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Changes in the inorganic nitrogen content of the soil solution with rice straw retention in northeast China

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ABSTRACT

Research the effects of straw retention (SRT) and nitrogen fertilizer on nitrogen concentration in soil solution and yield during the growth period of rice. This study was conducted to explore the variation of nitrogen concentration in soil solution by continuous location plot experiment, pot experiment, and laboratory culture experiment. The results showed that the ammonium N (NH_4^+–N), nitrate N (NO_3^-–N), and mineral N contents of the soil solution gradually decreased with increasing rice growth. Moreover, the N contents of the soil solution gradually increased with an increasing rate of N fertilizer application; however, increasing the rate of N fertilizer application did not change the effect of SRT on the N content in the soil solution. Comparing SRT with straw removal (SRM), the NH_4^+–N in the soil solution increased by 29.08% (0.17 mg L^{-1}) over the rice-growing period; by contrast, the NO_3^-–N and mineral N contents decreased by 8.90% (0.47 mg L^{-1}) and 3.02% (0.29 mg L^{-1}), respectively. In the black soil region of Northeast China, SRT reduced the nitrate concentration in the soil solution, and the N contents mineral was lower than that of the straw. Under production conditions, SRT has the trend of increasing rice yield.

Keywords: Rice; Straw retention; Inorganic nitrogen; Soil solution

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1. Introduction

Ammonium N (NH_4^+–N) and nitrate N (NO_3^-–N) are the major forms of nitrogen (N) that are available for crop uptake, and 70% of the total ions absorbed by crops are NH_4^+ and NO_3^- [1]. A high inorganic N content in the soil is conducive to crop uptake [2]. However, excessive N fertilizer application can lead to increased NO_3^-–N accumulation in the lower soil layers [3–6]. With increasing N in the environment, NO_3^-–N has an increasingly obvious advantage in promoting crop growth [7]. Ammonium N derived from soil and fertilizers is rapidly transformed into NO_3^-–N through nitrification [8], resulting in lower NH_4^+–N and higher NO_3^-–N contents [9], with NH_4^+–N and NO_3^-–N providing the major sources of inorganic N for plants [10]. Nitrogen fertilizers can cause N loss via multiple pathways, such as runoff, leaching, denitrification, and volatilization [11–15]. Appropriately reducing the N application rate can decrease N loss [16,17] and conserve resources.

Straw crop residue is an important source of soil organic matter and plant nutrients [18]. In the vast agricultural areas of China, straw retention (SRT) is an effective strategy for maintaining soil fertility and crop yields [19]. Multi-year experiments have shown that SRT increases the soil organic matter [20]. In Canada, multi-year rotation studies on various crops demonstrated that SRT increased the NO_3^-–N content in the 0–15 cm surface soil layer [21,22]. In northeastern

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Thailand, an experimental study showed that mixing SRT with peanut and rice crops delayed N release from the soil during the early growth stage of rice; thus, this approach can improve the relation between N demand and supply as well as promotes rice growth and increases the yield [23]. Because SRT provides abundant C sources to the soil environment, it can cause a rapid, short-term increase in soil microorganisms. This material can also facilitate the fixation of inorganic N in the soil [24–26], leading to a relative shortage of inorganic N in the soil during early SRT stages. Over the entire crop growth period, SRT can effectively supplement the soil with N sources [27,28] and increase the total N in the soil [21,22,29–31]. The fixation and mineralization of N gradually become balanced over the SRT period [32]. Applying SRT with a small amount of N fertilizer can improve the N use efficiency [29,33]. Compared with inorganic fertilizer application alone, SRT plus inorganic fertilizer significantly increases soil total N, amino acid N, and acid-insoluble N [34], and this combination reduces N loss [33,35]. The positive interaction between straw and N affects both organic N accumulation and inorganic N mineralization in the soil [20]. Additionally, SRT can ensure the soil nutrient balance and increase the soil organic matter and nutrient-supplying capacity [21,22,30,31].

The soil solution is the foundation for nutrient adsorption by crops, and this solution directly affects nutrient uptake and utilization by crops, as well as their growth [36]. Additionally, the soil solution directly reflects the relationship between the soil supply and the uptake of nutrients by plants [37,38]. In this study, we performed a multi-year, continuous SRT plot experiment and a laboratory simulation experiment. A detailed analysis was conducted to evaluate SRT-associated changes in the mineral N content of the soil solution over the rice-growing period to provide a scientific reference for the application of N fertilizer to rice.

2. Materials and methods

2.1. Overview of the experimental fields

All the experiments in this study were conducted at the Xiangfang Experiment and Training Base at Northeast Agricultural University in China. This base is located in the town of Xingfu, Xiangfang District, Harbin city, Heilongjiang province, at the following geographical coordinates: longitude 126°22′–126°50′ and latitude 45°34′–45°46′. This region has a cold temperate continental climate with an annual precipitation of 500–550 mm, a frost-free period of approximately 140 d, and an accumulated temperature ≥10°C of approximately 2,700°C. There is no crop rotation. The cropping system consists of continuous rice cropping, and the soil used in the field experiments was a black soil.

2.2. Experimental design

This study was based on a previous experiment [38]. This study included three experiments: a field experiment, a pot experiment, and an incubation experiment. The field experiment (Experiment A) started in 2008. Soil base fertility is shown in Table 1. The size of the plots was 2 m × 2 m, and they were built using cement and were filled with testing soil at a depth of approximately 50 cm. The specific settings for the experimental plots have been detailed in previous studies [37,38]. The straw was cut into 5 cm-long pieces and was returned at the rate of 5 kg (12.5 t ha^{-1}) in each plot. The N content of the rice straw used for the test was 6.65 ± 0.02 g kg^{-1}. The plots were ploughed (20 cm) on May 20 and then soaked with water on May 25 every year. Rice was transplanted at a spacing of 30 cm × 13 cm on May 30, with three seedlings per hill. Beginning 10 d after transplant, samples of the soil solution were collected from the plots once every 10 d. The samples were collected eight times.

Experiment B consisted of a pot-based study conducted in 2012. In this experiment, 35 cm-diameter plastic buckets were used and filled with 15 kg of soil. Soil base fertility is shown in Table 1. Three holes were planted in each pot, with three seedlings per hole. Five N levels (N_0, N_1, N_2, N_3, and N_4) were established by applying 0 g (0 kg ha^{-1}), 1.05 g (150 kg ha^{-1}), 2.10 g (300 kg ha^{-1}), 3.15 g (450 kg ha^{-1}), or 4.20 g (600 kg ha^{-1}) of urea (N: 46%) to the five pots. One-half of the applied urea was used as basal fertilizer, and the other half was used as topdressing in the tillering stage. The N_2 level was the same as that of the P fertilizer used in Experiment A; 1.05 g of $Ca(H_2PO_4)_2$ (150 kg ha^{-1}) and 0.70 g of K_2SO_4 (100 kg ha^{-1}) were also applied as a basal fertilizer. The experiments were divided into two subgroups: SRT, in which 80 g of straw (12.5 t ha^{-1}) was added; and SRM. Experiment B was replicated five times, and the cultural management was the same as in Experiment A.

