3, and S4 by 68.95, 13.41, 28.51, and 53.70%, respectively. For fertilization treatments, the decomposition rate of S0 treatment was lower than that of S1, S2, and S3 treatments by 7.10, 12.11, and 5.26% at day 110 post-transplant. The correlation between the proportion of ammonium bicarbonate and average rate of decomposition within 0–35 days after transplanting was shown in Figure 2(b). According to the equation, straw decomposition rate was predicted to reach a maximum when the proportion of ammonium bicarbonate was 16.27%.

### 3.2 | Effect of ammonium bicarbonate combined with compound fertilizer on root growth of rice

As shown in Figure 3, the average root diameter, total number of roots, and total root length per plant of all treatments showed an increasing trend within 3–30 days after transplanting. However, the root vitality began to decrease at 24 days post-transplantation. Within 3–30 days after fertilization, the values of root vitality, total root number, and total root length increased first to a maximum and then decreased with increase in ammonium bicarbonate proportion. Within 3–30 days, the growth rates of root vitality, total root number, and total root length of rice in S2 treatment were significantly higher than those of S0, S1, S3, and S4 treatments. Compared with S0, S1, S3, and S4 treatments, the growth rates of root vitality total root number, and total root length of rice in S2 treatment increased by 44.89–88.91, 9.79–25.52, and 10.19–19.71%, respectively. There were no obvious differences in growth rates of root vitality, total root number, and total root length, among S0, S1, S3, and S4 treated rice. The average growth rate of root diameter in S0 and S4 treatments significantly higher than that of S1 and S3 treatments.

### 3.3 | Effect of ammonium bicarbonate combined with compound fertilizer on tillering of rice

Change in rice tillers number under each treatment was summarized as Figure 4. In 2019 and 2020, the tiller number of rice in each treatment was increased initially and decreased afterward. In the same growth period, the number of tillers in all

![Figure 3](image3.png)

**Figure 3**  Root growth of rice under each treatment in 2019. DAT—days after transplanting; the error bars are standard deviation ($n = 3$ or 10)
treatments tended to decrease in 2020 versus 2019. At 35-day post-transplant in 2019 and 2020, the tiller numbers for S2 treatment were obviously higher than that of S0, S1, S3, and S4 treatments. Besides, at 35-day post-transplant in 2019, the values of tiller number for in S1, S3, and S4 treatments were significantly higher than that of the S0. But, there was no obvious difference in the tillers number among S0, S3, and S4 treatments in 2020. In addition, in the both years, the tillers number for S3 and S4 decreased faster than that of S0 in the later growth stage.

3.4 | Effect of ammonium bicarbonate combined with compound fertilizer on leaf area index of rice

The leaf area index of each treatment was increased from tillering to full heading stage, and then decreased from the full heading to mature stage in both years (Table 2). At booting, full heading, and mature stages, the average value of leaf area index for all treatments was lower in 2020 than that of 2019, and the difference was extremely significant ($p \leq 0.01$). The leaf area index of rice increased first to a maximum then decreased, with the increasingly proportion of ammonium bicarbonate. The values of leaf area index for S3 and S4 treatments were significantly higher than that of S0 at tillering stage by 42.55‒45.81% in 2019 and 57.95‒60.07% in 2020, respectively. However, the leaf area index in S3 and S4 tended to decrease versus S0 treatment from booting to mature stage in the both two years. The leaf area index of S2 treatment was significantly higher than that of S0 treatment in each growth stage. The difference in leaf area index was not significant between S1 and S0 treatment, except at tillering stage in 2020.

3.5 | Effect of ammonium bicarbonate combined with compound fertilizer on dry matter accumulation in rice

As shown in Table 3, at full heading and mature stages, the average value of dry matter accumulation for all treatments was lower in 2020 than that of 2019, and the difference was extremely significant. But, no significant change was observed between the two years at tillering and booting stages. The dry matter accumulation was first increased to a maximum and then decreased as the proportion of ammonium bicarbonate rose. After fertilizer, the growth rate of dry matter accumulation for S2 treatment was faster than other treatments from tillering to mature stage in two years. In 2019 and 2020, the dry matter accumulation of S2 treatment was significantly higher than that of S0, S1, and S4 treatments at tillering and mature stage. In 2019, the values of dry matter accumulation for S3 and S4 treatments were higher than that for S0 at tillering stage, but lower at mature stage. At mature stage in 2020, the values for S3 and S4 were similarly lower than that for S0.

