Controlled-release N fertilizer to mitigate ammonia volatilization from double-cropping rice

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Abstract Controlled-release nitrogen fertilizer (CRNF) can effectively enhance crop yields and raise the efficiency of nitrogen fertilizer in agroecosystems. In the present study, the volatilization of NH₃ was determined by airflow enclosure chamber technique after the application of different CRNF rates in double-cropping rice fields in southern China for continuous 3 years. The early and late season rice (ESR and LSR) were cultivated each year. The results showed that the total NH₃ volatilization losses ranged from 25 to 56 kg N ha⁻¹ in ESR and from 32 to 61 kg N ha⁻¹ in LSR. The loss of N to the total applied N ranged from 12 to 29% in ESR and from 12 to 27% in LSR. The application of CRNF significantly reduced the cumulative NH₃ volatilization losses by 20–43% for ESR and by 20–32% for LSR compared with conventional urea application. CRNF in LSR was less effective to reduce NH₃ volatilization than that in ESR. Furthermore, the application of 80% of N rate in the form of CRNF gave higher grain yield and

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apparent nitrogen recovery efficiency (ANRE) than that of application of 100% of N rate from conventional urea. CRNF can effectively reduce NH$_3$ volatilization, and increase rice yield and ANRE. Considering higher price of CRNF, the application of CRNF at lower (20% applied N) rate than conventional urea in LSR may be a reasonable fertilization strategy for improving N use efficiency, environment effectiveness, and sustaining the development of rice production systems in double-cropping rice.

**Keywords** Ammonia (NH$_3$) volatilization · Paddy field · Grain yield · Urea

**Introduction**

Ammonia (NH$_3$) volatilization from agriculture sectors represents 80–90% of the total anthropogenic emission (Galloway and Cowling 2002; Zhang et al. 2010). The volatilization of NH$_3$ results in increasing the deposited N in land and water resources causing environmental pollution (Asman et al. 1998; Eissa and Negim 2018; Ding et al. 2020), which may have negative effects in the ecosystems (Goulding et al. 1998), such as acidification (Zhao et al. 2013), and changes in biodiversity (Stevens et al. 2004). Undoubtedly, NH$_3$ volatilization from agricultural fields becomes an important pathway for N loss (Cai 1997). In rice fields for instance, it was estimated that NH$_3$ volatilization losses reached up to 60% of the applied N fertilizer (Song et al. 2004; Griggs et al. 2007). In China, Shang et al. (2014) found that the cumulative NH$_3$ loss was 9.2–33.6% and 17.8–32.2% of the applied N to double-cropping paddy field. High N application rate is important to increase grain yields for demands of increasing population globally, but this results in serious N losses from paddy fields with low nitrogen-use efficiency (Huang et al. 2006; Chen et al. 2015). Nitrogen-use efficiency (NUE) for rice grown in China and fertilized with ammonium bicarbonate and urea was only 30–35%, and those losses accounted for about 50% of the applied N fertilizers (Huang et al. 2006). Ju et al. (2009) stated that fertilization rates which are applied by farmers often exceeded plant requirements, due to the difficulty in determination of optimum N rate accurately. Hence, Huang et al. (2010) reported that high rates of N fertilizer may increase crop yields, however, negatively affected the sustainable development and reduced the nitrogen use efficiency. Another negative effect of high N rates is the N losses through NH$_3$ volatilization which increases with increasing N rates (Tian et al. 2001; Zhao et al. 2009; Abou-Zaid and Eissa 2019; Eissa et al. 2016).

Rice (*Oryza sativa* L.) represents 50% of the world’s population food due to its high nutritive value with a especial interest in Asia (Qin et al. 2013). In China, double rice-other crop accounted for 41%, while annual double rice-cropping represented 15% (Shang et al. 2011). However, the nitrogen use efficiency (NUE) of fertilizers applied in the double-cropping rice system is commonly low in China, ranging from 30 to 40% and a large part of the applied N fertilizer is lost through NH$_3$ volatilization (Fan et al. 2006; Zhang and Zhang 2013; Chen et al. 2015). It was estimated that the ratio of NH$_3$ loss to applied N from rice-based cropping systems was 30–39% in the north China Plain (Zhu et al. 1988) and 5–18% in the Taihu Lake region of China (Tian et al. 2001). In south China due to the high temperatures and strong sunlight in summer, N loss via NH$_3$ volatilization reached 60% of the total applied nitrogen fertilizer (Song et al. 2004). NH$_3$ volatilization is influenced by several soil and environmental conditions including: the concentration of ammonium nitrogen (NH$_4^+$-N) in floodwater, soil pH, and temperature (Liu et al. 2007; Tian et al. 2001). A recent study by Adhikari et al. (2019) observed high pH buffering capacity of soil with higher organic matter content and vice versa, suggesting influence of organic matter on NH$_3$ emissions. Thus, investigation of the behavior of NH$_3$ volatilization under different environmental conditions is vital to increase N use efficiency and to reduce the environmental pollution specially for paddy fields conditions (Liu et al. 2015).