The laboratory simulation experiment (Experiment C) was conducted in 2012 with two treatments: one treatment with SRT and the other treatment with SRM. The experimental design and sampling time were consistent with Experiment C, as reported in a previous study [38]. The N content of the rice straw used for the test was 6.65 ± 0.02 g kg^{-1}. The mineral N contents of the culture medium were 15 mg L^{-1} (NO_3^-–N, 10.00 mg L^{-1}; NH_4^+–N, 5.00 mg L^{-1}) for Group I and 30 mg L^{-1} (NO_3^-–N, 20.00 mg L^{-1}; NH_4^+–N, 10.00 mg L^{-1}) for Group II. Sampling was conducted once per day at 1, 5, 10, 15, 20, 30, and 40 d after the beginning of cultivation, and the samples were collected from three bottles during each sampling period. Soil from a paddy field in which rice had grown for many years was selected, and the base fertility was as follows: 17.42 g kg^{-1} organic matter, 1.53 g kg^{-1} total N, 0.36 g kg^{-1} total P, 25.52 g kg^{-1} total K, 10.55 mg kg^{-1} NH_4^+–N,

Table 1
Basal fertility of the soil

Test	g kg^{-1}				mg kg^{-1}			
	Organic matter	Total N	Total P	Total K	NH_4^+–N	NO_3^-–N	Olsen P	Available K
Test A	23.92	1.48	0.83	21.91	14.62	30.29	41.95	130.17
Test B	17.42	1.53	0.36	25.52	10.55	42.63	14.97	137.57

42.63 mg kg^{-1} NO_3^-–N, 14.97 mg kg^{-1} Olsen P, and 137.57 mg kg^{-1} available K.

2.3. Collection and analysis of the soil solution

The soil solution sampling device is shown in Fig. 1. The working principle has been described elsewhere [38].

The NH_4^+–N in the soil solution was detected by measuring the total NH_4^+–N content in the solution with a B-324 Kjeldahl analyzer from Buchi Co. (Flawil, Switzerland).

The mineral N was detected in the soil solution after the NO_3^-–N was reduced to NH_4^+–N by $FeSO_4 \cdot 7H_2O$ and Zn; the total NH_4^+–N content was then measured in the solution with a B-324 Kjeldahl analyzer from Buchi Co., and the results indicated the mineral N contents in the soil solution.

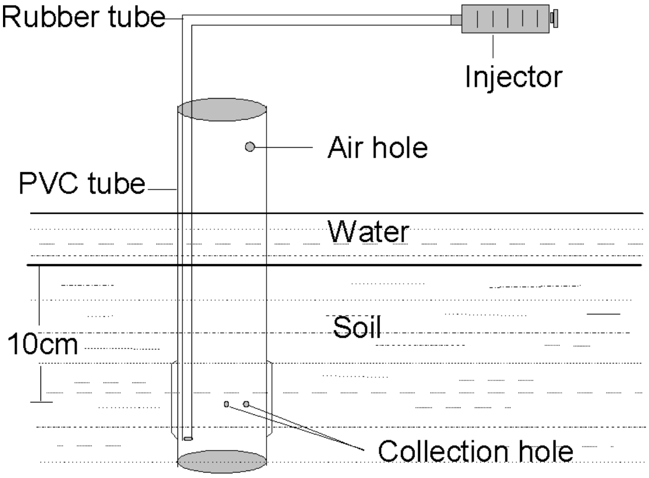

Fig. 1. Soil solution sampling device.

The NO_3^-–N content in the soil solution was calculated as the mineral N content minus the NH_4^+–N content. The effect of NO_2^-–N was ignored in this study.

2.4. Data processing

All the data from the collected soil solution samples were subjected to normality testing prior to a one-way analysis of variance with IBM SPSS Statistics 21.0 (SPSS Inc., Shanghai, China). To compare the mean treatment values, Duncan's multiple range test was used at a significance level of $p < 0.05$. Graphs were produced with Origin 9.0 software (OriginLab (Guangzhou Office), Guangzhou, China).

3. Results

3.1. NH_4^+–N content of the soil solution

Fig. 2 shows the changes in the NH_4^+–N content of the soil solution during the rice-growing seasons from 2012 to 2014. There were gradual decreases in the soil solution NH_4^+–N content during the rice growth stage, and the addition of urea topdressing at the tillering stage significantly increased the NH_4^+–N content of the solution. The experimental results from three consecutive years showed that the SRT treatment produced higher levels of NH_4^+–N in the soil solution compared with the SRM treatment.

Fig. 3 shows the changes in the NH_4^+–N content of the soil solution with different rates of N fertilizer application. The NH_4^+–N content showed dynamic changes over the rice-growing period. With the N_0 treatment, the NH_4^+–N content of the soil solution slowly decreased; the lowest value occurred 70 d after transplant. With an increasing N application rate, the NH_4^+–N contents of the soil solution at different stages

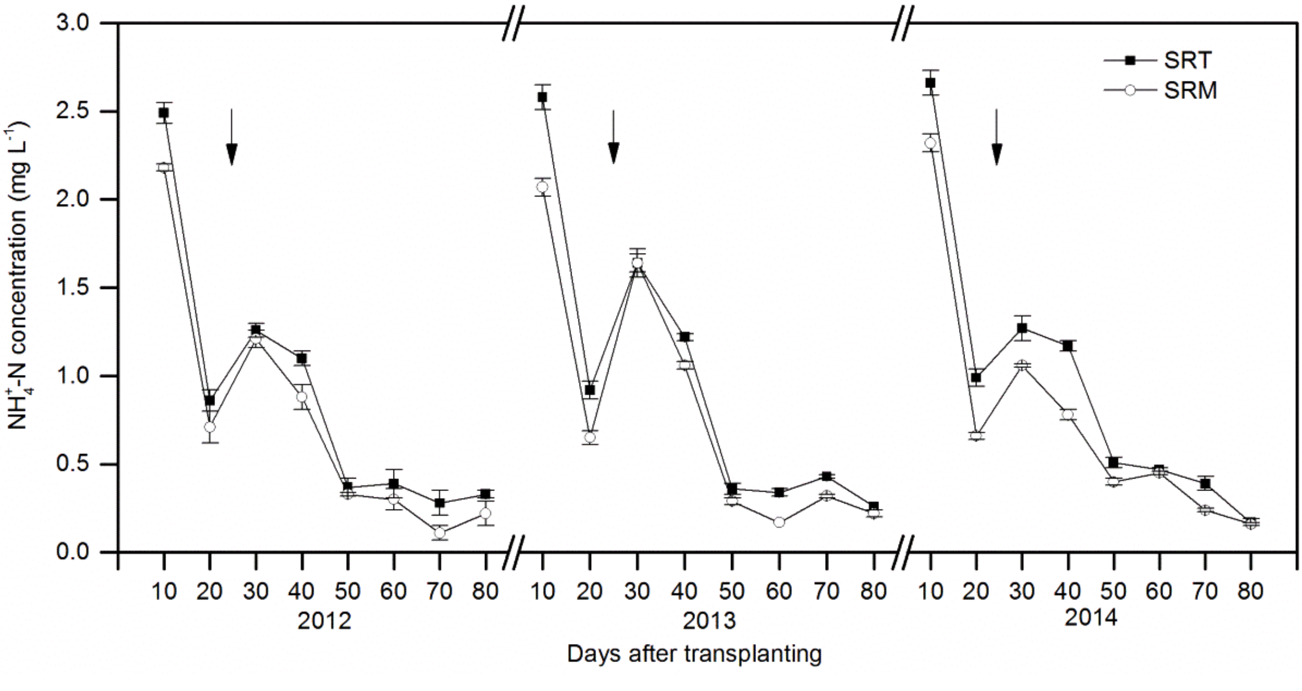

Fig. 2. Changes in NH_4^+–N concentration in the soil solution. SRT, straw retained; SRM, straw removed. The N topdressing application is represented by "↓" symbol.