3.6 | Effect of ammonium bicarbonate combined with compound fertilizer on N use efficiency in rice

N use efficiency under each treatment was summarized in Table 4. The average values of total N, apparent N utilization, agronomic N utilization, and partial factor productivity in all treatments were significantly lower in 2020 than those in 2019, and the difference was extremely significant. But, there was no significant difference in physiological N utilization between the two years. In 2019 and 2020, the amount of total N, apparent N utilization, agronomic N utilization, and partial factor productivity first increased and then decreased, as the proportion of ammonium bicarbonate rose. The values of the four indicators in S3 and S4 treatments were significantly lower than that of S0, S1, and S2 treatments, including total N, apparent N utilization, agronomic N utilization, and partial factor productivity. After fertilization, the values of the four indicators in S2 treatment were distinctly higher than those in S0, S1, S3, and S4 treatments in the both years. Compared with the conventional fertilization method (S0), these values were increased by 4.05‒19.48% of apparent N utilization, agronomic N utilization, and partial
factor productivity in S2 treatment in two years. In 2020, the values of the four indicators were obviously increased in S1 treatment, when compared to S0.

### 3.7 Effect of ammonium bicarbonate combined with compound fertilizer on rice yield and yield components

In the both years, the grain yield first increased and then decreased with the increasingly proportion of ammonium bicarbonate (Table 5). In the two years, the yield of rice under S2 treatment was significantly higher than those of S0, S3, and S4 treatments, while the values for S3 and S4 were lower than that of S0. The grain yield of S2 treatment was significantly higher than that of S0 treatment by 4.06% (2019) and 5.66% (2020). But, there was no significant difference in rice yield between of S1 and S0 treatments in the both years. Furthermore, the correlation between the proportion of ammonium bicarbonate and grain yield was shown in Figure 5. The plots of equations \(y_1\) and \(y_2\) were convex parabolic. According to equation \(y_1\) and \(y_2\), grain yields were predicted to reach a maximum when the proportion of ammonium bicarbonate was 14.24% (2019) and 14.96% (2020).

As shown in Table 5, the panicles number and filled-grain percentage were significantly lower in 2020 than those in 2019. However, spikelet per panicle and 1000-grain yield showed opposite trend. In the both years, the number of panicles, filled-grain percentage, and 1000-grain weight for S2 treatment were significantly increased, when compared with the other treatments. But, the values of the three indicators for S3 and S4 treatments were lower than those in S0 treatment. In addition, the difference in yield components was not obvious between S1 and S0.