The applications of N fertilizers are normally split for maximum rice production in China, with 2–4 top dressings as broadcast application during each crop season, but this often result in very low NUEs, severe N loss, and environmental contamination (Peng et al. 2002; Almaroai and Eissa 2020; Al-Sayed et al. 2020; Rekaby et al. 2020). Although NH$_3$ volatilization has been reported in Chinese double rice-cropping system under long-term fertilization (Shang et al. 2014), but few literatures have been showed the impacts of controlled release forms on NH$_3$ volatilization in...
double-cropping rice grown in paddy soils. Controlled-release nitrogen fertilizer (CRNF) has been found in a number of production systems to improve NUEs (Grant et al. 2012). The use of controlled-release nitrogen fertilizer is one of the methods of fertilization optimization in agriculture production (Chen et al. 2014; Nardi et al. 2018). Yang et al. (2012) reported that the use of controlled release urea augmented the apparent N use efficiency as high up to 50%, while the apparent N use efficiency of the traditional form of urea fertilizer was only about 24%. However, the agronomic and environmental effectiveness of CRNF on NH₃ volatilization in a double rice-cropping system are not well known. Hence, the present study investigated 3 year-field NH₃ volatilization from double cropping rice fields under different controlled-release N application rates. The objectives were to (1) evaluate the influence of CRNF application on NH₃ volatilization in double-cropping rice fields; (2) explore the effects of CRNF on grain yields and NUEs of double-cropping rice. The outcome of the study would optimize agricultural management strategies to achieve increased grain yields and mitigate NH₃ losses from double rice production in southern China.

Materials and methods

Experimental site

Field experiments were conducted from late March to July (ESR) and from July to October (LSR) of 2013, 2014, and 2015 in the same field in Hua yuan village, Liuyuan County, Hunan Province, China (28° 19′ N, 113° 49′ E), where cropping regime is dominated by the double-cropping rice systems. The experimental field was left fallow between April and November after every second growing season. The climate is typical continental sub-tropical humid monsoon with an average annual temperature of 17.3 °C, and an average annual rainfall of 1171.6 mm. The soil at the experimental site was derived from alluvial deposit and classified as loamy clay (Alluvial nitisols) (Soil Survey Staff 2010). Basic soil properties were as follows: pH = 5.61, organic matter = 16.62 g kg⁻¹, total N = 1.21 g kg⁻¹, total P = 0.54 g kg⁻¹, total K = 11.51 g kg⁻¹, available N = 48.93 mg kg⁻¹, available P = 21.25 mg kg⁻¹, and available K = 155.68 mg kg⁻¹.

Experimental design and management

The resin-coated urea (42% N, a releasing period of 3 months, made by Kingenta Ecological Engineering Co. Ltd., Shandong, China) was used as a controlled-release nitrogen fertilizer (CRNF). The conventional urea (46% N) fertilizer was used for comparison. The experiment included the application of 100, 90, 80, and 70% of the recommended N dose which is 150 and 180 kg N ha⁻¹ for ESR and LSR, respectively. Treatment without N fertilization served as control.

Hybrid rice varieties that used in this study were “Lingliangyou 268” and “HYou 159” for ESR and LSR, respectively. The ESR and LSR were cultivated at a density of 300,000 plants ha⁻¹ (16.7 cm × 20.0 cm), and 250,000 plants ha⁻¹ (20.0 cm × 20.0 cm), respectively. Rice seedlings were transplanted on 9 May (2013), 17 April (2014), 25 April (2015) and harvested on 19 July (2013), 21 July (2014), 17 July (2015) for ESR, followed by LSR with transplanting on 24 July (2013), 29 July (2014), 23 July (2015) and harvesting on 23 October (2013), 25 October (2014), 1 November (2015). After transplanting, maintain shallow water for a week, maintain irrigation later, promote tillering, medium-term sun field, cultivate strong culms. Wet and shallow water irrigation was used in booting and filling stages, and dry out in milk stage until harvest. Each treatment was replicated three times with a plot size of 20 m² (4.0 m × 5.0 m) in a complete randomized block design.

Measurement of NH₃ volatilization

Chamber and the continuous airflow enclosure method were used to measure NH₃ volatilization flux in each plot of paddy field (Huang et al. 2006). The dimension of the volatilization chamber was 200 mm in diameter and 150 mm in height. The airflow rate generated by a
pump was adjusted to 15–20 times per min. After fertilization, the NH$_3$ emission rate was measured twice a day, in the morning and afternoon. Air was continuously pumped for 2 h and allowed to flow through NH$_3$ absorbent material (2% H$_3$BO$_3$) for each treatment, and the amount of trapped NH$_3$ in the acid was titrated with 0.02 mol L$^{-1}$ H$_2$SO$_4$. Chambers were moved away to avoid any effects after measurement. During the experimental period, measurements continued every day until no significant difference in the trapped NH$_3$ between N treatments and the control. Air temperature was also recorded at the same time. Daily NH$_3$ emission was calculated by the average rates measured each day. Total NH$_3$ emission was calculated by the sum of the daily emission during the growing period. Climatic data for air temperature (°C), and rainfall (mm) were obtained from nearby weather station (within 0.1 km of field site).