increased to varying degrees. Urea topdressing markedly increased the NH_4^+–N contents of the soil solution. Compared with SRM, SRT increased the mean NH_4^+–N contents of the soil solution at different stages by 0.027 ± 0.005 mg L^{-1}, 0.096 ± 0.025 mg L^{-1}, 0.098 ± 0.035 mg L^{-1}, 0.131 ± 0.039 mg L^{-1}, and 0.156 ± 0.039 mg L^{-1} at the five N levels (N_0, N_1, N_2, N_3, and N_4, respectively). On average, SRT increased the NH_4^+–N content of the soil solution by 0.102 ± 0.029 mg L^{-1}.

Table 2 shows the equation fitting of theNH_4^+–N content of the soil solution with the changes in the urea application rate. There was a positive correlation between the NH_4^+–N content of the soil solution and the rate of N fertilizer application. The maximum increase in NH_4^+–N content occurred 10 d after transplant, followed by the increase that occurred 30 d after transplant. Thereafter, the increase in NH_4^+–N content in the soil solution gradually decreased, and the NH_4^+–N content was close to 0 mg L^{-1} at 70 d after transplant.

Fig. 4 shows the changes in the NH_4^+–N content of soil extracts under the laboratory cultivation conditions. The straw application increased the NH_4^+–N content of the soil solution. The SRT treatment results were higher than the SRM treatment results by 0.957 mg L^{-1} in Group I and by 1.759 mg L^{-1} in Group II. Longer cultivation durations produced a variable pattern of change in the NH_4^+–N content of the solution. The NH_4^+–N contents at different stages were relatively low and had small differences. The NH_4^+–N contents were higher in Group II compared with that in Group I for both treatments at all the cultivation stages.

3.2. NO_3^-–N content in the soil solution

Fig. 5 illustrates the NO_3^-–N content trend in the soil solution during the rice-growing period from 2012 to 2014. With rice growth, for the two treatments, the NO_3^-–N and NH_4^+–N contents showed a similar pattern of change, with an overall pattern of "decrease-increase-decrease." Compared with NH_4^+–N, the soil solution contained significantly higher NO_3^-–N, which is the primary form of mineral N in the solution. The NO_3^-–N contents in the solution were significantly higher 10 d after transplant than on the other dates. At 10–40 d after transplant, the NO_3^-–N content of the soil solution was higher in the SRT treatment group than in the SRM treatment group, although to varying degrees. However, the opposite trend was observed 50–60 d after transplant, and the result for the SRT treatment was lower than for the SRM treatment. At 70 d after transplant, the NO_3^-–N content in the solution was low and showed no significant difference between the two treatments.

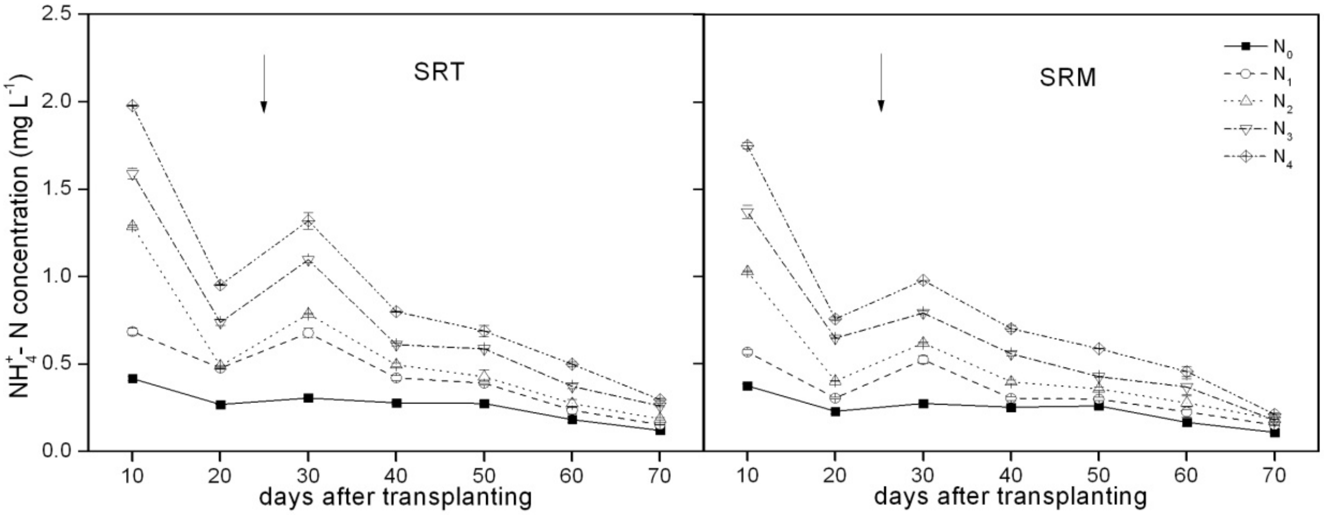

Fig. 3. Changes in the NH_4^+–N soil solution content under pot culture conditions. SRT, straw retained; SRM, straw removed. N_0: 0 kg ha^{-1}, N_1: 150 kg ha^{-1} urea, N_2: 300 kg ha^{-1} urea, N_3: 450 kg ha^{-1} urea, N_4: 600 kg ha^{-1} urea.

Table 2
Relationship between N fertilizer applied and NH_4^+–N concentration in solution

Days after transplanting	SRT		SRM	
	Equation	R^2	Equation	R^2
10	$y = 0.011x + 0.386$	0.987	$y = 0.010x + 0.306$	0.988
20	$y = 0.004x + 0.259$	0.949	$y = 0.004x + 0.186$	0.959
30	$y = 0.007x + 0.347$	0.980	$y = 0.004x + 0.300$	0.985
40	$y = 0.003x + 0.268$	0.974	$y = 0.002x + 0.227$	0.922
50	$y = 0.003x + 0.273$	0.978	$y = 0.003x + 0.210$	0.962
60	$y = 0.002x + 0.158$	0.946	$y = 0.002x + 0.152$	0.985
70	$y = 0.001x + 0.111$	0.976	$y = 0.000x + 0.118$	0.897

SRT, straw retained; SRM, straw removed; x, N fertilizer application rate (kg ha^{-1}); y, NH_4^+–N concentration in soil solution (mg L^{-1}).

