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ORIGINAL ARTICLE

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 NH_3 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 NH_3 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 NH_3 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 NH_3 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 NH_3 volatilization in a double rice-cropping system are not well known. Hence, the present study investigated 3 year-field NH_3 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 NH_3 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 NH_3 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. Hence, the CRNF was applied at 0 kg N ha^{-1} (Control), 150/180 kg N ha^{-1} (CRNF1), 135/162 kg N ha^{-1} (CRNF2), 120/144 kg N ha^{-1} (CRNF3), and 105/126 kg N ha^{-1} (CRNF4), in comparison with 150 and 180 kg N ha^{-1} for conventional urea (UREA) in ESR and LSR, respectively. The CRNF, urea, and potassium chloride were used as split fertilization, at pre-planting (60%) and tillering stage (40%). The fertilizer application rate, time of application, and method of application in the early and late cropping seasons are shown in Table 1.

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 m^2 (4.0 m × 5.0 m) in a complete randomized block design.

Measurement of NH_3 volatilization

Chamber and the continuous airflow enclosure method were used to measure NH_3 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

Table 1 Fertilizer application rate and method in the early and late cropping seasons

Season	Fertilizer type	Application date	Fertilizer application rate/(kg ha^{-1})						Application method
			Control	Urea	CRNF1	CRNF2	CRNF3	CRNF4	
Early rice	Urea	Base	0.0	90.0	0.0	0.0	0.0	0.0	Incorporated
		Topdressing	0.0	60.0	0.0	0.0	0.0	0.0	Broadcasted
	CRNF	Base	0.0	0.0	90.0	81.0	72.0	63.0	Incorporated
		Topdressing	0.0	0.0	60.0	54.0	48.0	42.0	Broadcasted
	Calcium superphosphate	Base	72.0	72.0	72.0	72.0	72.0	72.0	Incorporated
	Potassium chloride	Base	54.0	54.0	54.0	54.0	54.0	54.0	Incorporated
		Topdressing	36.0	36.0	36.0	36.0	36.0	36.0	Broadcasted
Late rice	Urea	Base	0.0	108.0	0.0	0.0	0.0	0.0	Incorporated
		Topdressing	0.0	72.0	0.0	0.0	0.0	0.0	Broadcasted
	CRNF	Base	0.0	0.0	108.0	97.2	86.4	75.6	Incorporated
		Topdressing	0.0	0.0	72.0	64.8	57.6	50.4	Broadcasted
	Calcium superphosphate	Base	60.0	60.0	60.0	60.0	60.0	60.0	Incorporated
	Potassium chloride	Base	63.0	63.0	63.0	63.0	63.0	63.0	Incorporated
		Topdressing	42.0	42.0	42.0	42.0	42.0	42.0	Broadcasted

The contents of urea (N), calcium superphosphate (P_2O_5), and potassium chloride (K_2O) were 46%, 12%, and 60%, respectively

Data in the table are nutrient amounts of the fertilizers

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_3BO_3) for each treatment, and the amount of trapped NH_3 in the acid was titrated with 0.02 mol L^{-1} H_2SO_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). NH_3 volatilization was greatly increased by increasing rate of applied N for ESR across the 3 years. Application of CRNF obviously reduced NH_3 losses by an average of 29–42% compared with that of application of UREA across the years in ESR. Additionally, there was a linear relationship between amounts of NH_3 emission (y_{ESR}) and N rates (x_{ESR}) of CRFNF treatments for ESR across years ($y_{ESR} = 0.1578x_{ESR} + 13.47$, $R^2 = 0.9966$, $p < 0.01$).

From basal fertilizer to topdressing fertilizer period, the average temperature and precipitation were 29.0 °C and 8.1 mm for LSR (Suppl Fig. 1). The temporal patterns in NH_3 volatilization fluxes after basal fertilization for LSR were different from those in ESR (except for 2013; Figs. 1, 2). The NH_3 volatilization increased immediately and peaked 1–3 days after basal fertilization, and gradually 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.