Measurement of grain yield and apparent nitrogen recovery efficiency (ANRE)

The soil physicochemical properties and nutrients content during the experimental period were measured using methods described by Lu et al. (2000). Grain yield was determined by harvesting the whole plot, adjusted to the standard 14% moisture content. Yield components including effective panicle $m^{-2}$, spikelet $m^{-2}$, 1000-grain weight, and grain filling percentage derived from 5 plants, were selected from each plot randomly (Qin et al. 2013). The N content in the stems, leaves, and spikelets were determined by micro-Kjeldahl digestion (Bremner and Mulvaney 1982). Apparent nitrogen recovery efficiency (ANRE) was estimated as percentage of the difference in the total N uptake between the N treatment and the control in comparison to total N inputs.

Statistical analysis

Data was checked for normality by Kolmogorov–Smirnov (K–S) test and no transform was necessary. Analyses of variance (ANOVA) were achieved by the general linear model procedure of SPSS (Ver. 17, SPSS, Chicago, IL, USA). Means of years and treatments were compared based on the least significant difference (LSD) test for each season at $p < 0.05$ probability level. Differences in seasonal NH$_3$
volatilization over 2013–2015 were calculated from fertilization treatments, years, and their interactions by using a two-way ANOVA.

**Results**

Ammonia volatilization losses in double-cropping rice field

From basal fertilizer to topdressing fertilizer period, the average temperature and precipitation were 21.3 °C and 11.8 mm for ESR (Suppl Fig. 1). NH$_3$ volatilization losses were very low during the basal fertilizer period in ESR (Fig. 1 and 2). The values of NH$_3$ volatilization fluxes were similar in the studied CRNF treatments and no significant differences occurred between CRNF treatments. Generally, the average rates of NH$_3$ volatilization augmented with time and reached the maximum values within 3 days after fertilization, and then decreased. NH$_3$ volatilization rate peaks were higher after topdressing fertilization than basal fertilization for ESR. One week later, NH$_3$ volatilization from each treatment approached the control value. Hence, 52–60% of the total emissions obtained in the case of topdressing fertilizer period from the fertilization treatments for ESR.

Seasonal cumulative NH$_3$ volatilization significantly varied with the fertilization treatments ($p < 0.001$) and years ($p < 0.01$), whereas it was not significantly affected by their interactions in ESR ($p > 0.05$; Table 2). Fertilizer application significantly increased NH$_3$ volatilization in LSR across years (Table 2). Application of CRNF reduced NH$_3$ losses by an average of 26.7–40.6% compared with that of UREA treatment across the years in LSR. Additionally, there was a linear relationship between amounts of NH$_3$ emission ($y_{LSR}$) and N rates ($x_{LSR}$) of CRNF treatments for LSR across years ($y_{LSR} = 0.1474x_{LSR} + 14.063$, $R^2 = 0.9982$, $p < 0.01$), whereas the ratios of N loss to the applied N also showed a downward trend across the years for LSR.

Response of rice yield and apparent nitrogen recovery efficiency to controlled-release nitrogen fertilizer

Rice grain yield of ESR and LSR varied significantly among years and treatments (Table 3). The yield components were significantly affected by years ($p < 0.05$ to $p < 0.001$, except for panicles m$^{-2}$ and grain filling in ESR and spikelets m$^{-2}$ in LSR), as well as by the treatments ($p < 0.01$ to $p < 0.001$, except for grain filling and 1000-grain weight), whereas their interactions were not significant ($p > 0.05$). CRNF1 gave the maximum yield all over the years and seasons, whereas the lowest one was observed in the control treatments. Across the years, the average grain yields in LSR were 15–40% higher than those in ESR. In most cases, CRNF1 gave the highest grain yields for ESR, followed by CRNF2 which gave the highest grain yields in the case of LSR. The CRNF2 treatments in LSR produced higher grain yield than the traditional urea. Overall, the maximum grain yield of ESR was achieved from CRNF1, moreover, there declined to a low level similar to the control after less than 1 week. A strong volatilization occurred immediately after topdressing fertilization, although the fluxes varied substantially among plots. The peak values of NH$_3$ volatilization rates in LSR were similar to that in ESR. NH$_3$ volatilization rate peaks were also higher after topdressing fertilization than that after basal fertilization in LSR. NH$_3$ volatilization dropped rapidly after 1 week until closed to background level. Hence, 54.5–61.6% of the total emissions occurred after topdressing fertilization for the fertilizer treatments in LSR.

