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Effect of Deep Placement of Large Granular Fertilizer on Ammonia Volatilization, Soil Nitrogen Distribution and Rice Growth

Pingyao Zhou [1,2], Zhen Zhang [1,2], Linsen Du [1,2], Geng Sun [1,2], Liang Su [1,2], Zhiyu Xiao [1,2], Chunwang Li [1,2], Zhichang Wang [1,2], Zhihua Xiao [1,2], Teng Hu [1,2], Keming Wang [1,2], Fang Ni [1,2], Shuping Wang [3] and Hua Wang [1,2,*]

[1] College of Resources and Environment, Hunan Agricultural University, Changsha 410128, China
[2] Key Laboratory for Rural Ecosystem Health in the Dongting Lake Area of Hunan Province, Changsha 410128, China
[3] Hunan Longzhou Farm Equipment Holdings Co., Ltd., Yueyang 414400, China
* Correspondence: wangchina926@hunau.edu.cn

Abstract: Excessive fertilization is often applied to produce rice. To reduce nitrogen loss and improve nitrogen use efficiency (NUE), we studied the effects of application depth (surface application, 5 and 10 cm) and shape of nitrogen fertilizers (row application and deep application of large granular fertilizer) on rice growth, soil N distribution and ammonia volatilization. The results showed that grain yield, shoot biomass and total dry biomass of the treatment with N in large granular fertilizer applied at 10 cm depth were significantly higher than those of all other treatments. Moreover, compared with the surface application, the N recovery efficiency and the N agronomic efficiency of deep application treatments were enhanced by 18.1–52.3% and 35.6–95.6%, respectively. Deep application significantly increased NH_4^+-N concentration at their fertilization points. During the growth season, N in large granular fertilizer treatments (mixed with clay to form an unusually large pellet of 1.0–1.5 cm in diameter) distributed closer to the roots, while N in other treatments, including row application treatments, was more widely distributed. Compared with the surface application, deep application significantly reduced NH3 volatilization and NH_4^+-N concentration in surface water by 58.7–64.8% and 26.0–72.5%, respectively. Furthermore, the NH_3 volatilization from large granular treatment was 7.6–11.0% lower than that in the row application. In conclusion, applying N in large granular fertilizer at 10 cm depth reduces ammonia volatilization, and improves rice growth and grain yield, indicating improved NUE and lowered environmental risks.

Keywords: rice; deep application; nitrogen; biomass; NH_3 volatilization

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1. Introduction

Rice is the staple food for approximately 65% of the Chinese population [1,2]. Nitrogen (N), as one of the most essential elements for the growth of crops, is of great importance for food production [3,4]. Nitrogen application in China averages 305 kg N per ha compared to 74 kg N per ha worldwide [5]. Currently, ammonia emissions in many countries (e.g., China, India), are increasing, with agricultural activities (e.g., fertilizer application) contributing much to atmospheric ammonia. Globally, an average of 18% of N fertilizer is lost through ammonia emissions [6]. However, an overdose of N application did not further increase the crop yield; rather it decreased the N use efficiency (NUE). In single-season rice cultivation, NUE was only 25–30% [7,8]. This is often attributed to the improper fertilization methods that lead to large amounts of N losses in the environment, and consequently cause environmental pollution and trigger a series of environmental problems [9].

Reactive nitrogen can move into water and the atmosphere through runoff, leaching, and gas evaporation [10], and further cause soil degradation, water eutrophication, groundwater pollution, and ammonia pollution, as well as the greenhouse effect [11,12]. Among these N-related problems, ammonia volatilization is a major pathway of N loss in China, accounting for 14.4–21.0% of total N applied [13]. Ammonia in the atmosphere can react with gases such as sulfur oxides and nitrogen oxides, and thus accelerate the formation of haze, effective haze mitigation is achievable by control measures of NH_3, nitrogen oxides, and sulfur oxides emission [14]. Haze can gather near-surface aerosols, reducing atmospheric visibility and exacerbating air pollution, adversely affecting people's health and socio-economic development [15]. To improve the NUE, and thus reduce the negative environmental impact as well as ensure the economic benefits of farmers, many new and practical N applications methods, e.g., urease/nitrification inhibitor incorporation [16], controlled release fertilizer [17], and deep fertilization methods [18], have been proposed.

Nitrogen application method greatly affects rice production and NUE. Deep fertilization is an effective way to reduce N loss. Depth normally considered a range: >5 cm [19–21]. Nutrients required can be located near the root zone, which reduces the N loss and enhances the N uptake, and therefore improves rice yield and NUE [22,23]. Some studies have shown that deep application can provide a high NH_4^+-N concentration for plants and prolong the availability of N [24]. Therefore, compared with surface fertilization, deep fertilization can not only delay the release of fertilizer, but also provide essential nutrients in the critical period for plants [25]. However, most of the previous studies described the distribution of N in rice fields after seeding, but the N distribution during the main growth period for rice remains unclear [18]. In China, the scale of ecological agriculture in paddy fields is increasing. Aquatic animals are cultivated in paddy fields to achieve 'one water and two uses' and maximize the benefits of land resources [26]. However, most of the nitrogen produced by farmland fertilization, residual feed, animal manure, and so on exists in the form of ammonia, resulting in deterioration of water quality and affecting animal growth [27,28]. Some previous studies investigated the technologies of adsorbed ammonia nitrogen in surface water by changing feed and planting aquatic plants to achieve a safe concentration in aquaculture water quality [29,30]. However, it is still unclear to fundamentally reduce the ammonia nitrogen concentration in surface water to ensure the growth of aquatic animals.

Large particle fertilizers cost lower than controlled-release fertilizers. Compared with slow and controlled fertilizer, large particle fertilizer does not add polluting materials [31]. Herein, the objectives of this study were to investigate the impacts of the deep application of large fertilizer granular [32] and fertilization depth on the growth of rice, N distribution in soil profile, and the ammonia volatilization from rice field.

2. Materials and Methods

2.1. Experimental Location and Materials

Pot experiments were conducted at Yunyuan Base of Hunan Agricultural University, Changsha County, Hunan Province, China (113°04′ E, 28°11′ N), from late June to late September 2020. The site is located in a semitropical monsoon climate area. The annual mean temperature is 17.2 °C, and the annual accumulated temperature is 5457 °C. The average annual precipitation is 1361.6 mm, which is mainly from April to October. The soil used in the study was deep soil (depth > 100 cm). The texture of soil is clay. The parent material of soil is fluvial deposits. The parent material of soil is fluvial deposits. The basic chemical properties of the test soil show that the soil pH was 5.43, total N was 0.85 g kg^{-1}; total P was 0.31 g kg^{-1}, total K was 14.39 g kg^{-1}, Alkaline N was 51.44 mg kg^{-1}, available P was 6.75 mg kg^{-1}, available K was 165.24 mg kg^{-1}, organic matter was 8.50 g kg^{-1}.

Ammonium sulfate, ammonium bisphosphate and potassium (K) chloride were applied as N, phosphorus (P) and K fertilizers. The rate of N fertilizer varied with treatment while the amount of P and K fertilizer was 150 kg P_2O_5 ha^{-1} and 200 kg K_2O ha^{-1} for all treatments. The rice variety is mega rice. The growth period is 92 days.

2.2. Experimental Design

The fertilizer balls were prepared by mixing the fertilizers and red soil: clay ratio of 2:1, making fertilizer balls with a diameter of 1~1.5 cm, the fertilizer balls involved N, P and K mixed clay. The balled fertilizers were dried in a 30 °C oven for approximately two days. Fertilizer balls were applied between two rice lines by an injector [32]. The content of N, P, and K fertilizer was 10.59% (N), 3.31% (P_2O_5), and 8.82% (K_2O) for large granular fertilizer.

The pot experiment was carried out in plastic containers of length 42 cm × breadth 31.5 cm × depth 22.5 cm. There were seven treatments showed in Table 1. Each treatment had twelve replicates, and each stage had three replicates. Plastic film and a bird-proof net were used to protect the experiments from precipitation and birds.

Table 1. Fertilization treatments.