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

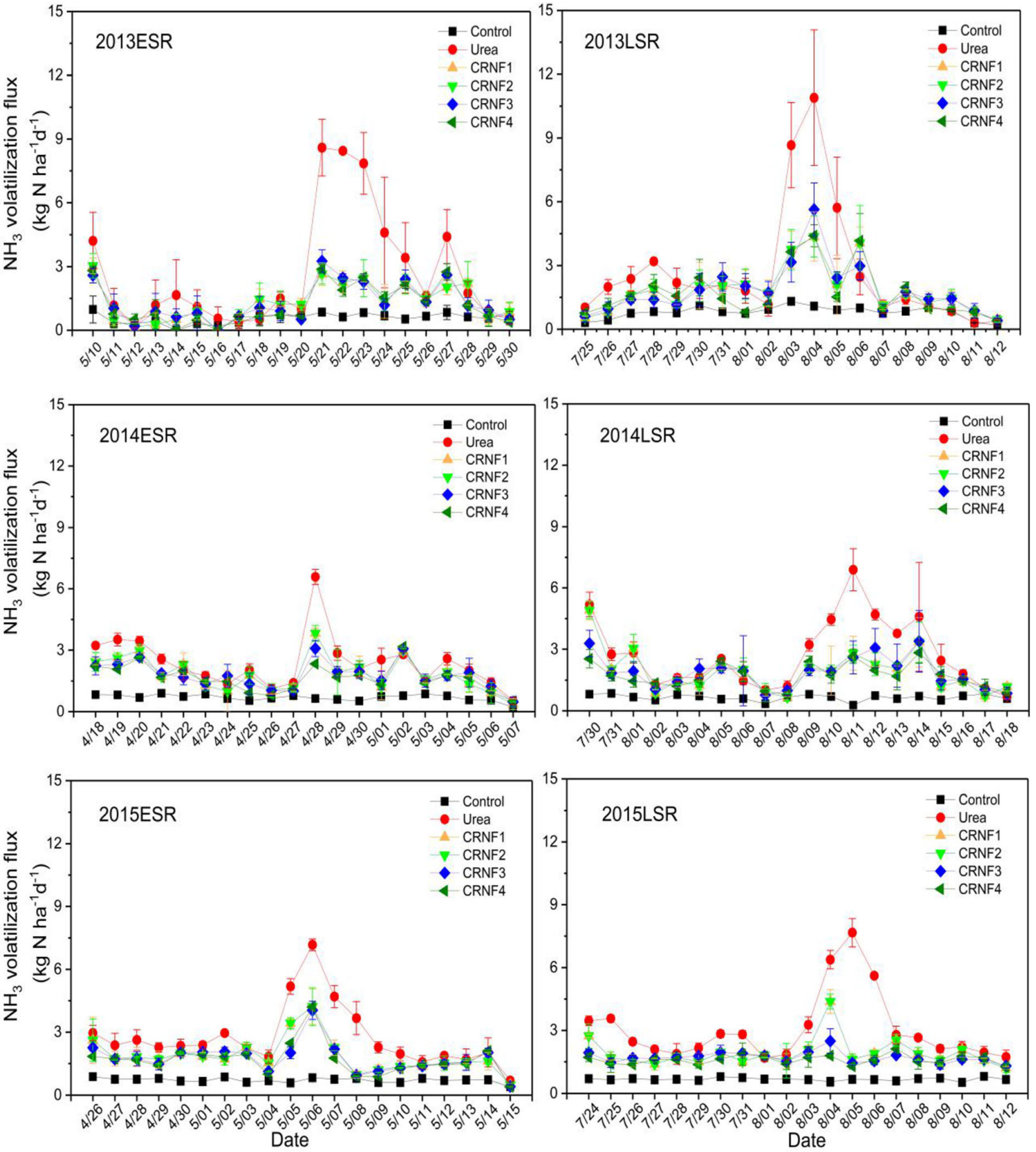

Fig. 1 Seasonal variation of NH_3 fluxes from the surface of paddy fields for ESR and LSR from 2013 to 2015. Control: no nitrogen fertilizer; UREA: 100% Urea -N; CRNF1: 100% controlled-release -N; CRNF2: 90% controlled-release -N; CRNF3: 80% controlled-release -N; CRNF4: 70% controlled-release -N. ESR: 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	LSR
2013	Control	4.97a	6.71b	6.99c	8.31b	11.97c	15.02b	–	–	–	–
	Urea	13.54a	17.73a	42.04a	32.82a	55.58a	50.55a	29.08a	19.73a	30.59b	20.34b
	$CRNF_1$	10.74a	13.12ab	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	6.28c	6.52c	13.76c	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	18.38ab	16.66a	34.28a	42.90ab
	$CRNF_4$	16.41b	15.88b	16.68b	18.67b	33.09b	34.54b	18.41ab	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	17.42bc	16.58b	20.81b	37.24bc	38.23c	17.12b	15.34b	30.14b	49.95a
	$CRNF_3$	18.46c	17.39bc	16.45b	16.77c	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