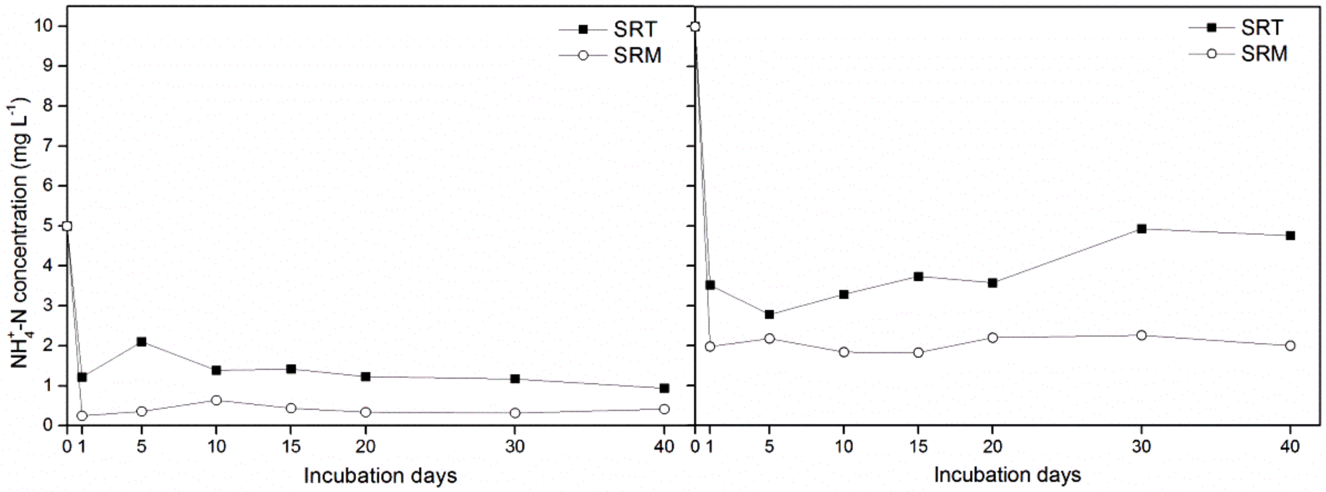

Fig. 4. Changes in the NH_4^+–N soil solution content under laboratory cultivation conditions. SRT, straw retained; SRM, straw removed.

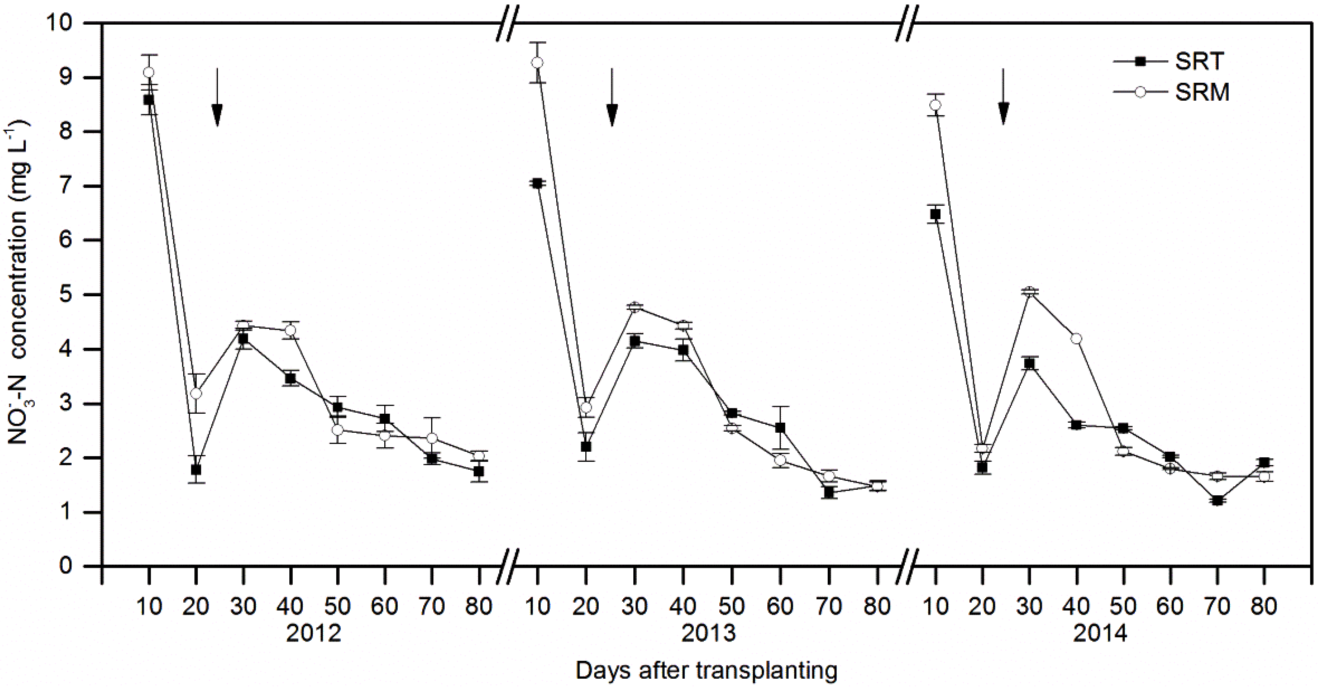

Fig. 5. Changes in NO_3^-–N concentration in the soil solution. SRT, straw retained; SRM, straw removed. The N topdressing application is represented by "↓" symbol.

Fig. 6 illustrates the dynamic changes in the NO_3^-–N content of the soil solution with different rates of N fertilizer application. The trend of theNO_3^-–N content was generally consistent with that of the NH_4^+–N content, which gradually decreased in the soil solution over time. Topdressing substantially increased the NO_3^-–N content of the soil solution. The primary difference was that the NO_3^-–N content of the soil solution was significantly higher than the NH_4^+–N content. The NO_3^-–N content of the soil solution in the SRT treatment group remained lower compared with SRM treatment at different sampling stages. Compared with SRM, SRT decreased the mean NO_3^-–N contents of the soil solution at different stages by 0.587 ± 0.158 mg L^{-1}, 0.322 ± 0.175 mg L^{-1}, 0.515 ± 0.177 mg L^{-1}, 0.619 ± 0.28 mg L^{-1}, and 0.522 ± 0.22 mg L^{-1}at the five N levels (N_0, N_1, N_2, N_3, and N_4, respectively). On average, SRT reduced the NO_3^-–N content of the soil solution by 0.513 ± 0.202 mg L^{-1}.

Table 3 presents the equation fitting of the NO_3^-–N content of the soil solution with the changes in urea application rate. There was a positive correlation between the NO_3^-–N content of the soil solution and the rate of urea application. The maximum increase in NO_3^-–N content appeared 30 d after transplant. The increase in NO_3^-–N content was significantly greater at 10–40 d than at 50–70 d after transplant.