### 4 DISCUSSION

#### 4.1 Effect of ammonium bicarbonate combined with compound fertilizer on straw decomposition

Nitrogen application can accelerate the decomposition of straw with high carbon–nitrogen ratio, which can provide nutrients for crop growth (Ghimire et al., 2017; Rezig et al., 2014). This may be due to the increased activities of N-acetyl-glucosamidase and L-leucine aminopeptidase by the application of exogenous nitrogen fertilizer in the early stage of straw decomposition, which shortened the straw decomposition cycle (Guo et al., 2018). In this present study, the decomposition degree of rice under S2 treatment was the fastest one in each growth period. Compared with compound
| Year | Treatment | Tillering stage | Booting stage | Full heading stage | Mature stage |
|------|-----------|-----------------|---------------|-------------------|-------------|
|      |           | (10^3 kg/ha)    | (10^3 kg/ha)  | (10^3 kg/ha)      | (10^3 kg/ha)|
| 2019 | CK        | 0.39 ± 0.03 d   | 2.81 ± 0.14 d | 10.75 ± 0.25 e   | 16.41 ± 0.18 d |
|      | S0        | 1.11 ± 0.03 c   | 6.75 ± 0.99 bc| 13.37 ± 0.05 bc  | 21.37 ± 1.41 b |
|      | S1        | 1.16 ± 0.09 bc  | 7.44 ± 0.53 ab| 13.62 ± 0.18 b   | 21.39 ± 1.33 b |
|      | S2        | 1.34 ± 0.04 a   | 7.64 ± 0.55 a | 14.15 ± 0.29 a   | 24.64 ± 2.06 a |
|      | S3        | 1.23 ± 0.05 b   | 6.63 ± 0.23 c | 13.07 ± 0.03 c   | 19.61 ± 0.32 bc|
|      | S4        | 1.17 ± 0.06 bc  | 6.29 ± 0.18 c | 12.47 ± 0.30 d   | 19.24 ± 0.30 c |
| Average |         | 1.07 ± 0.03    | 6.26 ± 0.34   | 12.90 ± 0.18     | 20.44 ± 0.92  |
| 2020 | CK        | 0.64 ± 0.17 c   | 3.85 ± 0.15 d | 8.63 ± 0.21 c    | 12.64 ± 0.20 e |
|      | S0        | 1.16 ± 0.02 b   | 6.36 ± 0.06 b | 9.97 ± 0.47 b    | 17.39 ± 0.16 c |
|      | S1        | 1.19 ± 0.17 b   | 7.06 ± 0.40 ab| 9.74 ± 0.43 b    | 18.03 ± 0.13 b |
|      | S2        | 1.52 ± 0.08 a   | 7.34 ± 0.40 a | 12.00 ± 0.70 a   | 20.14 ± 0.20 a |
|      | S3        | 1.27 ± 0.23 ab  | 6.25 ± 0.83 b | 9.55 ± 0.57 b    | 16.42 ± 0.34 d |
|      | S4        | 1.16 ± 0.15 b   | 4.80 ± 0.11 c | 9.43 ± 0.50 bc   | 16.16 ± 0.57 d |
| Average |         | 1.16 ± 0.13    | 5.95 ± 0.32   | 9.89 ± 0.45      | 16.80 ± 0.26  |

| Year (Y) | Treatment (T) | ** | ** | ** | ns | ** | ns | ** | ns |

**Note:** Values represent the mean ± standard deviation (n = 3). Different lowercase letters between N fertilizer treatments under the same time are significant differences according to the least significant difference (LSD) at the level of 0.05; * or ** is significant at the 0.01 or 0.05 level, respectively; ns represents no significant difference.
### TABLE 4  N use efficiency of rice under each treatment

| Year | Treatment | Total N (kg/ha) | ANUE (%) | AE (kg/kg) | PNUE (kg/kg) | PFP-N (kg/kg) |
|------|-----------|----------------|----------|------------|--------------|---------------|
|      |           | 2019           |          |            |              |               |
|      | CK        | 109.99 ± 0.60 f | /        | /          | /            | /             |
|      | S0        | 192.60 ± 0.33 c | 42.36 ± 0.14 c | 14.87 ± 0.55 b | 35.10 ± 1.42 a | 51.84 ± 0.59 b |
|      | S1        | 199.57 ± 0.98 b | 45.94 ± 0.74 b | 15.39 ± 0.33 b | 33.51 ± 0.47 b | 52.36 ± 0.28 b |
|      | S2        | 204.23 ± 0.65 a | 48.33 ± 0.41 a | 16.97 ± 0.09 a | 35.13 ± 0.46 a | 53.94 ± 0.13 a |
|      | S3        | 186.89 ± 0.85 d | 39.43 ± 0.40 d | 13.96 ± 0.16 c | 35.39 ± 0.28 a | 50.93 ± 0.20 c |
|      | S4        | 181.67 ± 1.91 e | 36.76 ± 0.68 e | 12.85 ± 0.32 d | 34.97 ± 0.78 a b | 49.82 ± 0.35 d |
|      | Average   | 179.16 ± 0.60 b | 42.56 ± 0.26 | 14.81 ± 0.11 | 34.82 ± 0.29 | 51.78 ± 0.16 |
|      |           | 2020           |          |            |              |               |
|      | CK        | 99.18 ± 0.53 f | /        | /          | /            | /             |
|      | S0        | 172.27 ± 0.85 c | 37.48 ± 0.17 c | 14.44 ± 0.47 c | 38.52 ± 1.31 ab | 45.79 ± 0.19 c |
|      | S1        | 176.76 ± 2.04 b | 39.78 ± 0.90 b | 15.80 ± 0.60 b | 39.75 ± 2.34 a | 47.15 ± 0.06 b |
|      | S2        | 186.51 ± 2.34 a | 44.78 ± 1.15 a | 17.03 ± 0.36 a | 38.06 ± 1.78 bc | 48.38 ± 0.47 a |
|      | S3        | 169.39 ± 1.24 d | 36.01 ± 0.70 d | 13.38 ± 0.48 d | 37.17 ± 1.74 c | 44.73 ± 0.17 d |
|      | S4        | 166.61 ± 0.92 e | 34.58 ± 0.49 e | 12.20 ± 0.28 e | 35.29 ± 1.24 d | 43.55 ± 0.42 e |
|      | Average   | 161.79 ± 1.13 b | 38.53 ± 0.60 | 14.57 ± 0.42 | 37.76 ± 1.61 | 45.92 ± 0.26 |