Seasonal cumulative NH$_3$ loss in LSR depended greatly on fertilization ($p < 0.001$), whereas it did not significantly vary with year or their interaction ($p > 0.05$; Table 2). Fertilizer application significantly increased NH$_3$ volatilization in LSR across years (Table 2). Application of CRNF reduced NH$_3$ losses by an average of 26.7–40.6% compared with that of UREA treatment across the years in LSR. Additionally, there was a linear relationship between amounts of NH$_3$ emission ($y_{LSR}$) and N rates ($x_{LSR}$) of CRNF treatments for LSR across years ($y_{LSR} = 0.1474x_{LSR} + 14.063$, $R^2 = 0.9982$, $p < 0.01$), whereas the ratios of N loss to the applied N also showed a downward trend across the years for LSR.
Fig. 1 Seasonal variation of NH₃ fluxes from the surface of paddy fields for ESR and LSR from 2013 to 2015. Control: no nitrogen fertilizer; UREA: 100% Urea-N; CRNF1: 100% controlled-release -N; CRNF2: 90% controlled-release -N; CRNF3: 80% controlled-release -N; CRNF4: 70% controlled-release -N. ESR: Early season rice; LSR: Late season rice. The vertical bars mean standard deviations of the means. Numbers and arrows represented N fertilizer application. Basal fertilizer was applied on one day before transplanting, tillering fertilizer on 21 May (2013), 27 April (2014), 5 May (2015) for ESR; and on 3 August (2013), 8 August (2014), 2 August (2015) for LSR.
Table 2 Cumulative NH$_3$ volatilization and its loss ratio to N applied and ANRE in both seasons across three years (2013–2015)

| Year | Treatment | NH$_3$-N volatilization loss (kg N ha$^{-1}$) | Ratio of NH$_3$-N to N rate (%) | ANRE (%) |
|------|-----------|---------------------------------------------|---------------------------------|----------|
|      | Basal     | Topdressing                                 | Total                           |          |
|      | ESR       | LSR                                         | ESR                            | LSR      | ESR       | LSR       | ESR       | LSR       | ESR       |
| 2013 | Control   | 4.97a                                       | 6.71b                           | 11.97c   | 15.02b    | –         | –         | –         | –         |
|      | Urea      | 13.54a                                      | 17.73a                          | 20.04a   | 23.82a    | 55.58a    | 50.55a    | 29.08a    | 19.73a    | 30.59b    | 20.34b    |
|      | CRNF$_1$  | 10.74a                                      | 13.12a                          | 20.95b   | 23.35a    | 31.69b    | 36.47a    | 13.14b    | 11.91a    | 48.60a    | 48.27a    |
|      | CRNF$_2$  | 9.85a                                       | 13.93ab                         | 18.20bc  | 21.06ab   | 28.06bc   | 35.00a    | 11.91b    | 12.33a    | 49.21a    | 50.22a    |
|      | CRNF$_3$  | 9.30a                                       | 13.60ab                         | 17.99bc  | 21.01ab   | 27.29bc   | 34.60a    | 12.77b    | 13.60a    | 49.52a    | 51.09a    |
|      | CRNF$_4$  | 8.07a                                       | 12.91ab                         | 17.35bc  | 19.80ab   | 25.42bc   | 32.71a    | 12.81b    | 14.04a    | 50.76a    | 51.44a    |
| 2014 | Control   | 7.49c                                       | 7.01c                           | 13.56c   | 13.53c    | –         | –         | –         | –         |
|      | Urea      | 22.46a                                      | 21.56a                          | 25.01a   | 33.71a    | 47.47a    | 55.27a    | 22.47a    | 23.19a    | 23.67b    | 30.38c    |
|      | CRNF$_1$  | 19.27ab                                     | 20.07ab                         | 18.84b   | 24.22b    | 38.11b    | 44.29ab   | 16.23b    | 17.09a    | 27.14b    | 35.74bc   |
|      | CRNF$_2$  | 18.38b                                      | 19.28ab                         | 18.26b   | 19.16b    | 36.64b    | 38.44b    | 16.94b    | 15.38a    | 32.88a    | 41.11ab   |
|      | CRNF$_3$  | 17.32b                                      | 17.42ab                         | 18.50b   | 20.11b    | 35.82b    | 37.52b    | 18.38b    | 16.66a    | 34.28a    | 42.90ab   |
|      | CRNF$_4$  | 16.41b                                      | 15.88b                          | 16.68b   | 18.67b    | 33.09b    | 34.54b    | 18.41b    | 16.68a    | 35.59a    | 45.67a    |
| 2015 | Control   | 7.22d                                       | 6.85d                           | 6.91c    | 6.53d     | 14.13d    | 13.38e    | –         | –         | –         |
|      | Urea      | 27.19a                                      | 24.82a                          | 27.65a   | 36.41a    | 54.84a    | 61.23a    | 27.13a    | 26.58a    | 25.58c    | 27.40b    |
|      | CRNF$_1$  | 23.25b                                      | 18.45b                          | 18.42b   | 23.29b    | 41.67b    | 41.74b    | 18.36b    | 15.76b    | 26.99bc   | 49.36a    |
|      | CRNF$_2$  | 20.67bc                                     | 17.42c                          | 16.58b   | 20.81b    | 37.24bc   | 38.23c    | 17.12b    | 15.34b    | 30.14b    | 49.95a    |
|      | CRNF$_3$  | 18.46c                                      | 17.39bc                         | 16.45b   | 17.67c    | 34.91c    | 34.16d    | 17.31b    | 14.43b    | 34.16a    | 51.91a    |
|      | CRNF$_4$  | 17.80c                                      | 15.74c                          | 15.88b   | 16.23c    | 33.68c    | 31.96d    | 18.62b    | 14.75b    | 36.56a    | 48.48a    |