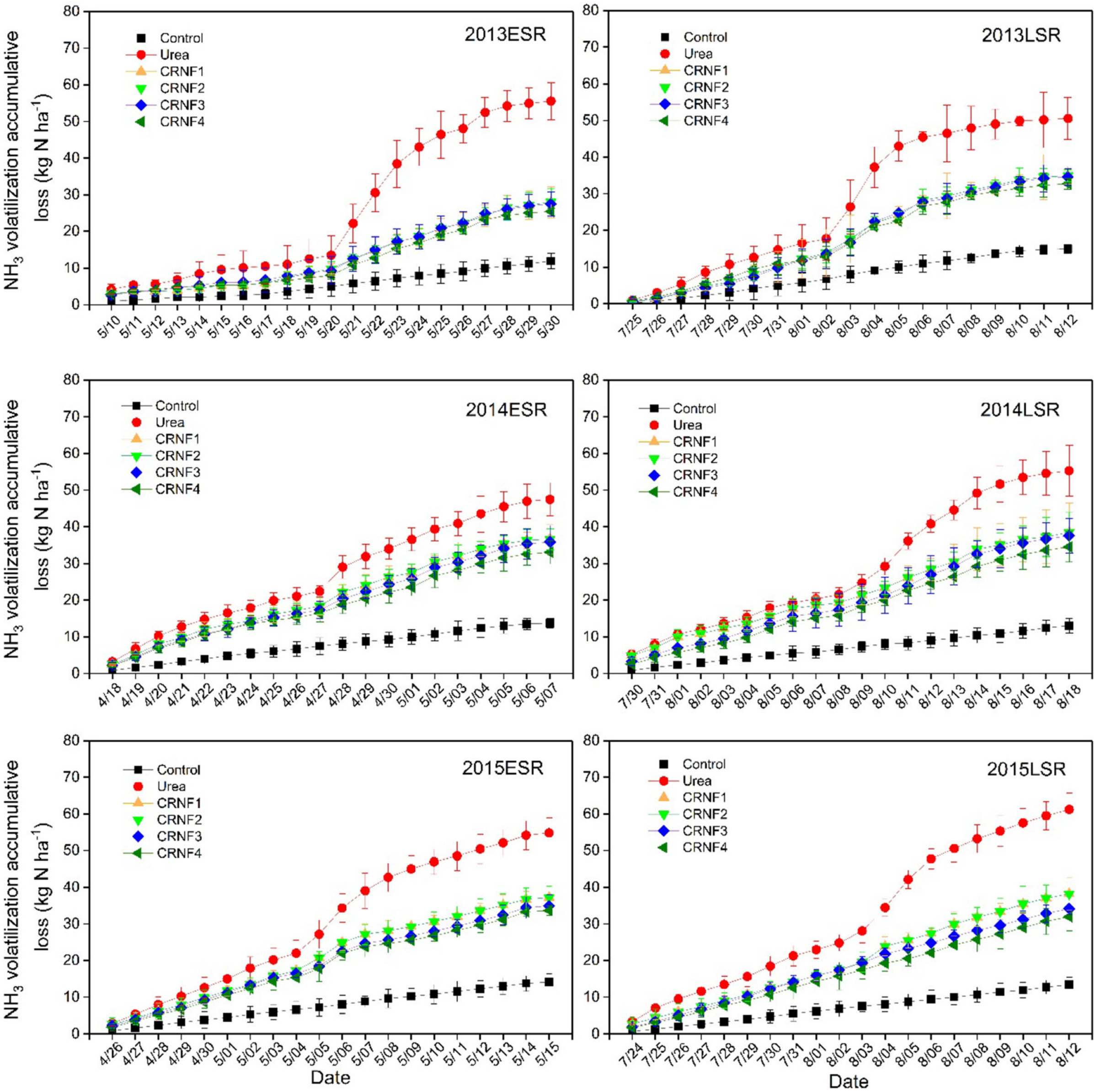

Fig. 2 Changes of cumulative NH_3 volatilization flux from the surface of paddy fields for ESR and LSR from 2013 to 2015. Control: no nitrogen fertilizer; UREA: 100% Urea -N; CRNF1: 100% controlled-release -N; CRNF2: 90% controlled-release -N; CRNF3: 80% controlled-release -N; CRNF4: 70% controlled-release -N

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

Table 3 Yield and yield components for ESR and LSR across different treatments and seasons (2013–2015)

Year/treatment	Panicles m^{-2}		Spikelets panicle^{-1}		Grain filling %		Spikelets m^{-2} (× 10^3)		1000-grain weight (g)		Grain yield (t ha^{-1})	
	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	78.03b	85.09a	91.86a	27.55a	25.97a	23.38b	26.90a	5.56ab	5.46c
CRNF1	342a	352a	83.23a	86.11ab	87.02a	91.28a	28.38a	30.53a	24.53a	26.44a	5.83a	6.86a
CRNF2	326a	342a	79.05a	91.44a	86.28a	91.68a	25.77ab	31.30a	24.38a	26.51a	5.25b	6.97a