**Note:** Values represent the mean ± standard deviation (n = 3). Different lowercase letters between N fertilizer treatments under the same time are significant differences according to the least significant difference (LSD) at the level of 0.05; * or ** is significant at the 0.01 or 0.05 level, respectively; ns represents no significant difference.

### TABLE 5  Rice yield and its components under each treatment

| Year | Treatment | Panicle (10⁴ ha⁻¹) | Spikelet per panicle | Filled-grain percentage (%) | 1000-Grain weight (g) | Grain yield (10³ kg/ha) |
|------|-----------|--------------------|---------------------|----------------------------|-----------------------|------------------------|
|      |           | 2019               |                     |                           |                       |                        |
|      | CK        | 245.83 ± 4.17 c    | 178.86 ± 4.87 cd    | 80.29 ± 2.59 bc           | 26.88 ± 0.21 c        | 7.21 ± 0.01 e          |
|      | S0        | 273.61 ± 6.36 b    | 182.41 ± 1.89 bc    | 82.30 ± 1.44 ab           | 28.81 ± 0.47 b        | 10.11 ± 0.12 bc        |
|      | S1        | 274.31 ± 11.47 ab  | 176.28 ± 1.04 de    | 84.06 ± 0.93 ab           | 29.41 ± 0.12 a        | 10.31 ± 0.16 ab        |
|      | S2        | 283.33 ± 2.08 a    | 171.75 ± 2.87 e     | 85.00 ± 0.75 a            | 29.53 ± 0.34 a        | 10.52 ± 0.03 a         |
|      | S3        | 265.97 ± 1.20 b    | 186.09 ± 2.02 ab    | 77.99 ± 2.88 cd           | 28.57 ± 0.24 b        | 9.93 ± 0.04 c          |
|      | S4        | 252.08 ± 5.51 c    | 189.43 ± 3.61 a     | 76.06 ± 3.51 d            | 28.34 ± 0.08 b        | 9.22 ± 0.20 d          |
|      | Average   | 265.86 ± 3.55     | 180.81 ± 0.24       | 80.95 ± 1.17              | 28.59 ± 0.11          | 9.55 ± 0.04            |
|      |           | 2020               |                     |                           |                       |                        |
|      | CK        | 187.50 ± 15.02 b   | 193.67 ± 5.51 bc    | 75.78 ± 0.11 cd           | 28.93 ± 0.11 c        | 6.11 ± 0.13 d          |
|      | S0        | 225.69 ± 39.11 a   | 187.14 ± 6.10 cd    | 76.90 ± 0.52 bc           | 29.26 ± 0.19 b        | 8.93 ± 0.04 b          |
|      | S1        | 226.39 ± 11.47 a   | 186.06 ± 1.93 cd    | 77.38 ± 0.39 b            | 29.49 ± 0.05 a        | 9.19 ± 0.01 ab         |
|      | S2        | 238.19 ± 6.36 a    | 183.48 ± 0.73 d     | 80.37 ± 0.24 a            | 29.63 ± 0.11 a        | 9.43 ± 0.09 a          |
|      | S3        | 212.50 ± 3.61 ab   | 206.33 ± 10.87 a    | 75.11 ± 1.51 d            | 28.65 ± 0.04 d        | 8.82 ± 0.15 b          |
|      | S4        | 218.06 ± 5.24 ab   | 203.40 ± 4.32 ab    | 75.14 ± 0.13 d            | 28.45 ± 0.03 e        | 8.09 ± 0.62 c          |
|      | Average   | 218.06 ± 8.76      | 193.35 ± 3.00       | 76.78 ± 0.30              | 29.07 ± 0.05          | 8.43 ± 0.10            |