Source of variation

| Y     | 41.38*** | 10.32*** | 4.59* | 0.18 ns | 5.33** | 1.25 ns | 2.94 ns | 3.11 ns | 42.49*** | 6.07** |
| T     | 18.95*** | 24.29*** | 35.93*** | 24.61*** | 43.97*** | 37.68*** | 10.09*** | 7.26*** | 10.86*** | 30.22*** |
| Y × T | 1.14 ns  | 0.82 ns  | 2.45* | 0.27 ns | 1.08 ns | 0.50 ns | 1.13 ns | 0.36 ns | 1.32 ns  | 2.41*   |

Control: no nitrogen fertilizer; UREA: 100% Urea -N; CRNF1: 100% controlled-release -N; CRNF2: 90% controlled-release -N; CRNF3: 80% controlled-release -N; CRNF4: 70% controlled-release -N

Urea -N. ESR: Early season rice; LSR: Late season rice. Y: Year; T: Treatment; Y × T: Year × Treatment. Values followed by different letters in a column are significant at the 5% level ($p < 0.05$). ns, non-significant

*Significant at the 0.05 probability level. **Significant at the 0.01 probability level. ***Significant at the 0.001 probability level. Ratio of NH$_3$-N to N rate: Ratio of NH$_3$ volatilized (kg N ha$^{-1}$) to the amount of applied N (kg N ha$^{-1}$). ANRE, Apparent N recovery efficiency
were non-significant different between the grain yield obtained from CRNF2 and conventional urea \( (p > 0.05) \). In general, the maximum grain yield of LSR was obtained from CRNF2 and all the CRNF treatments gave higher yield than conventional urea.

All over the years and seasons, panicles \( m^{-2} \) had showed the same trends of grain yield (Table 3). The lowest values of spikelets panicle\(^{-1}\) were found in the control treatment. However, spikelets panicle\(^{-1}\) did not vary significantly \( (p > 0.05) \) between CRNF1 and UREA. Spikelet \( m^{-2} \) across the years was ranked as follows: CRNF1 > UREA > CRNF2 > CRNF3 > CRNF 4 >Control in ESR, and CRNF2 > CRNF 1 >CRNF3 > UREA > CRNF4 > Control in LSR. On the other hand, neither CRNF2 nor CRNF3 differed significantly \( (p > 0.05) \) from UREA in