Treatment	Fertilizer Types	Fertilizer Depths	Nitrogen Application Rate
N_0	--	--	--
S300	surface application	0 cm	300 kg N ha^{-1}
S210	surface application	0 cm	210 kg N ha^{-1}
R5	row application	5 cm	210 kg N ha^{-1}
R10	row application	10 cm	210 kg N ha^{-1}
B5	deep application	5 cm	210 kg N ha^{-1}
B10	deep application	10 cm	210 kg N ha^{-1}

Rice was transplanted on 22 June 2020 (seedlings of 21 days old). Four rice seedlings were planted in each container, arranging in two pairs. The planting density was 15 cm × 15 cm (Figure 1). For treatments S300 and S210, 75% N fertilizer was applied as base fertilizer, and 25% was applied as topdressing at tillering stage. Fertilizers in deep fertilization treatments were applied twice, before and after rice transplanting. Nitrogen and P were applied before transplanting the rice seedlings. The application rate is 60 kg N ha^{-2} and 75 kg P_2O_5 ha^{-2}, respectively. For other treatments, base fertilizer was applied once by deep fertilization after rice transplanting. For the row application method, soil was first excavated a 5 cm or 10 cm depth ditch. Fertilizers were then spread evenly. Between the two lines, and the ditch was finally covered by soil. Rice in all pots were harvest on September 21, 2020. A 5 cm of water layer was maintained during the rice growing season.

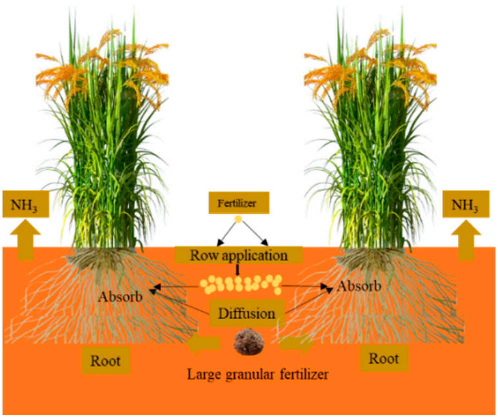


Figure 1. Schematic diagram of potted plants.

2.3. Sample Collection and Analysis

2.3.1. Soil Chemical Properties

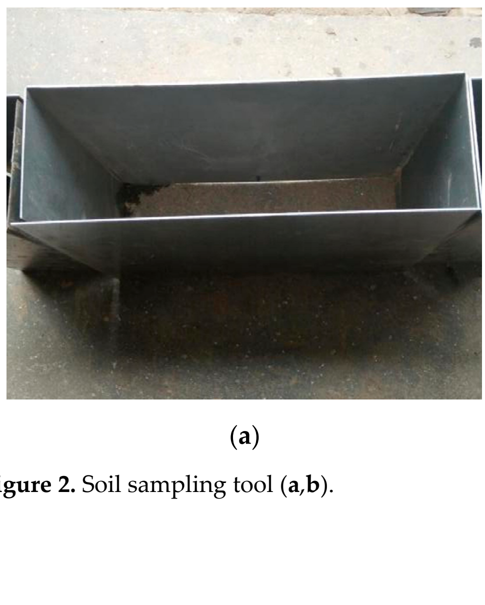
Soil total nitrogen content was weighed and measured by the Kjeldahl apparatus after the air-dried soil samples with 100 mesh sieve holes were digested with mixed accelerator and H_2SO_4. The contents of total phosphorus and total potassium in soil were measured by visible spectrophotometer and flame spectrophotometer after adding H_2SO_4 and $HClO_4$ to dry soil samples with 100 mesh sieve pores. Soil available phosphorus content was measured by visible spectrophotometer after adding phosphorus-free activated carbon and 50 mL 0.5 mol L^{-1} $NaHCO_3$ to air-dried soil samples with 20 mesh sieve holes. The content of available potassium in soil was measured by flame photometer after adding 50 mL 1 mol L^{-1} NH_4OAc to the air-dried soil samples with 20 mesh sieve holes. In the determination of soil alkaline nitrogen, air-dried soil samples with 20 mesh sieve holes were weighed and determined by the alkaline hydrolysis diffusion method. Soil organic matter weighed 100 mesh sieve air-dried soil samples, adding $K_2Cr_2O_7$-H_2SO_4 solution after cooking, using 0.2 mol L^{-1} $FeSO_4$ solution titration.

2.3.2. Dry Biomass and Grain Yield

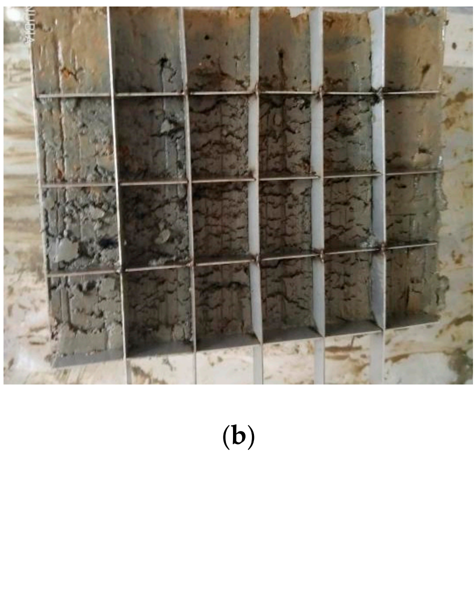
During the growing season, rice samples (4 plants) were taken at tillering (13 July), full heading (23 August), filling (6 September), and maturity stage (21 September), respectively. The samples were washed with distilled water and divided into roots, stems, leaves, and panicles. We harvested three pots in each period, after removing plants from the soil, and slowly washed them with water until the root was thoroughly emerged. All plant samples, including the rice grain at maturity, were treated at 105 °C for 30 min and then oven-dried at 65 °C till constant weights.

2.3.3. Soil Nitrogen Transfer and Transformation

Stainless steel frames were used for soil sampling at the tillering, full heading, filling, and maturity stages (Figure 2). Centering on the fertilizer point, the frame had a length of 15 cm, a width of 5 cm, and a depth of 20 cm. The soil was later cut into small cubes of 2.5 cm length. Two soil cubes at equal distances on both sides of the fertilizer point were pooled as one sample. Soil NH_4^+-N and NO_3^--N were extracted from 5.00 g fresh soil samples, by 50 mL 2 mol L^{-1} KCl. Then the sample was placed in constant temperature water bath with a constant temperature, 25 °C, speed at 220 rpm, for 30 min of vibration time to determine the total N in soil extract right after extraction by continuous Flow Analyzer.



(**a**)



(**b**)

Figure 2. Soil sampling tool (**a**,**b**).

2.3.4. Determination of NH_3 Volatilization in Rice Field

In this experiment, NH_3 volatilization was measured by closed chamber extraction. The closed chamber was cylindrical organic glass (with an inner diameter of 14 cm and a height of 15 cm). When determining ammonia volatilization, 100 mL of 0.05 mol L^{-1} H_2SO_4 was used as ammonia absorption liquid, and a flow meter was used to set the air exchange rate of 15–20 times the chamber size per minute [33]. The daily pumping time is morning (9:00–11:00) and afternoon (15:00–17:00), and 4 h represents the daily NH_3 volatile flux.

Ammonia volatilization was monitored after the first fertilization until no significant differences between fertilized treatments and the control. The collected ammonia volatile absorbent was analyzed using an AA3 flow analyzer.

2.3.5. Determination of NH_4^+-N Concentration in Surface Water

While monitoring ammonia volatilization, we collected surface water to determine NH_4^+-N concentration. It was determined by 0.45 μm membrane extraction with an AA3 flow analyzer.

2.4. Data Analysis

Calculation of Ammonia Volatilization

The ammonia volatilization was calculated using the following equation:

$$F = \frac{C \times V \times 6 \times 10^{-6}}{\pi \times r^2 \times 10^{-4}}$$

where F means the NH_3 emission flux (kg ha^{-1} d^{-1}); C means NH_4^+-N concentration in the absorber; V means the dilute sulfuric acid absorbs liquid volume (L); the 6 represents conversion to one-day emission flux; the 10^{-6} represents mg conversion to kg; r is the radius of the closed chamber collecting ammonia volatilization; 10^{-4} represents m^2 conversion to ha.

The loss rate of ammonia volatilization was calculated by the equation below:

$$R = (F_W - F_0)/f$$

where R represents loss rate of ammonia volatilization (%); F_W represents the cumulative Flux of NH_3 Emission in N region (kg ha^{-1} d^{-1}); F_0 represents the cumulative Flux of NH_3 Emission in Non-nitrogen Application region (kg ha^{-1} d^{-1}); f represents fertilizer N application (kg ha^{-1}).

The calculation formulas of nitrogen recovery efficiency (NRE) and nitrogen agronomic efficiency (NAE) are as follows:

$$NRE = (N - N_0)/F$$

$$NAE = (GY - GY_0)/F$$

where N means the N uptake of aboveground parts of plants under N application, N_0 is the N uptake of aboveground parts of plants without N application, GY is the dry biomass of grain under N application, GY_0 represents the dry biomass of grain without N application, and F represents the N application amount of fertilizer.