The period of rapid straw decay occurs within 1 month after SRT, and the straw decomposition is fast and stable during this period. As shown in Fig. 7, 1 d after the beginning of cultivation, the NO_3^-–N content of the soil solution

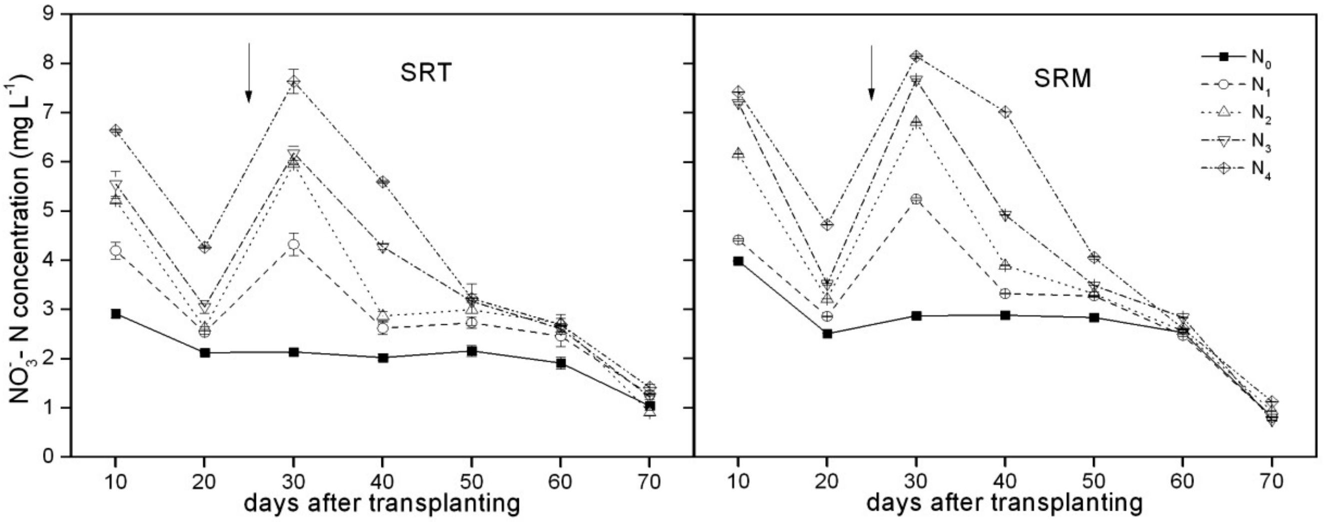

Fig. 6. Changes in the NH_4^+–N soil solution content under pot culture conditions.SRT, straw retained; SRM, straw removed. N_0: 0 kg ha^{-1}, N_1: 150 kg ha^{-1} urea, N_2: 300 kg ha^{-1} urea, N_3: 450 kg ha^{-1} urea, N_4: 600 kg ha^{-1} urea.

Table 3
Relationship between N fertilizer applied and NO_3^-–N concentration in solution

Days after transplanting	SRT		SRM	
	Equation	R^2	Equation	R^2
10	$y = 0.025x + 3.142$	0.970	$y = 0.028x + 3.904$	0.939
20	$y = 0.013x + 1.958$	0.855	$y = 0.014x + 2.341$	0.898
30	$y = 0.037x + 2.674$	0.938	$y = 0.037x + 3.551$	0.920
40	$y = 0.025x + 1.716$	0.927	$y = 0.028x + 2.430$	0.898
50	$y = 0.007x + 2.340$	0.873	$y = 0.007x + 2.860$	0.903
60	$y = 0.005x + 2.131$	0.665	$y = 0.001x + 2.491$	0.345
70	$y = 0.002x + 1.028$	0.308	$y = 0.001x + 0.770$	0.345

SRT, straw retained; SRM, straw removed; x, N fertilizer application rate (kg ha^{-1}); y, NO_3^-–N concentration in soil solution (mg L^{-1}).

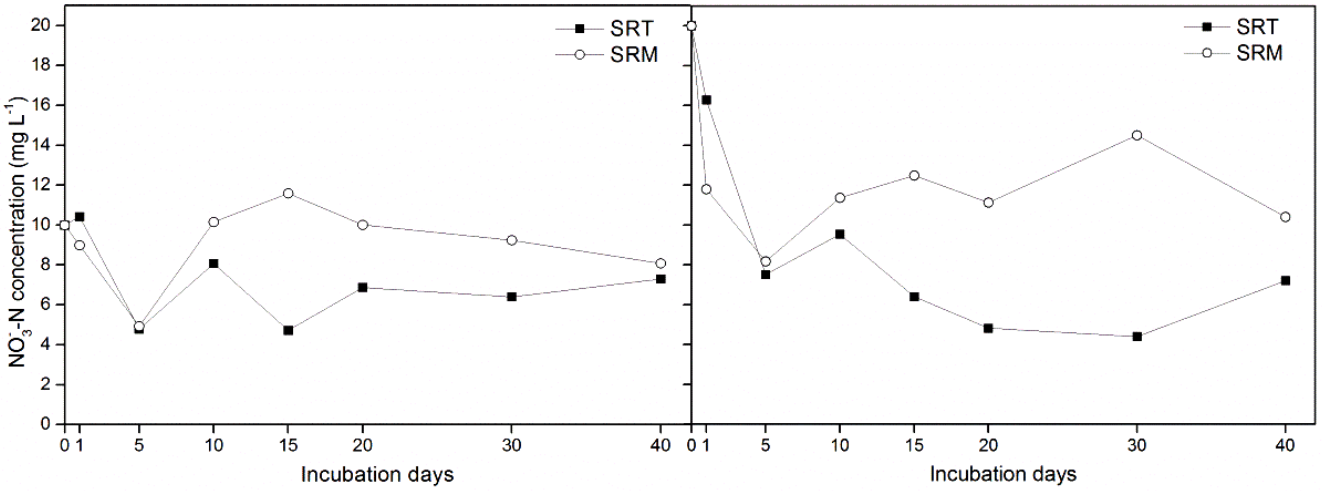

Fig. 7. Changes in the NO_3^-–N soil solution content under laboratory cultivation conditions. SRT, straw retained; SRM, straw removed.

was significantly higher for the SRT compared with the SRM treatment. During the period from 5 to 10 d after the start of cultivation, a new soil equilibrium system replaces the initial one. This period was affected by numerous factors. However, the NH_4^+–N concentration generally increased, and the NO_3^-–N concentration generally decreased. After 10 d (including the 10th day), the NO_3^-–N content in the SRM treatment was significantly higher than that in the SRT treatment by 2.058 mg L^{-1} in Group I and by 3.387 mg L^{-1} in Group II. A comparison between the two groups' results collected at the same time showed that the NO_3^-–N content was significantly higher for Group II compared with Group I. After 5 d of cultivation, the NO_3^-–N content in the solution did not differ significantly between the SRT and SRM treatments.

3.3. Mineral N in the soil solution

Mineral N, which primarily includes NH_4^+–N and NO_3^-–N, is the major form of N that is absorbed and utilized by plants. The mineral N content directly determines N absorption and utilization by crops. Fig. 8 depicts the trend in the mineral N content of the soil solution as a function of time after transplant and during the rice-growing period from 2012 to 2014. The results showed that the mineral N trend was consistent with that of NO_3^-–N. The NO_3^-–N content accounted for the vast majority of the total mineral N content, significantly exceeded the NH_4^+–N content, and constituted the major part of the mineral N in the soil solution. At 10–40 d after transplant, the SRT treatment produced lower mineral N contents in the soil solution compared with the SRM treatment. The opposite trend was observed from 50 to 60 d after transplant, namely, the soil solution mineral N was higher in the SRT compared with the SRM treatment. No significant difference occurred between the treatments 70 d after transplanting.