**Fig. 2** Changes of cumulative NH\(_3\) volatilization flux from the surface of paddy fields for ESR and LSR from 2013 to 2015. Control: no nitrogen fertilizer; UREA: 100% Urea -N; CRNF1: 100% controlled-release -N; CRNF2: 90% controlled-release -N; CRNF3: 80% controlled-release -N; CRNF4: 70% controlled-release -N.
| Year/treatment | Panicles m⁻² | Spikelets panicle⁻¹ | Grain filling % | Spikelets m⁻² (× 10³) | 1000-grain weight (g) | Grain yield (t ha⁻¹) |
|---------------|-------------|---------------------|----------------|-------------------------|---------------------|---------------------|
|               | ESR | LSR | ESR | LSR | ESR | LSR | ESR | LSR | ESR | LSR | ESR | LSR | ESR | LSR |
| 2013          |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Control       | 258b| 213b| 60.74b | 65.74c | 84.56a | 91.54a | 15.70c | 14.01b | 24.16a | 26.22a | 2.57d | 3.35d |
| UREA          | 340a| 333a| 81.05a | 88.35b | 91.80a | 90.78b | 27.55a | 25.97a | 23.36b | 26.90a | 5.64ab| 5.48c |
| CRNF1         | 342a| 352a| 83.23a | 86.11c | 91.28a | 93.06a | 28.13a | 30.53a | 24.25a | 26.44a | 5.83a | 6.86a |
| CRNF2         | 326a| 342a| 79.05a | 91.44a | 86.28a | 91.68a | 25.77ab| 31.30a | 24.16a | 26.31a | 4.71c | 6.55a |
| CRNF3         | 312ab| 335a| 79.89a | 85.91ab| 87.80a | 91.49a | 24.81ab| 28.76a | 24.16a | 26.31a | 4.71c | 6.55a |
| CRNF4         | 284ab| 330a| 77.79a | 84.08ab| 84.29a | 90.33a | 22.10b | 27.74a | 24.15a | 25.96a | 4.55c | 5.99b |
| 2014          |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Control       | 296a| 293b| 57.58c | 57.43a | 86.27a | 91.06ab| 17.04b | 16.66b | 24.05a | 31.08a | 2.52c | 4.49c |
| UREA          | 318a| 417a| 81.87ab| 68.95a | 78.16a | 89.47a | 26.07a | 28.50a | 24.47a | 30.09a | 4.76a | 6.99b |
| CRNF1         | 316a| 470a| 87.52a | 72.55a | 87.13a | 89.96ab| 27.38a | 33.88a | 23.50a | 29.44a | 5.07a | 7.25a |
| CRNF2         | 336a| 483a| 77.89abc| 72.40a | 81.41a | 93.06a | 25.66a | 35.41a | 23.00a | 29.44a | 4.88a | 7.30a |
| CRNF3         | 366a| 473a| 64.50bc| 64.91a | 79.55a | 88.36b | 23.61ab| 30.67a | 24.04a | 29.77a | 4.75a | 7.28a |
| CRNF4         | 310a| 428a| 60.82c | 65.60a | 85.22a | 89.34ab| 18.77b | 28.13a | 23.98a | 31.77a | 4.38b | 6.84b |
| 2015          |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Control       | 272b| 235b| 59.66a | 79.42b | 89.36a | 87.03b | 15.99b | 18.71b | 21.58a | 31.20a | 3.77b | 3.55b |
| UREA          | 350a| 338a| 67.83a | 89.45ab| 84.05a | 88.52ab| 23.27a | 30.26a | 22.83a | 30.56a | 5.18a | 5.46d |
| CRNF1         | 326ab| 363a| 70.59a | 90.06ab| 87.01a | 90.15a | 22.95a | 32.78a | 21.23a | 31.28a | 5.25a | 7.12a |
| CRNF2         | 336a| 328a| 71.19a | 94.71a | 85.61a | 90.69a | 23.84a | 31.13a | 22.53a | 31.52a | 5.24a | 6.70b |
| CRNF3         | 320ab| 328a| 69.33a | 95.16a | 82.93a | 89.97a | 22.19a | 31.01a | 22.30a | 30.57a | 5.12a | 6.55b |
| CRNF4         | 290ab| 298ab| 71.90a | 95.69a | 85.09a | 89.61ab| 20.91a | 28.51a | 20.50a | 30.40a | 5.10a | 5.83c |

Source of variation

| Year (Y) | 0.53 ns | 45.89*** | 3.82* | 41.50*** | 3.58 ns | 5.91** | 3.37* | 1.77 ns | 21.59*** | 42.89*** | 28.51*** | 124.09*** |
| Treatment (T) | 3.76** | 16.39*** | 5.68*** | 6.06*** | 1.61 ns | 1.72 ns | 15.23*** | 16.18*** | 0.45 ns | 0.17 ns | 162.16*** | 414.21*** |
| Y × T | 0.63 ns | 0.79 ns | 1.27 ns | 0.60 ns | 0.93 ns | 1.42 ns | 0.66 ns | 0.27 ns | 1.16 ns | 0.65 ns | 8.09*** | 6.91*** |

Control: no nitrogen fertilizer; UREA: 100% Urea -N; CRNF1: 100% controlled-release -N; CRNF2: 90% controlled-release -N; CRNF3: 80% controlled-release -N; CRNF4: 70% controlled-release -N

ESR early season rice, LSR late season rice, T treatment, Y year. Values followed by different letters in a column are significant at the 5% level (p < 0.05). ns, non-significant *Significant at the 0.05 probability level. **Significant at the 0.01 probability level. ***Significant at the 0.001 probability level
ESR, but they recorded higher spikelets m$^{-2}$ than that of UREA by 16% and 7% in LSR. There was no particular trend for grain-filling percentage.

Apparent N recovery efficiency (ANRE) varied significantly among years, treatments, and years × treatments ($p < 0.05$ to $p < 0.001$; except for Y × T in ESR) across the seasons (Table 3). UREA had significant lower ANRE values than that of the treatments with CRNF across the years and seasons, while ANRE in the CRNF treatments tended to decrease with increasing application rates across the years and seasons. The highest ANRE was obtained in CRNF4, which was significantly ($p < 0.05$) higher than that of CRNF1 in seasons 2014 and 2015. Higher ANRE was found in LSR than that in ESR during the continuous 3 years, although it fluctuated across years.