The data were analyzed through analysis of variance (ANOVA) using the SPSS18.0 (Norman H. Nie、C. Hadlai (Tex) Hull and Dale H. Bent; SPSS; American) software. The statistical differences between treatment means were determined by the least significant difference (LSD) ($p < 0.05$).

3. Results

3.1. Effects of Fertilization on Dry Biomass Quality and Yield of Plants

3.1.1. Dynamics of Rice Dry Biomass

During the growth season, the root biomass of different fertilization treatments varied significantly. Under the traditional application of nitrogen fertilizer, the S300 treatment increased by 12.74% and 7.36% respectively compared with the S210 treatment at the filling and maturity stage. At the same fertilization depth, the root biomass of the B5 treatment increased by approximately 1.0% compared with that in the R5 treatment during filling and maturity stage. The root biomass of the B10 treatment increased by 2.2% and 1.4% at both stages, compared with those of the R10 treatment. The root biomass of deep application of 10 cm (B10, R10) increased by 4.69–5.93% and 3.36–3.22%, respectively, compared with deep application of 5 cm (B5, R5) at the filling and mature stage. In addition, root biomass in B10 increased by 0.9% compared with conventional N treatment at maturity.

In general, shoot showed significant differences between treatments, as well as the total biomass of rice. The shoot biomass and total biomass of S300 treatment were 14.56%, 11.83%, 17.48%, 28.53%, and 21.34%, 11.73%, 18.60%, 20.48% higher than those of S210 treatment in the tillering, full heading, filling and maturity stage, respectively, indicating that in the soil with low fertility, reducing the amount of nitrogen fertilizer by 30% under scattered fertilization would affect the growth of rice. At the same fertilization depth, the shoot dry biomass and total dry biomass of B5 treatment were respectively 1.6%, 0.8%, 5.3%, 6.7%, and 7.5%, 1.1%, 2.1%, 4.7% higher than those of R5 treatment at tillering, full heading, filling and maturity stage. The shoot dry biomass and total dry biomass of B10 were 11.9%, 3.3%, 6.7%, 5.9%, and 7.1%, 3.1%, 5.2%, 4.3% higher than those of R10 treatment at tillering, full heading, filling and maturity stage, separately. The dry biomass of deep application of 5 cm (B5, R5) was lower than those of deep application of 10 cm (B10, R10), indicating that plant nutrient absorption was mainly concentrated in the vicinity of 10 cm below the root, which promoted the absorption of nutrient and affected rice yield (Table 2).

Table 2. Dry biomass of medium rice at different growth stages under different fertilization methods.

Growth Period	Treatment	Dry Biomass (g Plot^{-1})					
		Leaf	Stem and Sheath	Panicle	Root	Shoot	Shoot + Root
Tillering	S300	17.82 ± 0.36	22.14 ± 0.40 ^{b}	-	19.74 ± 0.72 ^{a}	39.96 ± 0.75 ^{b}	59.70 ± 1.15 ^{a}
	S210	16.98 ± 0.48	17.90 ± 0.04 ^{d}	-	14.31 ± 0.09 ^{c}	34.88 ± 0.45 ^{c}	49.20 ± 0.36 ^{c}
	R5	16.33 ± 1.27	19.79 ± 0.25 ^{c}	-	15.63 ± 0.50 ^{b}	36.12 ± 1.46 ^{c}	51.75 ± 1.74 ^{c}
	R10	17.47 ± 0.13	21.94 ± 0.48 ^{b}	-	17.11 ± 0.41 ^{b}	39.41 ± 0.35 ^{b}	56.52 ± 0.52 ^{b}
	B5	16.69 ± 1.05	20.02 ± 0.37 ^{c}	-	18.91 ± 0.39 ^{a}	36.71 ± 0.90 ^{c}	55.62 ± 1.05 ^{b}
	B10	17.62 ± 0.32	26.46 ± 0.58 ^{a}	-	16.45 ± 0.69 ^{b}	44.08 ± 0.83 ^{a}	60.53 ± 0.14 ^{a}
		$p = 0.678$	$p < 0.05$		$p < 0.05$	$p < 0.05$	$p < 0.05$
Full heading	S300	65.21 ± 2.05 ^{a}	185.70 ± 1.55 ^{a}	39.02 ± 0.52 ^{a}	87.96 ± 0.27	288.08 ± 7.36 ^{a}	376.04 ± 7.10 ^{a}
	S210	58.19 ± 1.22 ^{b}	166.14 ± 1.49 ^{b}	33.28 ± 0.50 ^{b}	78.94 ± 2.64	257.61 ± 0.84 ^{b}	336.55 ± 2.96 ^{b}
	R5	59.27 ± 0.46 ^{ab}	180.07 ± 0.97 ^{a}	35.13 ± 0.35 ^{b}	80.90 ± 6.38	274.47 ± 1.04 ^{ab}	355.37 ± 7.42 ^{ab}
	R10	61.67 ± 3.15 ^{a}	183.85 ± 5.76 ^{a}	36.90 ± 1.88 ^{a}	84.91 ± 1.88	284.43 ± 6.04 ^{a}	367.34 ± 4.18 ^{a}
	B5	61.14 ± 0.20 ^{a}	180.09 ± 1.83 ^{a}	35.50 ± 0.88 ^{ab}	82.62 ± 3.34	276.72 ± 1.71 ^{ab}	359.34 ± 4.86 ^{ab}
	B10	66.27 ± 2.13 ^{a}	186.41 ± 3.24 ^{a}	39.12 ± 0.26 ^{a}	86.86 ± 1.88	291.80 ± 4.26 ^{a}	378.66 ± 3.66 ^{a}
		$p = 0.054$	$p < 0.05$	$p < 0.05$	$p = 0.403$	$p < 0.05$	$p < 0.05$
Filling	S300	61.20 ± 0.26 ^{a}	174.19 ± 2.16 ^{a}	81.40 ± 0.41 ^{a}	152.68 ± 0.38 ^{a}	316.79 ± 2.07 ^{a}	469.47 ± 2.24 ^{a}
	S210	44.16 ± 0.49 ^{c}	153.30 ± 0.45 ^{d}	63.94 ± 0.65 ^{c}	135.43 ± 1.03 ^{c}	261.40 ± 0.20 ^{e}	395.83 ± 1.20 ^{e}
	R5	45.59 ± 1.80 ^{c}	164.97 ± 1.56 ^{c}	70.32 ± 0.42 ^{b}	144.48 ± 0.58 ^{b}	273.77 ± 3.19 ^{d}	425.36 ± 1.39 ^{d}
	R10	54.37 ± 0.86 ^{b}	174.80 ± 1.60 ^{a}	70.80 ± 0.23 ^{b}	151.25 ± 0.66 ^{a}	299.97 ± 0.96 ^{b}	451.22 ± 1.45 ^{b}
	B5	52.72 ± 0.47 ^{b}	157.86 ± 1.36 ^{b}	70.63 ± 0.06 ^{b}	145.91 ± 1.96 ^{b}	288.33 ± 1.98 ^{c}	434.23 ± 2.65 ^{c}
	B10	61.49 ± 0.75 ^{a}	175.99 ± 0.40 ^{a}	82.46 ± 1.90 ^{a}	154.56 ± 1.69 ^{a}	319.93 ± 2.07 ^{a}	474.49 ± 3.72 ^{a}
		$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
Maturity	S300	57.36 ± 0.55 ^{a}	171.23 ± 0.29 ^{a}	101.01 ± 0.75 ^{a}	168.90 ± 1.45 ^{a}	329.60 ± 1.34 ^{a}	498.49 ± 1.60 ^{a}
	S210	38.91 ± 1.56 ^{d}	147.79 ± 2.17 ^{cd}	69.73 ± 4.81 ^{d}	157.32 ± 2.73 ^{c}	256.43 ± 5.43 ^{d}	413.75 ± 6.21 ^{d}

R5	45.54 ± 0.19 c	152.15 ± 1.54 c	84.13 ± 2.22 c	162.87 ± 1.75 b	281.83 ± 2.45 c	444.70 ± 4.01 c
R10	52.19 ± 0.39 b	167.49 ± 2.28 b	96.51 ± 1.80 a	168.11 ± 1.15 a	316.19 ± 3.11 b	484.30 ± 1.97 b
B5	49.92 ± 0.59 c	156.21 ± 2.31 c	94.53 ± 2.41 ab	164.87 ± 1.44 ab	300.37 ± 3.55 c	465.53 ± 2.95 c
B10	57.89 ± 0.64 a	173.88 ± 0.82 a	103.07 ± 2.00 a	170.41 ± 1.13 a	334.83 ± 2.55 a	505.25 ± 1.45 a
	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$

Different letters within each column of a growth stage indicate the treatments differ at the $p < 0.05$ statistical significance level (Mean ± SE, $n = 3$).