Fig. 9 shows the changes in the mineral N content of the soil solution with different rates of N fertilizer application. Mineral N is the major form of N absorbed by plants. The mineral N content of the soil solution can reflect the N-supplying capacity of the soil environment. In this study, SRT reduced the mineral N content of the soil solution. Compared with SRM, SRT reduced the mean mineral N contents of the soil solution at different stages by 0.589 ± 0.132 mg L^{-1}, 0.354 ± 0.162 mg L^{-1}, 0.431 ± 0.165 mg L^{-1}, 0.546 ± 0.238 mg L^{-1}, and 0.513 ± 0.276 mg L^{-1} at the five N levels (N_0, N_1, N_2, N_3, and N_4, respectively). On average, SRT reduced the mineral N content of the soil solution by 0.487 ± 0.195 mg L^{-1}. The mineral N content of the soil solution gradually decreased over time, but urea topdressing markedly increased the mineral N content. There was an upward trend in the mineral N content of the soil solution with an increase in urea application rate, which could be fitted by a linear equation (Table 4). The increase in the mineral N content of the soil solution was significantly higher than that of the NH_4^+–N content. The increase in the mineral N content at 10–40 d was markedly greater than that at 50–70 d after transplant.

Fig. 10 shows the changing trend of the inorganic N content of the soil solution; this trend was similar to that of NO_3^-–N. On the first day after the straw application, the mineral N was significantly higher in the solution from the SRT compared with the SRM-treated soil. At 5–10 d, the difference in the mineral N content between the solutions from the two soil treatments was not significant, primarily because the NO_3^-–N content of the solutions was high. After 10 d, the mineral N content was significantly higher in the solution from the SRM-treated soil compared with the SRT-treated soil. During the entire cultivation process, the SRM treatment results were higher than the SRT treatment results by 1.100 mg L^{-1} for Group I and by 1.626 mg L^{-1} for Group II. A comparison of the different mineral N concentrations of the two groups at each time point showed that the concentration in Group II was always higher than that in Group I. The overall trend was for the treatments with high mineral N concentrations to produce significantly higher results than

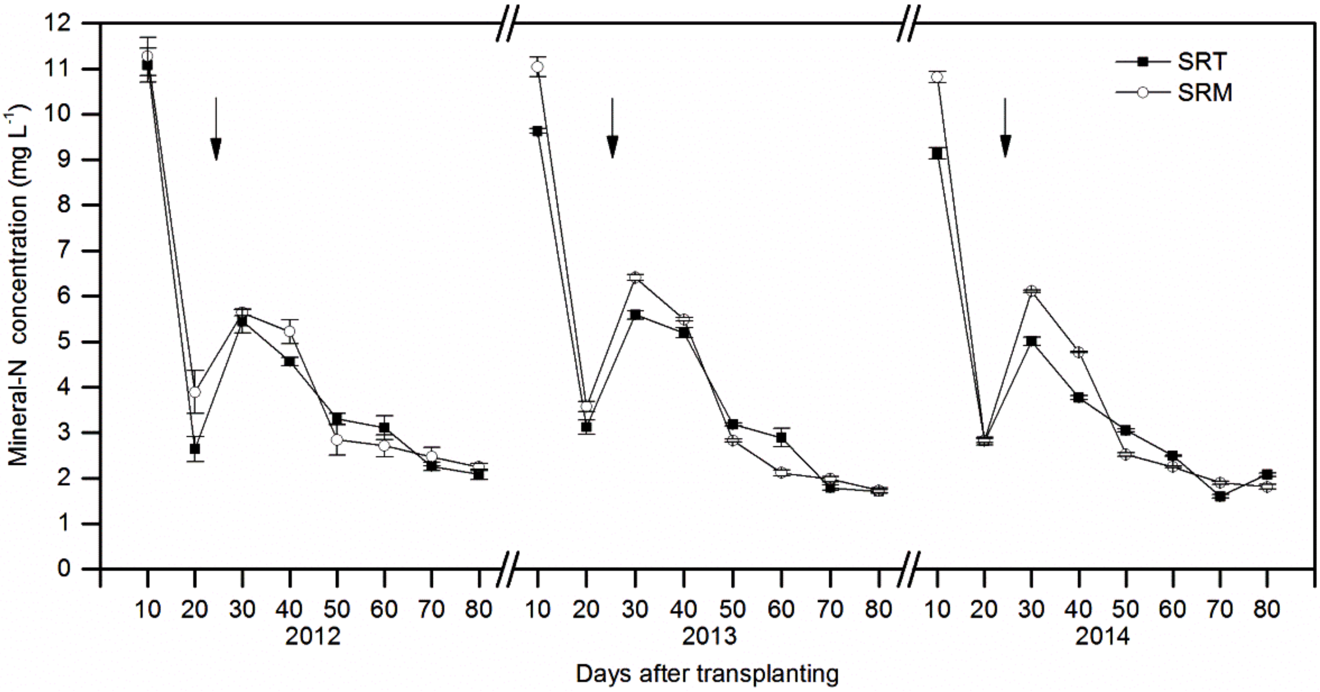

Fig. 8. Changes in mineral N concentration in the soil solution. SRT, straw retained; SRM, straw removed. The N topdressing application is represented by "↓" symbol.

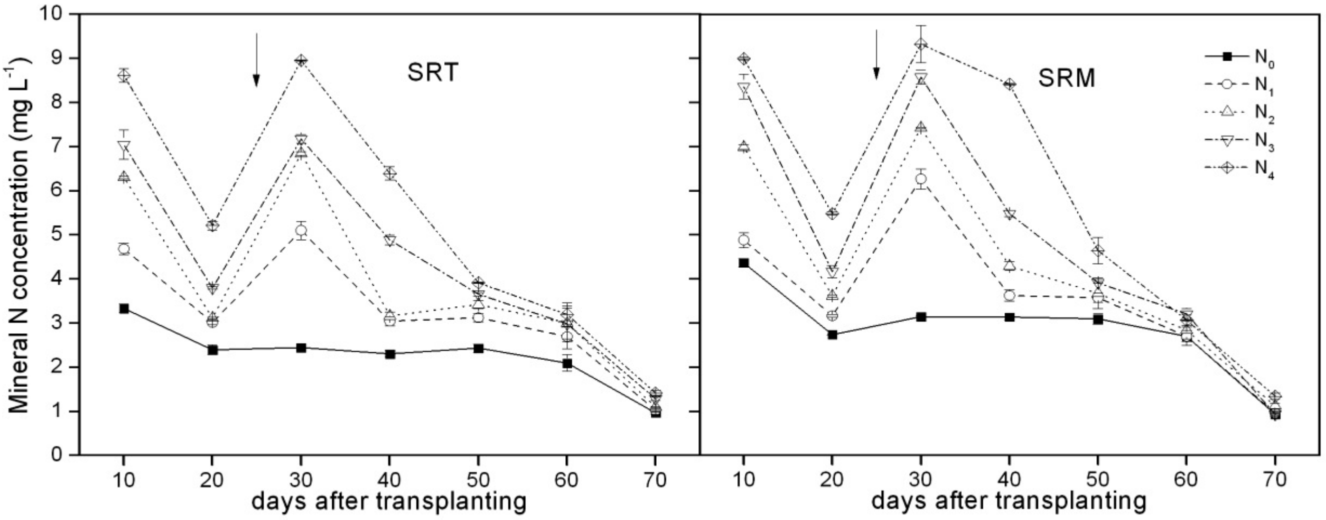

Fig. 9. Changes in the NH_4^+–N soil solution content under pot culture conditions. SRT, straw retained; SRM, straw removed. N_0: 0 kg ha^{-1}, N_1: 150 kg ha^{-1} urea, N_2: 300 kg ha^{-1} urea, N_3: 450 kg ha^{-1} urea, N_4: 600 kg ha^{-1} urea.