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	89.47ab	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	3.35e
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***	2.58 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 ($Y_{NH3} = 0.1521x_N + 27.533$, $R^2 = 0.9976^{**}$, $p < 0.01$) (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

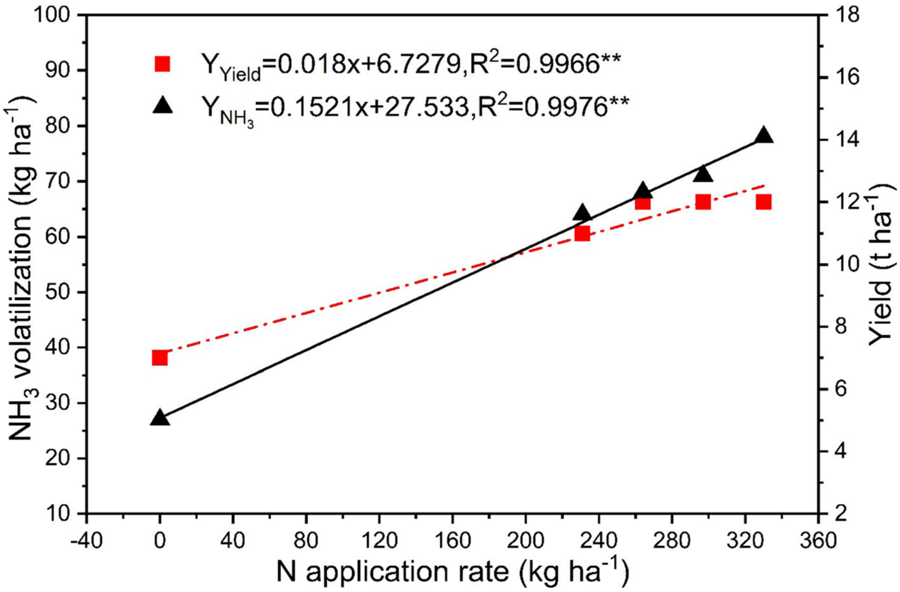

Fig. 3 Total NH_3 volatilization loss and grain yield as a function applied N of double-season rice

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 gave 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^{-1} possessed the highest significantly positive correlation (ESR: $r = 0.830$; LSR: $r = 0.914$; $p < 0.01$) with the grain yield, followed by panicles m^{-2} (ESR: $r = 0.696$; LSR: $r = 0.830$; $p < 0.01$). 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 retrun 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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