3.1.2. Rice Grain Yield, NRE, and NAE

Among the fertilization treatments, the yield of the B10 treatment was similar to that of the S300 treatment. Compared with S210 treatment, deep application treatment (R5, R10, B5, B10) increased yield by 20.98%, 41.75%, 39.63%, 56.37%, respectively (Table 3). At the same fertilization depth, the yield of the B5 treatment was 15.42% higher than that of the R5 treatment. The yield of the B10 treatment was 10.32% higher than that of the R10 treatment.

Table 3. Effects of different fertilization methods on grain yield and N use efficiency.

Treatment	N Uptake of Aboveground Parts of Plants	NRE	NAE	Grain Yield
	g Plot^{-1}	%	kg kg^{-1}	t ha^{-1}
S300	4.42 ± 0.03 a	24.66 ± 0.19 d	4.94 ± 0.53 c	32.47 ± 2.56 a
S210	3.22 ± 0.12 d	23.26 ± 1.14 d	3.65 ± 0.47 d	20.93 ± 1.58 b
R5	3.64 ± 0.01 c	27.46 ± 0.14 c	4.95 ± 0.94 c	25.32 ± 3.19 b
R10	4.07 ± 0.03 b	31.77 ± 0.26 b	6.23 ± 0.17 ab	29.67 ± 0.56 a
B5	3.92 ± 0.09 b	30.22 ± 0.91 b	6.10 ± 0.62 b	29.23 ± 2.11 ab
B10	4.44 ± 0.07 a	35.42 ± 0.65 a	7.14 ± 1.09 a	32.73 ± 3.69 a
N_0	0.87 ± 0.01 e	-	-	8.56 ± 0.12 c
	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$

Different letters within each column mean treatments differ at the $p < 0.05$ statistical significance level (Mean ± SE, $n = 3$).

As compared with S300, while reducing N fertilizer by 30%, NRE of deep application increased by 18.07–52.28%. When compared to the S210 treatment, the NAE of deep application increased by 35.62–95.62%. Among them, the B10 treatment showed the highest NRE. At the same fertilization depth, the NRE and the NAE of the B5 treatment increased by 10.05% and 23.23% respectively, compared with the R5 treatment. The NRE and NAE of B10 treatment were 11.49% and 14.61% higher than those of the R10 treatment, respectively. The results showed that deep application helped N uptake of rice plants, reducing N loss and improving N utilization efficiency.

3.2. Diffusion Dynamics of Soil NH_4^+-N and NO_3^--N by Fertilization Method

3.2.1. Vertical and Horizontal Distribution of Soil NH_4^+-N

Effects of fertilization on NH_4^+-N distribution in soil are shown in Figure 3. For the conventional N fertilizer treatments (S300, S210), the NH_4^+-N is mainly distributed on the soil surface, and the concentration in the top soil is higher than that in the bottom soil. The NH_4^+-N concentrations of S300 were ranged in 144.51–255.19 mg kg^{-1}, 149.01–183.96 mg kg^{-1}, 71.05–87.54 mg kg^{-1}, 34.90–55.02 mg kg^{-1}; S210 NH_4^+-N concentrations ranged from 144.33–196.34 mg kg^{-1}, 136.23–186.25 mg kg^{-1}, 47.63–68.38 mg kg^{-1}, 22.66–43.54 mg kg^{-1} at the tillering, full heading, filling and maturity stage. For deep treatment, all fertilization depths (5 cm, 10 cm) in soil showed the highest concentration of NH_4^+-N, formed the center of fertilization, and gradually spread to the surrounding soil. The soil NH_4^+-N concentration under large granular fertilizer deep application was mainly concentrated in the horizontal direction 5–7.5 cm, the vertical direction 3–15 cm soil layer, around the rice root system, slowed down the diffusion rate of the NH_4^+-N, and then ensured the sufficient nutrient supply during the rice growth period. However, the distribution of soil NH_4^+-N concentration in different fertilization depths was different under the row deep application. The NH_4^+-N concentrated in the horizontal direction of 0–5 cm and the vertical direction of 3–9 cm soil area under the deep application of 5 cm, the soil NH_4^+-N mainly concentrated in the horizontal direction of 3–7.5 cm, the vertical direction of 3–15 cm soil layer under the depth of 10 cm.

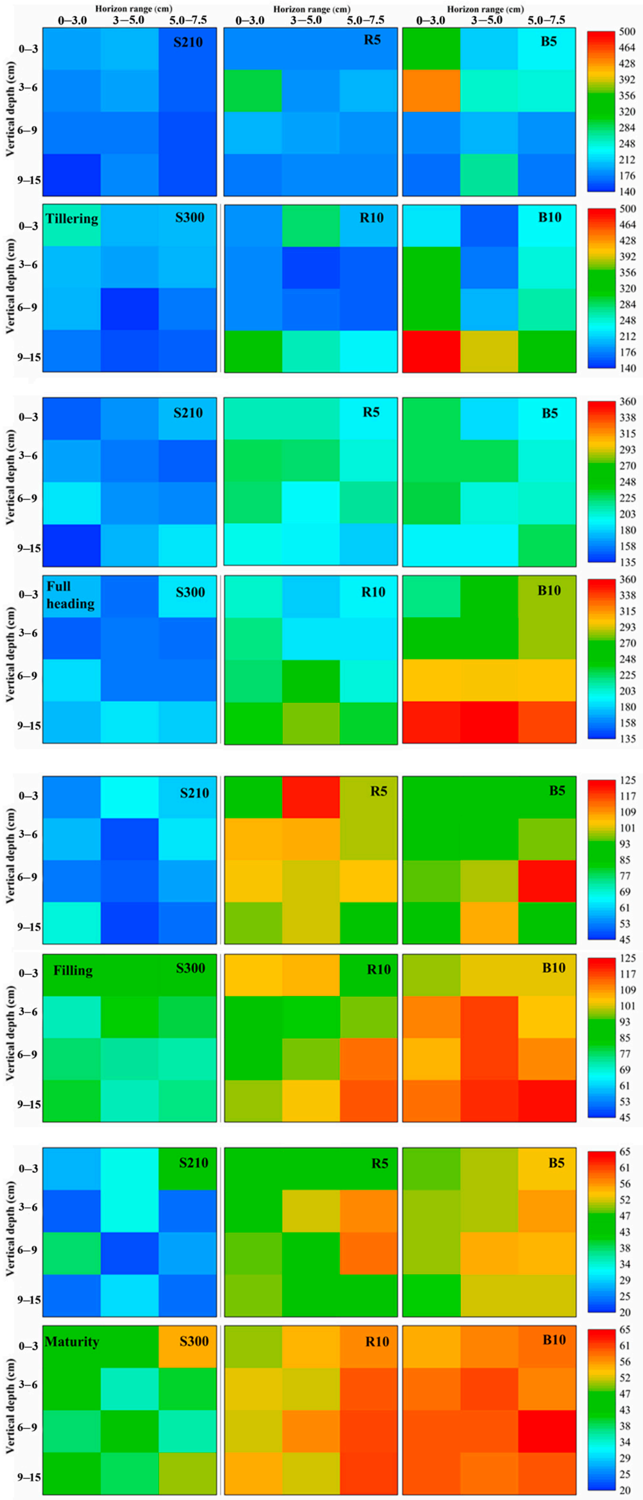


Figure 3. $NH4^+$-N content in different soil layers at tillering stage, full heading stage, filling stage and maturity stage (mg/kg).