**Note:** Values represent the mean ± standard deviation (n = 3). Different lowercase letters between N fertilizer treatments under the same time are significant differences according to the least significant difference (LSD) at the level of 0.05; * or ** is significant at the 0.01 or 0.05 level, respectively; ns represents no significant difference.
fertilizer (S0 treatment), the ammonium bicarbonate combined with compound fertilizer was a more effective fertilization method for straw decomposition. Their result was similar to previous research (Tang et al., 2020). Compared with previous reports (Takakai et al., 2018; Agustina et al., 2019), this present study not only provided a nitrogen application method that was conducive to straw decomposition, but also analyzed the correlation between ammonium nitrogen fertilizer and straw decomposition through regression model. The regression analysis showed that straw decomposition rate was significant correlation with the proportion of ammonium bicarbonate at early growth period (35 DAT), and the optimal nitrogen application ratio for straw decomposition was 16.27%. Moreover, their results indicated that excessive ammonium bicarbonate could reduce the decomposition rate of straw. This may be because the more ammonium bicarbonate in base fertilizer, the less likely it can provide a long-term N source for straw decomposition.

4.2 Effect of ammonium bicarbonate combined with compound fertilizer on early root growth of rice

The changes in root morphology (root number, root length, and root diameter etc.) are related with concentrations of mineral nutrient in root system (Zhang et al., 2016), and root vitality of rice is very vital to the growth and development of aboveground parts (Sheng et al., 2003). Previous research showed that the partial ammonium supply can stimulate the accumulation of root-derived auxin in the root vessels and promote lateral roots to form highly branched roots in an emergency (Meier et al., 2020). In this study, the greater amount of ammonium bicarbonate applied, and it was not more beneficial to the growth of rice roots. Presumably, on the one hand, there is a threshold for effective nitrogen uptake by rice roots; on the other hand, excessive ammonium bicarbonate fertilizer may make soil alkaline, which is not conducive to root growth (Lv et al., 2013). Specifically, within 3–30 days, the growth rate of root vitality, total root number, and total root length first increased to a maximum and then decreased, with the increase in the ammonium bicarbonate proportion. The suitable amount of ammonium bicarbonate was 20% (S2 treatment) for higher the growth rate of root vitality, total root number, and total root length. The average growth rate of root vitality, total root number, and total root length were no longer significantly improved when the amount of ammonium bicarbonate exceeded 20%.

4.3 Effect of ammonium bicarbonate combined with compound fertilizer on population quality and grain yield of rice

Rice population qualities (tillers number, leaf area index, and dry matter accumulation etc.) are the basis for yield formation. Previous studies have determined that panicles number is affected by tillering ability (Wu et al., 1998), and grain yield is highly significantly correlation with maximum leaf area index and leaf area index duration (Tao et al., 2006), as well as whole plant biomass is significantly positively correlated with grain yield (Ye et al., 2013). In this present study, although the values of tillers number, leaf area index, dry matter accumulation, and grain yield were decreased in 2020 compared with 2019, the change regularity for each treatment was consistent over the two years. Compared to 2019, frequent precipitation and increased rainfall in 2020 may be the main the reason for this phenomenon. Our results showed that application of S2 method had a better effect on rice growth at each growth period. The number of tillers, leaf area index, dry matter accumulation, and grain yield were no longer significantly improved when the amount of ammonium bicarbonate exceeded 20%.