**Discussion**

**NH$_3$ volatilizations**

In the present study, the total NH$_3$ volatilizations was 25.4–55.6 kg N ha$^{-1}$ (11.9–29.1% of the applied N) in early rice season, while in the case of late rice one it was 32.0–61.2 kg N ha$^{-1}$ (11.9–26.6% of the applied N). Shang et al. (2014) found that the cumulative NH$_3$ loss was 9.2–33.6% and 17.8–32.2% of the applied N, for the early and late rice season, respectively and similar results were confirmed by Zhao et al. (2009). However, under a Japanese paddy field, Hayashi et al. (2006) found that the total volatilization of NH$_3$ was only 1.4 ± 0.8% to the total applied nitrogen throughout rice cultivation. The discrepancy in NH$_3$ volatilization losses may be due to the differences in the measurement method of NH$_3$ volatilization and field conditions. The fluxes of NH$_3$ volatilization had been underestimated by 20–30% by the dynamic chamber method in Japanese paddy fields in earlier study (Hayashi et al. 2008). In the current study, the application of CRNF reduced NH$_3$ volatilization by 19.7–43.0% for ESR and 19.9–31.8% for LSR in comparison with conventional form of urea fertilizer when the same applied N rates were applied. Wang et al. (2007) found that coated urea reduced NH$_3$ volatilization by 75–89% in comparison with conventional urea at the same application rate under rice–wheat rotation system. Zheng et al. (2004), also found that N loss through NH$_3$ volatilization could be reduced by about 54% through application of CRNF in flooded paddy soils. Increasing the NH$_4^+$-N concentration in the surface water is the main factor affecting the NH$_3$ volatilization (Li et al. 2008; Xu et al. 2012; Chen et al. 2015). The CRNF used in the present study had a releasing period of 90 days; this slow N release characteristic could closely match the demand for N during the rice growth period, thus would effectively decrease NH$_4^+$-N in the soil and water surface, and consequentially reduced NH$_3$ emission from double-cropping rice field. On the other hand, the amount of N application was also one of the major factors affecting NH$_3$ volatilization (Li et al. 2008). Nitrogen losses through volatilization of NH$_3$ increase with N rate increasing (Tian et al. 2001; Huang et al. 2006; Zhu et al. 2013). We also found that the cumulative NH$_3$ volatilization losses of double-cropping seasons increased linearly with N application rates of CRNF treatments across the years ($Y_{\text{NH3}} = 0.1521x_N + 27.533$, $R^2 = 0.9976^{**}$, $p < 0.01$) (Fig. 3). Compared with the CRNF1 treatment, reducing N rate by 10–30% could further decrease NH$_3$ volatilization losses in double-cropping rice seasons. Considering the effects of application of CRNF on grain yield and NUE, reducing CRNF rate by 20% has been recommended as the appropriate application rate of CRNF for double-cropping rice. In the present study, there were significant effect of timing of fertilization in terms of the cumulative NH$_3$ volatilization after N application; higher NH$_3$ volatilization losses occurred during top-dressing fertilizer period than in the basal fertilizer period, and accounted for 52.0–60.0% and 54.5–61.6% of the total NH$_3$ losses for ESR and LSR across the years, respectively (Table 2). Contrary result has been reported by Chen et al. (2015), who found more cumulative losses of NH$_3$ volatilization in basal method than top-dressing one, and they ascribed this to 2.3 times higher N rate in the basal fertilizer one than that of the top-dressing one. Interestingly, the N rates of basal fertilizer in the present study was 1.5 times that of the top-dressing method, while contrast results of NH$_3$ volatilization occurred in the two split fertilizer periods, so we speculated that different fertilizing modes may be the main reason. The topdressing fertilizer was surface-applied urea, whereas the basal fertilizer with urea incorporated by puddling into the ploughed layer. The movement of NH$_4^+$ from the topsoil to the floodwater was effectively decreased and their positive charge...
NH$_4^+$ could be absorbed by soil particles, resulting in reduction of NH$_3$ volatilization (Hayashi et al. 2006; Tian et al. 2001). Although higher NH$_3$ volatilization was found in the top-dressing fertilizer period, more effective effect of application CRNF on reducing NH$_3$ volatilization appeared during this period than that in basal fertilizer period, this may contribute to the slow release of nutrition of CRNF when they were broadcasted into the soil surface as the same as conventional urea (Hayashi et al. 2008).

Application of CRNF in LSR was inferior to that in ESR in reducing NH$_3$ volatilization loss compared with conventional urea application, probable reason for this phenomenon was the differences in weather conditions between ESR and LSR. Less rain, higher temperatures, and higher light intensity (Suppl Fig. 1) were found in LSR, which resulted in increased urease activity, accelerated urea hydrolysis, and increased NH$_3$ volatilization (Wu et al. 2009). Similar results were also reported by Adhikari et al. (2020) with increased emissions at conditions with lesser rainfall and higher temperature compared to higher rainfall and lower temperature.