For deep treatment, the maximum soil NH_4^+-N concentration all appeared at tillering stage. At the same fertilization depth, NH_4^+-N at 5 cm depth concentrated in a 3–6 cm depth (vertical), 0–3 cm (horizontal) soil area, showing its highest concentration, R5 treatment was 292.96 mg kg^{-1}, B5 treatment was 437.54 mg kg^{-1}. The NH_4^+-N in depth of 10 cm existed in a 9–15 cm depth (vertical) and 0–3 cm (horizontal) soil area, and the highest concentration R5 treatment was 317.82 mg kg^{-1}, B10 treatment was 496.31 mg kg^{-1}. During the growth period, the soil NH_4^+-N content decreased. After maturity, the NH_4^+-N concentration range of R5 treatment was 44.07–57.97 mg kg^{-1}, and that of B5 treatment was 47.82–55.53 mg kg^{-1}. The NH_4^+-N concentration range of the R10 treatment was 49.71–61.10 mg kg^{-1}, and that of the B10 treatment was 55.17–64.34 mg kg^{-1}. The concentration of NH_4^+-N in the 5 cm soil layer was concentrated in a 3–9 cm vertical direction and 3–7.5 cm horizontal direction. NH_4^+-N concentration in 10 cm deep soil was finally concentrated in 3–15 cm in the vertical direction and 3–7.5 cm in the horizontal direction. Therefore, when the fertilization depth is 10 cm, the soil NH_4^+-N content has been maintained at a high level, so that the nutrients of rice will not be lost quickly during the growth process, the nutrient utilization ratio of the plant will be improved, and the plant will grow better.

3.2.2. Vertical and Horizontal Distribution of Soil NO_3^--N

As shown in Figure 4, at the tillering stage, the traditional nitrogen fertilizer application treatment was mainly on the soil surface (0–3 cm), the concentration of NO_3^--N was 10.93–43.72 mg kg^{-1}; the deep application treatment was mainly inside the soil at fertilization sites (3–15 cm), the concentration of NO_3^--N was 5.98–32.48 mg kg^{-1}. The NO_3^--N concentration of conventional N fertilizer was significantly higher than those of deep application. The concentrations of NO_3^--N at full heading, filling, and maturity stage under the conventional N fertilizer application were 4.3–19.77 mg kg^{-1}, 8.82–11.64 mg kg^{-1} and 7.49–10.52 mg kg^{-1}, respectively. The NO_3^--N concentrations at full heading, filling and maturity stage were 2.32–17.90 mg kg^{-1}, 7.38–10.25 mg kg^{-1} and 4.70–9.00 mg kg^{-1}, respectively, under the deep application of large granular fertilizer. The NO_3^--N concentrations at full heading, filling and maturity stage were 6.91–19.46 mg kg^{-1}, 8.37–12.40 mg kg^{-1} and 5.29–7.05 mg kg^{-1}, respectively, under the treatment of deep row application. The NH_4^+-N concentration of inorganic N in soil is mainly NH_4^+-N, NO_3^--N relatively low. As well, the effects of fertilization on soil NO_3^--N concentration in different treatments were similar. Therefore, the NH_4^+-N in fertilizer is rarely converted to NO_3^--N.

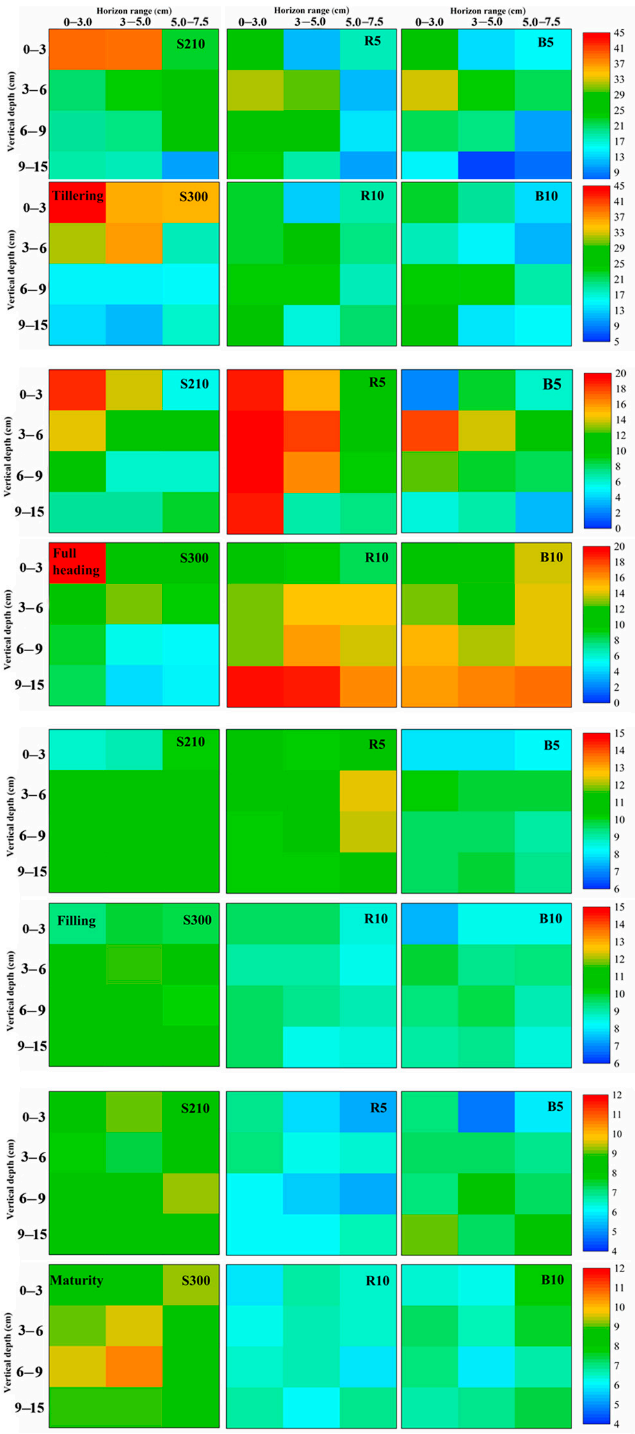


Figure 4. NO_3^--N content in different soil layers at tillering stage, full heading stage, filling stage and maturity stage (mg/kg).

3.3. Effects of Fertilization Methods on Ammonia Volatilization in Paddy Field

3.3.1. Dynamics of Ammonia Volatilization Flux

Ammonia volatilization peak of each fertilization treatment appeared on the first day after the application of base fertilizer (Figure 5). The volatilization rate of S300 treatment was 8.67 kg ha^{-1} d^{-1}, while that of B10 was only 3.05 kg ha^{-1} d^{-1}. The peak value of the S210 treatment is 41.18% lower than that of the S300 treatment. Moreover, the peak value of other deep application treatments (R5, R10, B5) was 58.71–63.32% lower than that of the S300 treatment. At the same fertilization depth, the peak value of ammonia volatilization flux of B5 treatment was similar to that of R5, while the peak value of ammonia volatilization flux in B10 treatment was 4.1% lower than that in R10 treatment.

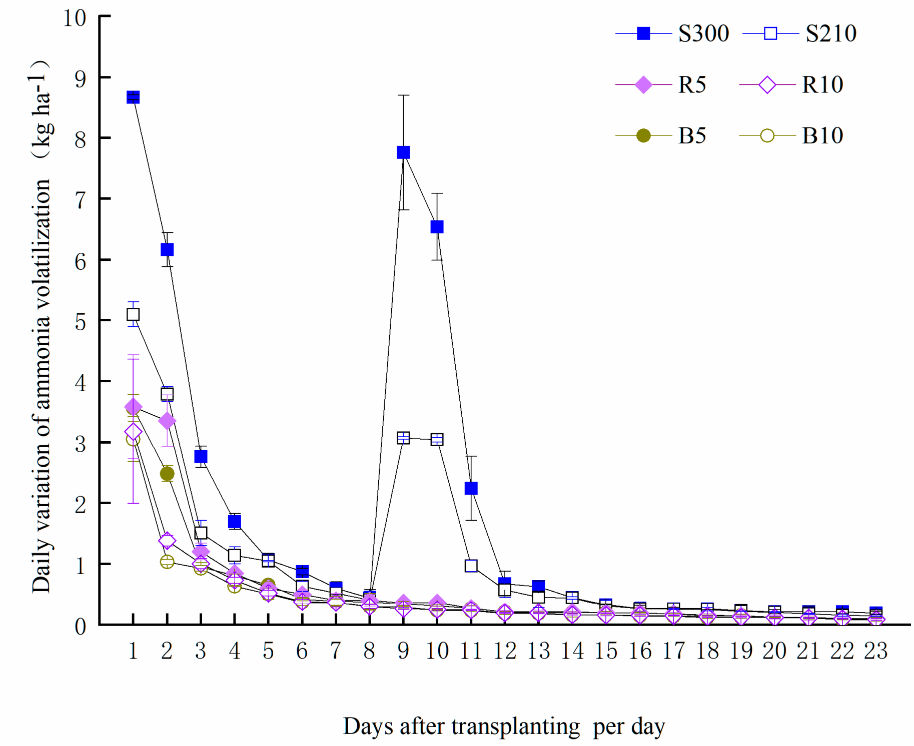


Figure 5. Daily variation of ammonia volatilization in different fertilization treatments.