![Graph showing the correlation between the proportion of ammonium bicarbonate and grain yield](image)
(Cai et al., 1986), resulting in insufficient nutrients in subsequent periods. In addition, a convex parabolic correlation was obtained between the proportion of ammonium bicarbonate and grain yield. According to the formula, the optimal ratio of ammonium bicarbonate was calculated as 14.60% (a two-year average), which maybe has guiding significance in agricultural practice.

### 4.4 Effect of ammonium bicarbonate combined with compound fertilizer on N use efficiency of rice

N source significantly affects the N use efficiency (Liu et al., 2018). Early studies have shown that the different forms of N fertilizer can improve N use efficiency compared with the single form of N fertilizer (Ke et al., 2017). In our study, the amount of total N, apparent N utilization, agronomic N utilization, and partial factor productivity of rice plants first increased to a maximum and then decreased, with the increase in ammonium bicarbonate. This result may be due to the highest decomposing rate of straw under S2 treatment, which could provide the most nitrogen for plant growth. Our results suggest that excessive ammonium bicarbonate in the base fertilizer could reduce the amount of total N, apparent N utilization, agronomic N utilization, and partial factor productivity in rice plants. Moreover, the optimal N utilization rate in the base fertilizer was of 20% of ammonium bicarbonate (S2).

### 4.5 The effect mechanism of ammonium bicarbonate combined with compound fertilizer on straw decomposition and rice growth

As shown in Table 6, compared with the conventional fertilization method (S0 treatment) and other proportions of ammonium bicarbonate (S3 and S4 treatments), S2 treatment was the optimal fertilization method. This may be because S2 treatment can quickly and lastingly provide nitrogen for the decomposition of straw, and the timely supply of exogenous nitrogen can increase the activities of N-acetylglucosamidase and L-leucine aminopeptidase in the early stage of straw decomposition. The increased activity of these enzymes is conducive to the decomposition of straw. The nitrogen in straw and nitrogen fertilizer can provide sufficient nutrients for rice growth. Therefore, S2 treatment could alleviate straw decomposition-induced growth inhibition of tiller and root at the early growth stage, improve the leaf area index, dry matter accumulation of rice in each growth stage, and increase N utilization efficiency and grain yield. Compared with S0 treatment, the insufficient ammonium bicarbonate of S1 treatment resulted in not significant effects on grain yield. By the contrast, excessive ammonium bicarbonate of S3 and S4 treatments caused nutrients insufficient in subsequent period, consequently decreased N utilization efficiency and grain yield. Furthermore, the regression analysis showed that the optimal proportion of ammonium bicarbonate for straw decomposition and grain yield was 16.27% and 14.60%, respectively. This study mainly analyzed the agronomic characteristics of rice and straw decomposition under different fertilization treatments, further research about the change in soil N content, microbial communities, and their functions is needed in future.

### 5 CONCLUSION

After wheat straw was return to the field, the combination of 20% ammonium bicarbonate and 30% compound fertilizer as the base fertilizer was more conducive to straw decomposition, rapid growth of roots and tillers in early growth period, and increasing N utilization efficiency and grain yield than the conventional fertilization method (50% compound fertilizer). Moreover, the early decomposition rate of straw and rice yield is significantly correlated with the proportion of ammonium bicarbonate; the regression analysis showed that the optimal ratios of ammonium bicarbonate for increasing straw decomposition and grain yield were relatively close, 16.27% and 14.60%, respectively.

### CONFLICTS OF INTEREST

The authors declare no conflicts of interest.
AUTHOR CONTRIBUTIONS
Bilin Lu conceived and designed the research framework. Jichao Tang, Ruoyu Zhang, and Hechao Li performed the experiments. Jiali Tan analyzed the data and wrote the manuscript. Zhengrong Hu, Wenjie Song, and Xin Wen revised the manuscript. Bilin Lu supervised the work and finalized this manuscript. All authors read and approved the manuscript.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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