Rice yield and apparent nitrogen recovery efficiency

The increase in plant output is the ultimate outcome of the availability of growth factors at optimum limits, keeping in mind preserving the integrity of the ecosystem. Nitrogen is an essential nutrient and plants need it in large quantities, therefore, farmers raise fertilizer rates in order to increase the obtained yield, but this leads to environmental damage and a decrease in the efficiency of added nitrogen fertilizer (Griggs et al. 2007; Zhao et al. 2009; Eissa et al. 2013, 2014; El-Mahdy et al. 2018 Eissa and Roshdy 2018). The obtained results of the present research clearly showed the superiority of controlled-release nitrogen fertilizer (CRNF) over the conventional urea in the double-season rice rotation. The controlled-release nitrogen fertilizer has several advantages over the conventional urea specially under rice production conditions (Yang et al. 2012; Geng et al. 2015). Efficiency of nitrogen fertilizer applied to rice fields is influenced by the elevated levels of soil moisture (Hameed et al. 2019). In this study, based on the same applied N rate, CRNF greatly enhanced the grain yield in comparison with conventional urea for early and late season rice, and even when the CRNF was reduced by 20% of applied N rate, the CRNF gave the same yield for early season rice but this treatment gave higher yield for late season.
rice compared with the full recommended dose from conventional urea. In another long-term field experiment with rice-oilseed rape rotation system, Geng et al. (2015) reported that the application of controlled-release N fertilizer could give the same rice yield compared with conventional urea application and saved 50% of the applied N. More significant effects of CRNF application were found on the yields of late rice season (LSR) than that of early rice season. The shorter growing season of ESR, lower temperature, and other negative environmental conditions may explain that phenomenon. The increase of grain yield could result from the increase in spikelets panicle\(^{-1}\) or panicles m\(^{-2}\) (Eissa 2014; Qin et al. 2013). The panicle m\(^{-2}\) is influenced by tiller number which depends on the N input and rice varieties (Fu 2001; Qin et al. 2013). Fu (2001) found that controlled-release nitrogen fertilizer alone or combined applications of urea dramatically increased the panicles m\(^{-2}\) and spikelets panicle\(^{-1}\) which caused remarkable increases in the grain yield of rice. The results of the current study, obviously confirmed the results found by Fu (2001). The application of CRNF could provide enough N nutrition in the middle and late growth stage periods of rice, thus increase the size of grain sink, such as spikelets panicle\(^{-1}\) or panicles m\(^{-1}\), and consequentially improve the obtained grain yield (Ji et al. 2007). Moreover, the spikelets m\(^{-2}\) possessed the highest significantly positive correlation (ESR: \(r = 0.830; \text{ p}<0.01\)) with the grain yield, followed by panicles m\(^{-2}\) (ESR: \(r = 0.696; \text{ p}<0.01\)) and spikelets panicle\(^{-1}\) (ESR: \(r = 0.914; \text{ p}<0.01\)). Based on the correlation analysis of panicles m\(^{-2}\), spikelets m\(^{-2}\) and the rice grain yield, the main reason for the grain yield increase by CRNF is the increased panicles m\(^{-2}\) and spikelets m\(^{-2}\).

The previous studies about different types of controlled release N-fertilizers e.g., resin-coated, thermosetting, S-coated, and mineral-coated have been reported that CRNF increased crop yields and fertilizer N use efficiencies (Li et al. 2005). The apparent N use efficiencies under the conditions of the present research with CRNF were about 50% in both ESR and LSR in 2013, which were significantly higher than that the conventional urea treatment. Yang et al. (2012) reported that the use of controlled release urea augmented the apparent N use efficiency as high up to 50%, while the apparent N use efficiency of traditional form of urea fertilizer was only about 24%. The release of N from controlled urea matched the N requirement of rice plant during the different growth stages, thus increased N uptake and obtained high N use efficiency (Kaneta et al. 1994). The N use efficiencies in the treatments with CRNF decreased obviously in the following 2-year (2014 and 2015), possibly due to the changes in the environmental conditions mainly precipitation and temperature (Lyu et al. 2015).

Conclusions

Emission of ammonia from paddy soils causes nitrogen loss and it is considered a source of environmental pollution. The use of controlled-release N fertilizer (CRNF) is a good strategy to increase N fertilizer efficiency and to mitigate the ammonia (NH\(_3\)) volatilization from double-cropping rice in in paddy soils. CRNF has a long releasing period (90 days) and this slow N release behavior matches the rice plants demand for N during the different growth stages, thus it effectively decreases NH\(_4^+\)-N in the soil and water surface, and consequentially reduces NH\(_3\) emission from double-cropping rice field. The findings of the current 3 years field studies clearly showed that N application rates for double-cropping rice can be reduced by 20% without yield loss. Framers want to obtain high yield by increasing N application rate which causes the elevation of NH\(_3\) volatilization. The use of CRNF increases the economic reutrn which realizes aspirations of rice farmers without increasing N rates. This result is of particular importance to rice farmers, as well as protecting the environment from pollution. The releasing period of CRNF must be studied in different climatic conditions to assess its efficiency to supply rice plant with their N requirement. Moreover, the efficiency of CRNF must be studied under different irrigation systems to renew its efficiency and ability to reduce NH\(_3\) emissions.

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