On the 9th day after topdressing, the second ammonia volatilization peak appeared in the conventional fertilizer treatments. At this time, the ammonia volatilization amounts of S300 and S210 treatments were 7.76 kg ha^{-1} d^{-1} and 3.07 kg ha^{-1} d^{-1}, respectively, which were both lower than each of their first peaks, due to the low N application of tillering fertilizer. There were no second peaks in other treatments due to the lack of topdressing. Subsequently, ammonia volatilization of each fertilization treatment showed a downward trend, until the 23rd day after fertilization, ammonia volatilization of each fertilization treatment and no fertilization treatment (N_0) were not significantly different.

3.3.2. Ammonia Volatilization Loss and Loss Rate

During the monitoring period of ammonia volatilization in rice fields (in total of 23 days), the ammonia volatilization loss and ammonia volatilization loss rate of the conventional N fertilizer spread treatment were the highest, ammonia volatilization loss was 42.76 kg ha^{-1} and 24.70 kg ha^{-1}, respectively. Ammonia volatilization loss rate was 12.30% and 9.0% respectively (Table 4). The cumulative ammonia volatilization loss of the N_0 treatment was the lowest, and the cumulative ammonia volatilization loss of the B10 treatment was at a very low level in the fertilization treatment, and there was a significant difference among the fertilization treatments. The cumulative loss of ammonia volatilization ranked as S300 > S210 > R5 > B5 > R10 > B10, and the cumulative loss of ammonia volatilization of B10 was significantly lower than all other fertilized treatments.

Table 4. Ammonia volatilization loss and ammonia volatilization loss rate with different fertilization methods.

Treatment	Nitrogen Application	Total Ammonia Volatilization	Ammonia Volatilization Loss Rate
	kg ha^{-1}	kg ha^{-1}	%
N_0	0	5.85 ± 2.00 ^{g}	–
S300	300	42.76 ± 1.20 ^{a}	12.3
S210	210	24.70 ± 0.15 ^{b}	9.0
R5	210	13.84 ± 1.27 ^{c}	3.8
R10	210	10.30 ± 1.16 ^{e}	2.1
B5	210	12.47 ± 0.30 ^{d}	3.2
B10	210	9.57 ± 0.55 ^{f}	1.8

Different letters for total ammonia volatilization indicate treatments are different at the $p < 0.05$ statistical significance level (Mean ± SE, $n = 3$).

Deep application of N fertilizer reduction can significantly reduce ammonia volatilization loss, the ammonia volatilization loss rates of row deep application (R5, R10) were 3.80% and 2.12%, respectively, which were 69.10% and 82.76% lower than those of S300 treatment, respectively. The ammonia volatilization loss rates of deep application of large granular fertilizer (B5, B10) were 3.15% and 1.77%, respectively, which were 74.39% and 85.63% lower than those of S300 treatment, respectively. At the same fertilization depth, the ammonia volatilization loss rate of the B5 treatment was 17.19% lower than that of the R5 treatment. The ammonia volatilization loss rate of the B10 treatment was 16.64% lower than that of the R10 treatment. Therefore, the deeper the fertilization depth was, the lower the ammonia volatilization loss (rate) was. Under the same fertilization depth, the fertilization method of deep application of large granular fertilizer had the best effect on inhibiting ammonia volatilization loss. The above results showed that fertilization methods had a significant effect on ammonia volatilization loss. Deep application treatment could effectively reduce ammonia volatilization. As well, applying fertilizer at 10 cm depth was better than at 5 cm depth, which was better than surface application.

3.3.3. NH_4^+-N Concentration in Surface Water

The concentration of NH_4^+-N in surface water after fertilization was basically consistent with that of ammonia volatilization (Figure 6). The highest NH_4^+-N concentration in surface water appeared on the first day after fertilization, and then gradually decreased. The NH_4^+-N concentration of S300 treatment was 275.84 mg L^{-1} on the first day after the application of base fertilizer. The concentration of B10 was 118.73 mg L^{-1}. Compared with the S300 treatment, the peak of NH_4^+-N concentration decreased by 26.0–57.0% after deep fertilization. Under the same fertilization depth, the peak NH_4^+-N concentration of the B5 treatment was 17.3% lower than the R5 treatment, and the B10 treatment was 10.68% lower than the R10 treatment. After topdressing, the peak value of NH_4^+-N concentration in the S300 treatment was the highest, which was 128.28 mg L^{-1}. Compared with the S300 treatment, the peak value of NH_4^+-N concentration in deep topdressing treatment decreased by 56.4–72.5%. At the same fertilization depth, the NH_4^+-N concentration peak of the B5 treatment was 7.39% lower than that of the R5 treatment. B10 treatment decreased by 15.8% compared with the R10 treatment. There was no significant difference among the treatments after 23 days. The NH_4^+-N concentration in surface water of fertilization treatment was generally S300 > S210 > R5 > B5 > R10 > B10.

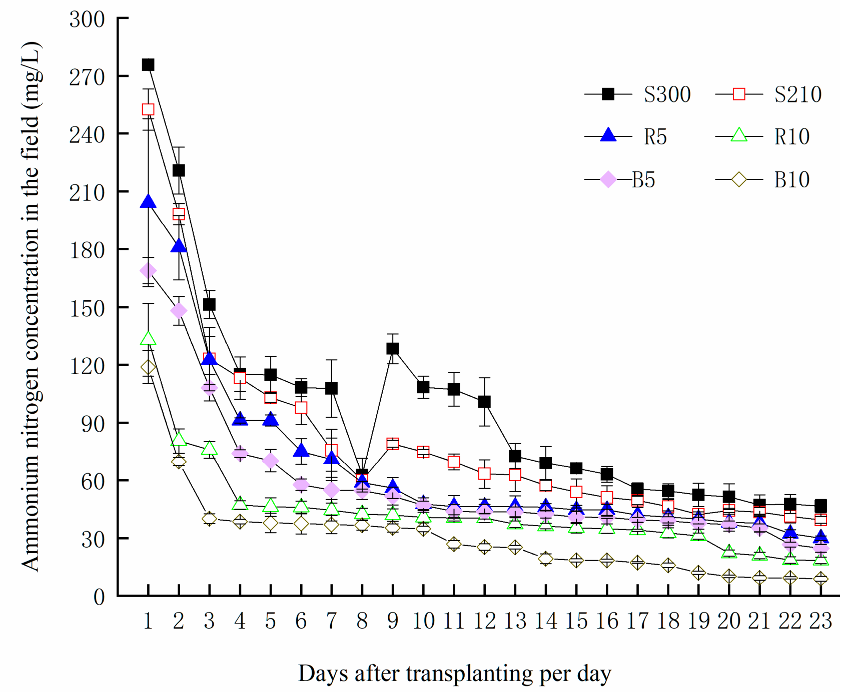


Figure 6. Daily variation of ammonium nitrogen concentration in surface water under different fertilization treatments.

4. Discussion

4.1. Effects of Fertilization on Soil N Distribution

The release and migration of N fertilizer in soil affected the absorption and utilization of N in rice. Previous studies showed that the soil depth of the paddy field is mainly in an anaerobic environment. Soil inorganic N is maintained as of NH_4^+-N. Deep fertilization increases the contact between particles and soil, and reduces the loss of N through runoff and other forms [33–35]. In this study, the soil NH_4^+-N concentration under deep application was significantly higher than that under conventional N application, and the soil NH_4^+-N was mainly concentrated in 6–15 cm. Rice roots were mainly distributed in the 0–20 cm tillage layer [36,37] The deep application of fertilizer over 7.5 cm obtained the maximum N availability, promoting the increase of nutrient concentration in the crop root zone, making rice fully absorb nutrients, and improving crop yield. This is why 5 cm and 10 cm depth were used as the fertilization depth under deep fertilization.