Table 4
Relationship between N fertilizer applied and mineral N concentration in solution

Days after transplanting	SRT		SRM	
	Equation	R^2	Equation	R^2
10	$y = 0.037x + 3.408$	0.990	$y = 0.037x + 4.166$	0.962
20	$y = 0.018x + 2.218$	0.889	$y = 0.018x + 2.528$	0.930
30	$y = 0.043x + 3.082$	0.940	$y = 0.042x + 4.012$	0.917
40	$y = 0.029x + 1.950$	0.913	$y = 0.036x + 2.500$	0.867
50	$y = 0.010x + 2.608$	0.938	$y = 0.010x + 3.088$	0.918
60	$y = 0.007x + 2.290$	0.842	$y = 0.003x + 2.644$	0.749
70	$y = 0.003x + 0.920$	0.953	$y = 0.002x + 0.888$	0.496

SRT, straw retained; SRM, straw removed; x, N fertilizer application rate (kg ha^{-1}); y, mineral N concentration in soil solution (mg L^{-1}).

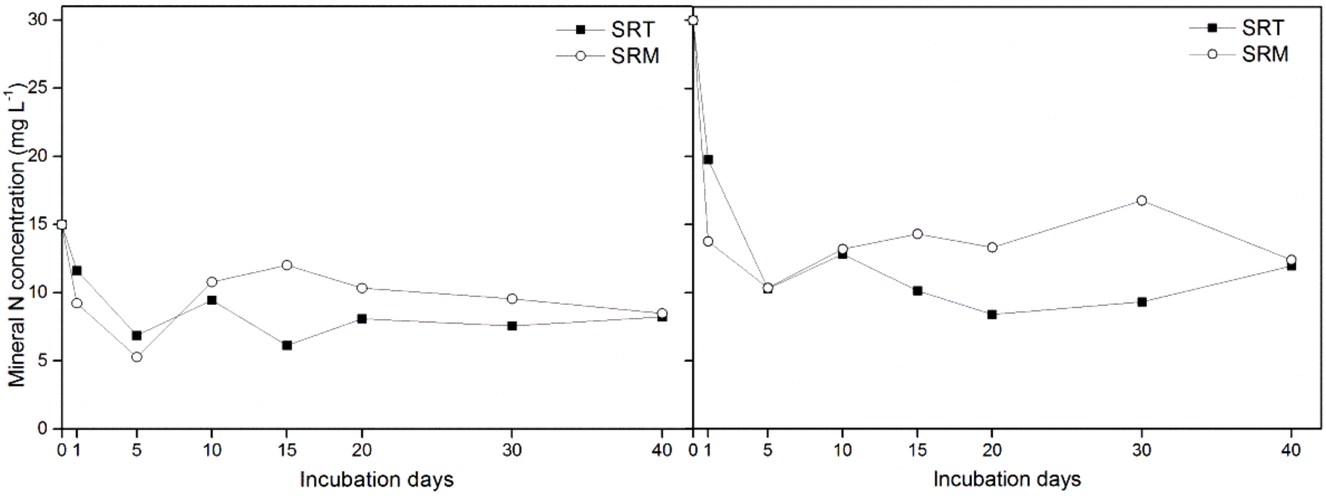

Fig. 10. Changes in the mineral N soil solution content under laboratory cultivation conditions. SRT, straw retained; SRM, straw removed.

those produced by the treatments with low mineral N concentrations. In addition, the inorganic N content of the solution from the SRT treatment gradually decreased, whereas the inorganic nitrogen content in the solution from the SRM treatment did not change significantly.

3.4. Rice yield

Table 5 shows the rice yield from Experiment A. The rice yield for the SRT treatment was higher than for the SRM treatment, and the average yield in 2012 differed from the yields in 2013 and 2014.

The trend of the rice yield in Experiment B was showed in Table 6; the rice yield of the SRM treatment showed unimodal changes with an increasing N application rate and reached the highest level at the N_2 level. The rice yield of the SRT treatment gradually increased with an increasing N application rate. SRT had no significant effects on rice yields at the N_0 and N_1 levels. However, the rice yield for the SRT treatment was significantly lower than for the SRM treatment at the N_2 level, whereas the opposite trend was observed at the N_3 and N_4 levels.

4. Discussion

4.1. Effect of SRT on NH_4^+–N

The results of this study showed that the NH_4^+–N content of the soil solution remained low during the rice-growing period. A previous study on well-aerated calcareous or strongly calcareous soils indicated that NH_4^+–N from either organic matter or N fertilizer is transformed into NO_3^-–N by nitrification over the short term and is incorporated into the soil [8]. The NH_4^+ ion is regarded as one of the two N sources (NH_4^+ and NO_3^-) that are used for plant growth; NH_4^+ is beneficial for plant growth in most cases [39]. In fact, NH_4^+ is a ubiquitous intermediate in plant metabolism. Compared with NO_3^-–N, NH_4^+–N can better improve rice plant tolerance to water stress [40]. However, an excessively high NH_4^+–N content significantly inhibits crop growth and yield [7, 41–43]. Rice grown in water is thought to favor NH_4^+. In this study, the laboratory cultivation and field plot experiments produced consistent results. In particular, SRT increased the NH_4^+–N content of the soil solution, with no clear relation between the increase and the time (days) after transplant. In the plot experiment, the average increase in the NH_4^+–N content was 0.17 mg L^{-1}, and the relative increase was 29.08%, which ensured NH_4^+–N absorption by the rice plants. An increase in N fertilizer application resulted in a gradual increase in the NH_4^+–N content of the soil solution; however, it did not alter the effect of SRT on the NH_4^+–N content. Compared with SRT, increasing N application affected the NH_4^+–N content of the soil solution more significantly.

Table 5
Effect of rice straw amendment on yield of rice (kg m^{-2})

	SRT	SRM
2012	0.8800 ± 0.0100a	0.8050 ± 0.0175b
2013	0.7675 ± 0.0181a	0.7450 ± 0.0150a
2014	0.8725 ± 0.0150a	0.8525 ± 0.0375a
Average	0.8400 ± 0.0143a	0.8008 ± 0.0100b

Note: Lowercase English letters indicate significant differences in the 0.05 level ($p = 0.05$).
SRT, straw retained; SRM, straw removed.