In addition, N distribution occurred mainly in the 0–5 cm soil layer [38], showing that NH_4^+-N diffusion rate was very slow in root zone fertilization mode, which could be maintained for about 2 months, and the diffusion range was only 4–13 cm below the soil surface [18]. The results of this study showed that deep fertilization could gradually migrate and spread around the fertilization point. Comparing the changes of NH_4^+-N concentration in different deep fertilization methods, the distribution of fertilizer N in the horizontal direction is 5–7.5 cm under the large granular deep fertilization. As well, the vertical direction distribution is mainly in the soil layer ranging from 3–15 cm. The migration distance of fertilizer N under the deep application varies by fertilization depth. The distribution of fertilizer N in the horizontal direction was 0–5 cm under the deep application of 5 cm, which was mainly distributed in the range of 3–9 cm in the vertical direction. The migration distance of fertilizer N in the horizontal direction was 3–7.5 cm under the deep application of 10 cm, while was mainly distributed in the range of 3–15 cm in the vertical direction. The results of the studies of Wu, etc., are similar [39]. The main reason may be that the fertilizer is loose and not concentrated enough compared with large granular fertilization, resulting in soil NH_4^+-N loss. Previous studies have shown that in the 60-day period of rice cultivation, the conventional N fertilizer application resulted in high NH_4^+-N content in the soil surface, while the deep application significantly increased the NH_4^+-N content around the fertilization point (the depth of deep application was 10 cm), and the duration was long [40,41]. This is consistent with the results of this study. In this study, the soil NH_4^+-N concentration under the deep application treatment was still high until the mature stage, which could ensure the continuous nutrient supply of plants in the growth period. However, the soil NH_4^+-N concentration under the conventional N fertilizer application treatment decreased due to excessive N loss. Since the effects of fertilization treatments on the vertical and horizontal migration of NO_3^--N in paddy soil were not significant in this study, it was not discussed.

4.2. Effect of Fertilization on Ammonia Volatility in Paddy Field

Previous studies showed that NH_4^+-N was buried under the soil surface layer by deep application, which reduced the loss of NH_3 volatilization [34,41]. Our results also showed that deep N application significantly reduced the cumulative NH_3 loss in rice growing season, and the loss rate of ammonia volatilization was only 1.8%-3.8%, and the deeper the depth was, the lower the loss rate of ammonia volatilization was. On the one hand, the reason is that deep application will make the NH_4^+-N concentration in the soil last for a long period, slow down the hydrolysis rate of fertilizer, and then reduce the NH_3 volatilization loss. Secondly, deep application increased the adsorption of NH_4^+-N on the soil exchange complex with a negative charge, which could reduce the NH_4^+-N concentration in surface water, thereby reducing the NH_3 volatilization loss [34,42]. The results showed that the loss rate of ammonia volatilization was lower than that of Shang etc. [43]. The main reason was that the N fertilizer used in this experiment was ammonium sulfate, which was the fertilizer to inhibit the loss of ammonia volatilization. In this study, under the same fertilization depth, ammonia volatilization loss of deep application of large granular fertilizer was significantly lower than that of row application. The result is similar to that of Ke etc. [17]. The reason may be the difference in fertilization shape. Large granular fertilizer act as a package., when fertilizer is applied, the film can hinder the loss of N; the row application release so fast that NH_4^+-N cannot stay the in soil for long period. Therefore, the above phenomenon further shows that reducing the NH_4^+-N concentration in the surface water is the reasonable way to reduce NH_3 volatilization in the paddy field.

NH_4^+-N mainly exists in the form of ionic ammonia and non-ionic ammonia, and non-ionic nitrogen (NH_3) is one of the important factors affecting the growth of aquatic animals (fish, crustaceans) [44]. In the ecological agriculture mode, in addition to farmland fertilization, aquatic animals also have the excretion of ammonia-containing products [45]. When the non-ionic ammonia in surface water increases, hemoglobin loses the function of carrying oxygen, reduces the oxygen-carrying capacity and energy metabolism of aquatic animals, inhibits the ammonia excretion of aquatic animals, and causes a series of physiological toxicity reactions such as hypoxia and organ failure and death [46,47]. The results of this study showed that deep application could significantly reduce the NH_4^+-N concentration in surface water and ensure the normal growth of aquatic organisms due to the deep burial of fertilizers in the soil layer and the reduction of volatilization in air.

4.3. Effects of Fertilization on Rice Growth

The essence of rice yield formation is the accumulation, transfer, and distribution of dry biomass [48]. Different from the previous experiments, the sub-surface soil of rice fields with relatively poor fertility was used in this experiment, and the experimental results are sensitive to the differences between different fertilization treatments. The N uptake of rice at the early growth stage was limited [24]. However, at the full heading stage, most N fertilizers were gradually absorbed. The accumulation and transfer of N at the full heading stage is a critical period for grain yield, since most of the dry biomass in leaves and stem sheaths are transferred to grains during this period, and 70% of the N absorbed by straw is transferred to grains in the meantime, which will keep the N accumulation in grains at a certain level during plant maturation [49]. As well, roots penetrating more than 20 cm into the soil, still can absorb nutrients from the soil [50]. In this study, compared with the conventional N fertilizer application, the dry biomass of deep application at the tillering stage was low, while the dry biomass showed an increasing trend after the heading stage, for the roots are mainly distributed in the shallow layer in the early stage. However, at the full heading stage, the root development gradually completes. The observation is comparable with the results from previous results [51,52]. Some research showed that the NRE of deep application increased by 30–54 %, and grain yield was significantly increased, compared with the conventional N fertilizer application [34,53]. Deep application increased the number of effective tillers in the early growth stage, and significantly increased the number of effective panicles and yield at maturity [39]. This study showed that the deep application of B10 significantly increased the dry biomass of each part of the rice plant and yield. The main reason can be that deep application gives the possibility for the rice roots to fully contact with fertilizer, provides high nutrient concentration to promote rice tillering, enhances root activity and increases yield during rice growth and development; [54] reported similar results. It is reported that deep fertilization does not lead to yield decline with a reduction in the application rate of N fertilizer by 28–44% [22].

Moreover, the results of this study showed that under the same fertilization depth, the rice yield under the treatment of the deep application of large granular fertilizer increased by 10.32–15.42% compared with that under the treatment of row deep fertilization. Under the same fertilization mode, the rice yield of deep application of 10 cm was higher than that of deep application of 5 cm. On the one hand, the row treatment fertilizer is loose, the fertilizer was released in the soil fast, and there was limited nutrient for the rice during the critical period of growth; on the other hand, the fertilization depth may not be enough for the loss of some nutrients in rice growth [34,37] studies showed that, NRE and grain yield had no correlation with fertilization depth. In this study, deep application significantly increased NRE and NAE. Although the N_0 treatment contained less N in our study, it was close to the atmospheric N deposition content and could be ignored. Grain yield was lowest at 20 cm, followed by deep 5 cm, Deep application of 10 cm is the best [37]. The main reason may be that N loss processes (such as nitrification and denitrification) differ in different soil depths [55].

5. Conclusions

Deep application can effectively inhibit ammonia volatilization and reduce N loss. Compared with conventional fertilization, deep application reduces the number of topdressing and can improve farmers' production efficiency. According to the migration characteristics of N in soil during the growth period of rice, deep application of large granular fertilizer promotes the growth of rice. It not only makes the fertilizer have full contact with the rice root system, but also provides sufficient nutrients for the vegetative growth stage of rice and slows down the release rate of N. The large granular fertilizer fertilization technology is worth exploring and developing, but the technology requires large labor costs. Therefore, it is necessary to further develop and promote large granular fertilization technology and fertilization equipment to reduce the production costs.