Table 6
Rice yield and nitrogen fertilizer application (g pot^{-1})

	SRM	SRT
N_0	58.76 ± 4.47a	59.24 ± 0.74a
N_1	70.96 ± 1.83a	76.66 ± 1.90a
N_2	112.78 ± 1.17a	83.92 ± 2.75b
N_3	87.04 ± 3.82b	106.22 ± 3.01a
N_4	78.54 ± 1.10b	119.89 ± 3.49a

Note: Lowercase English letters indicate significant differences in the 0.05 level ($p = 0.05$).
SRT, straw retained; SRM, straw removed.

A study by Wang et al. [44] in the rice–wheat rotation fields of southern China showed that the retention of wheat straw increased the NH_4^+–N concentration in solution by 11.5%–22.5%. Qiu et al. [34] label led Fluvisol with 15 N and confirmed that SRT significantly reduced the newly fixed NH_4^+–N. With an increasing degree of N mineralization, the fixation and mineralization of N were gradually equilibrated [32]. The combined effects of factors such as the decomposition and release of straw, the adsorption and desorption of soil, the nitrification and denitrification of N, microbe metabolism, and the volatilization of NH_4^+–N are the primary factors that influence N transportation and transformation processes in the soil solution.

4.2. Effect of SRT on NO_3^-–N

The NO_3^-–N content of soil substantially exceeds its NH_4^+–N content [9], and NO_3^-–N constitutes a major component of inorganic N. Ammonium N derived from soil and fertilizers is rapidly transformed into NO_3^-–N by nitrification [8], becoming a major source of inorganic N that is available to plants [10]. With increasing environmental N, the advantage of NO_3^-–N for promoting crop growth is increasingly obvious [7]. In this study, increasing N fertilizer application markedly contributed to the NO_3^-–N content of the soil solution during the early stage of the rice-growing period (10–40 d after transplant); SRT at different N application levels reduced the mean NO_3^-–N content of the soil solution by 0.513 ± 0.202 mg L^{-1}. In a typical rain-fed area in southern Spain, one study [45] also showed that excess N fertilizer application increased the amount of residual NO_3^-–N in the soil, most of which accumulated in the 30–60 cm layer. The accumulation of soil NO_3^-–N gradually increased with an increasing rate of N fertilizer application [5, 6]. Once it is leached from the crop root zone, NO_3^-–N will not be absorbed by crops, leading to fertilizer waste and groundwater pollution [46–48]. In this study, the results of the field plot experiment showed that the NO_3^-–N content was markedly higher than the NH_4^+–N content in the soil solution. Compared with the SRM treatment, SRT reduced the NO_3^-–N content of the soil solution by 8.9%. The results of the pot and laboratory cultivation experiments showed that in the absence of rice plantings, the SRT treatment produced a lower NO_3^-–N content in the soil solution, a result that was consistent with the field data. Numerous studies have shown that N application markedly influences the temporal and spatial distribution of mineral N in the soil. Reducing N applications and increasing the proportion of N topdressing can increase the grain yield, plant N absorption, and N use efficiency and can reduce NO_3^-–N leaching from the soil [19,45]. Supplementation with NO_3^-–N during the late growth period can improve the N nutrition of rice and increase rice grain yields. The results of this work showed that the inorganic N content of the soil solution significantly increased after the topdressing N fertilizer application on June 25 in 2012, 2013 and 2014.

4.3. Effect of SRT on mineral N

During the experiment, the inorganic N content of the soil solution was less than that of the soaking solution, indicating that soil soaking led to a decrease in the mineral N content of the solution. During the early stages of laboratory cultivation, the inorganic N content under the SRT treatment was significantly higher than that under the SRM treatment, indicating that SRT allowed for a quick release of soluble N as a supplement to the N in the soil [28]. A previous study found that straw application reduced the soil N content because the straw increased microbial N fixation [49]. The C/N ratio of the rice straw was generally50–60:1, and the C/N ratio of the organic matter from microbial decomposition was 20–30:1. Thus, the C/N ratio in the soil environment was improved because of SRT [26]. Our results showed that SRT reduced the mineral N content of the soil solution during the rice-growing period; on the contrary, N application increased the mineral N content, but it did not alter the effect of SRT on mineral N content. During the middle and late stages of cultivation, SRT treatment can cause a large increase in microorganisms; therefore, if the N source required for microbial metabolism is relatively lacking, the soil can compensate for the deficiency, resulting in the fixation of inorganic N [24–26].

The management of soil, crops, and fertilizers can affect the quantity and quality of N in soil [50]. Mineral N is the primary form of N absorbed by plants, and the amount of mineral N reflects the N supply capacity of the soil [51]. The decomposition of retained straw increases the demand for available N in the soil by organisms, which resulted in a significantly lower available N content in the soil 20–40 d after rice transplantation for the SRT compared with the SRM treatment. SRT can promote the microbial fixation of N [26], and a study by Abera et al. [27] employing different tropical soil conditions suggested that the application of plant residues can increase NO_3^-–N fixation, synchronous N uptake, and N release.

Straw crop residue is a primary source of organic matter and plant nutrients [18]. Experiments with SRT over many continuous years have increased the organic matter [20] and total N content of the soil [21,22,29–31]. SRT has also improved the fertility of the soil and the status and rate of nutrient absorption by crops [18,34]. The results of this study showed not only that the N content of the soil solution rapidly decreased with rice growth and did so because the N was used by organisms but also that a loss and fixation of N occurred. The uptake and utilization of N by plants and microorganism algal blooms increased the consumption of nitrogen; thus, the N content of the soil solution rapidly decreased to the original base line level. At 20–40 d after rice planting, the mineral N and NO_3^-–N contents of the soil were significantly lower under the SRT compared with the SRM treatment.

4.4. Effects of SRT and N fertilizer application on rice yield

The retention of straw affects the yield of crops [52]. The incorporation of SRT with inorganic fertilizers can improve the synchronization of N supply and crop uptake, reduce the risk of N leaching, and increase the yield of crops [53,54]. In this study, the inter-annual rice yield differed slightly in Experiment A, but SRT increased the rice yield. In Experiment B, the rice yield of the SRM treatment showed quadratic changes with an increasing rate of N application, and the highest yield was obtained at the N_2 level (conventional fertilizer application level used in local production); with the SRT treatment, the rice yield increased linearly with an increase in the N application rate. A field trial in the rice–wheat rotation system [55] indicated that the retention of wheat straw has an adverse effect on rice yield, mainly because the straw application increases N fixation and thus leads to soil N deficiency. Alternatively, early straw mulching results in the desynchronization of the soil supply and crop demand for nutrients. Moreover, rice yield is affected by climatic differences between regions [56].

5. Conclusions

Based on a long-term experiment conducted for 3 years, there were gradual decreases in the NH_4^+–N, NO_3^-–N, and mineral N contents of the soil solution with rice growth. Although the retention of rice straw altered the contents of the three N forms in the soil solution during the rice-growing period, there was no effect on the trends shown by the N forms within the soil solution. With retained straw, the NH_4^+–N content of the soil solution increased by 29.08% (0.17 mg L^{-1}) over the rice-growing period, and the NO_3^-–N and mineral N contents decreased by 8.90% (0.47 mg L^{-1}) and 3.02% (0.29 mg L^{-1}), respectively. N fertilizer application did not alter the change in the N forms of the soil solution with straw application, but it increased the N contents of the soil solution.

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