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References

1. Deng, N.; Grassini, P.; Yang, H.; Huang, J.; Cassman, K.G.; Peng, S. Closing yield gaps for rice self-sufficiency in China. *Nat. Commun.* **2019**, *10*, 1725. https://doi.org/10.1038/s41467-019-09447-9.
2. Li, Z.; Liu, Z.; Anderson, W.; Yang, P.; Wu, W.; Tang, H.; You, L. Chinese Rice Production Area Adaptations to Climate Changes, 1949–2010. *Environ. Sci. Technol.* **2015**, *49*, 2032–2037. https://doi.org/10.1021/es505624x.
3. Li, S.; Tian, Y.; Wu, K.; Ye, Y.; Yu, J.; Zhang, J.; Liu, Q.; Hu, M.; Li, H.; Tong, Y.; et al. Modulating plant growth–metabolism coordination for sustainable agriculture. *Nature* **2018**, *560*, 595–600. https://doi.org/10.1038/s41586-018-0415-5.
4. Yang, W.; Que, H.; Wang, S.; Zhu, A.; Zhang, Y.; He, Y.; Xin, X.; Zhang, X.; Ding, S. High temporal resolution measurements of ammonia emissions following different nitrogen application rates from a rice field in the Taihu Lake Region of China. *Environ. Pollut.* **2019**, *257*, 113489. https://doi.org/10.1016/j.envpol.2019.113489.
5. Wang, Y.; Lu, Y. Evaluating the potential health and economic effects of nitrogen fertilizer application in grain production systems of China. *J. Clean. Prod.* **2020**, *264*, 121635. https://doi.org/10.1016/j.jclepro.2020.121635.
6. Yang, Y.; Li, N.; Ni, X.; Yu, L.; Yang, Y.; Wang, Q.; Liu, J.; Ye, Y.; Tao, L.; Liu, B.; et al. Combining deep flooding and slow-release urea to reduce ammonia emission from rice fields. *J. Clean. Prod.* **2019**, *244*, 118745. https://doi.org/10.1016/j.jclepro.2019.118745.
7. Dong, Y.; Yuan, J.; Zhang, G.; Ma, J.; Hilario, P.; Liu, X.; Lu, S. Optimization of nitrogen fertilizer rate under integrated rice management in a hilly area of Southwest China. *Pedosphere* **2020**, *30*, 759–768. https://doi.org/10.1016/s1002-0160(20)60036-4.
8. Zhao, M.; Tian, Y.; Ma, Y.; Zhang, M.; Yao, Y.; Xiong, Z.; Yin, B.; Zhu, Z. Mitigating gaseous nitrogen emissions intensity from a Chinese rice cropping system through an improved management practice aimed to close the yield gap. *Agric. Ecosyst. Environ.* **2015**, *203*, 36–45. https://doi.org/10.1016/j.agee.2015.01.014.
9. Ding, W.; Xu, X.; He, P.; Zhang, J.; Cui, Z.; Zhou, W. Estimating regional N application rates for rice in China based on target yield, indigenous N supply, and N loss. *Environ. Pollut.* **2020**, *263*, 114408. https://doi.org/10.1016/j.envpol.2020.114408.
10. Liu, S.; Xie, Z.; Zeng, Y.; Liu, B.; Li, R.; Wang, Y.; Wang, L.; Qin, P.; Jia, B.; Xie, J. Effects of anthropogenic nitrogen discharge on dissolved inorganic nitrogen transport in global rivers. *Glob. Chang. Biol.* **2019**, *25*, 1493–1513. https://doi.org/10.1111/gcb.14570.
11. Spiertz, J.H.J. Nitrogen, sustainable agriculture and food security: A review. *Agron. Sustain. Dev.* **2010**, *30*, 43–55. https://doi.org/10.1051/agro:2008064.
12. Zhang, M.; Tian, Y.; Zhao, M.; Yin, B.; Zhu, Z. The assessment of nitrate leaching in a rice–wheat rotation system using an improved agronomic practice aimed to increase rice crop yields. *Agric. Ecosyst. Environ.* **2017**, *241*, 100–109. https://doi.org/10.1016/j.agee.2017.03.002.
13. Wang, H.Y.; Zhang, D.; Zhang, Y.T.; Zhai, L.M.; Yin, B.; Zhou, F.; Geng, Y.C.; Pan, J.T.; Luo, J.F.; Gu, B.J.; et al. Ammonia emissions from paddy fields are underestimated in China. *Environ. Pollut.* **2018**, *235*, 482–488. https://doi.org/10.1016/j.envpol.2017.12.103.
14. Wang, G.; Zhang, R.; Gomez, M.E.; Yang, L.; Zamora, M.L.; Hu, M.; Lin, Y.; Peng, J.; Guo, S.; Meng, J.; et al. Persistent sulfate formation from London Fog to Chinese haze. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 13630–13635. https://doi.org/10.1073/pnas.1616540113.
15. Li, Q.; Zhang, R.; Wang, Y. Interannual variation of the wintertime fog-haze days across central and eastern China and its relation with East Asian winter monsoon. *Int. J. Clim.* **2015**, *36*, 346–354. https://doi.org/10.1002/joc.4350.
16. Zhang, X.; Xiao, G.; Bol, R.; Wang, L.; Zhuge, Y.; Wu, W.; Li, H.; Meng, F. Influences of irrigation and fertilization on soil N cycle and losses from wheat–maize cropping system in northern China. *Environ. Pollut.* **2021**, *278*, 116852. https://doi.org/10.1016/j.envpol.2021.116852.
17. Ke, J.; He, R.; Hou, P.; Ding, C.; Ding, Y.; Wang, S.; Liu, Z.; Tang, S.; Ding, C.; Chen, L.; et al. Combined controlled-released nitrogen fertilizers and deep placement effects of N leaching, rice yield and N recovery in machine-transplanted rice. *Agric. Ecosyst. Environ.* **2018**, *265*, 402–412. https://doi.org/10.1016/j.agee.2018.06.023.
18. Yao, Y.; Zhang, M.; Tian, Y.; Zhao, M.; Zhang, B.; Zhao, M.; Zeng, K.; Yin, B. Urea deep placement for minimizing NH3 loss in an intensive rice cropping system. *Field Crop. Res.* **2018**, *218*, 254–266. https://doi.org/10.1016/j.fcr.2017.03.013.
19. Wu, P.; Liu, F.; Chen, G.; Wang, J.; Huang, F.; Cai, T.; Zhang, P.; Jia, Z. Can deep fertilizer application enhance maize productivity by delaying leaf senescence and decreasing nitrate residue levels? *Field Crop. Res.* **2021**, *277*, 108417. https://doi.org/10.1016/j.fcr.2021.108417.

20. Hou, P.; Yuan, W.; Li, G.; Petropoulos, E.; Xue, L.; Feng, Y.; Xue, L.; Yang, L.; Ding, Y. Deep fertilization with controlled-release fertilizer for higher cereal yield and N utilization in paddies: The optimal fertilization depth. *Agron. J.* **2021**, *113*, 5027–5039. https://doi.org/10.1002/agj2.20772.
21. Wu, P.; Chen, G.; Liu, F.; Cai, T.; Zhang, P.; Jia, Z. How does deep-band fertilizer placement reduce N2O emissions and increase maize yields?. *Agric. Ecosyst. Environ.* **2021**, *322*, 107672. https://doi.org/10.1016/j.agee.2021.107672.
22. Miah, A.M.; Gaihre, Y.K.; Hunter, G.; Singh, U.; Hossain, S.A. Fertilizer Deep Placement Increases Rice Production: Evidence from Farmers' Fields in Southern Bangladesh. *Agron. J.* **2016**, *108*, 805–812. https://doi.org/10.2134/agronj2015.0170.
23. Zhang, M.; Yao, Y.; Zhao, M.; Zhang, B.; Tian, Y.; Yin, B.; Zhu, Z. Integration of urea deep placement and organic addition for improving yield and soil properties and decreasing N loss in paddy field. *Agric. Ecosyst. Environ.* **2017**, *247*, 236–245. https://doi.org/10.1016/j.agee.2017.07.001.
24. Wang, D.; Xu, C.; Yan, J.; Zhang, X.; Chen, S.; Chauhan, B.; Wang, L.; Zhang, X. 15 N tracer-based analysis of genotypic differences in the uptake and partitioning of N applied at different growth stages in transplanted rice. *Field Crop. Res.* **2017**, *211*, 27–36. https://doi.org/10.1016/j.fcr.2017.06.017.
25. Zhu, C.; Xiang, J.; Zhang, Y.; Zhang, Y.; Zhu, D.; Chen, H. Mechanized transplanting with side deep fertilization increases yield and nitrogen use efficiency of rice in Eastern China. *Sci. Rep.* **2019**, *9*, 5653. https://doi.org/10.1038/s41598-019-42039-7.
26. Nayak, P.; Panda, B.; Lal, B.; Gautam, P.; Poonam, A.; Shahid, M.; Tripathi, R.; Kumar, U.; Mohapatra, S.; Jambhulkar, N. Ecological mechanism and diversity in rice based integrated farming system. *Ecol. Indic.* **2018**, *91*, 359–375. https://doi.org/10.1016/j.ecolind.2018.04.025.
27. Chaklader, R.; Fotedar, R.; Howieson, J.; Siddik, M.A.; Foysal, J. The ameliorative effects of various fish protein hydrolysates in poultry by-product meal based diets on muscle quality, serum biochemistry and immunity in juvenile barramundi, Lates calcarifer. *Fish Shellfish Immunol.* **2020**, *104*, 567–578. https://doi.org/10.1016/j.fsi.2020.06.014.
28. Martins, M.R.; Jantalia, C.P.; Polidoro, J.C.; Batista, J.N.; Alves, B.J.; Boddey, R.M.; Urquiaga, S. Nitrous oxide and ammonia emissions from N fertilization of maize crop under no-till in a Cerrado soil. *Soil Tillage Res.* **2015**, *151*, 75–81. https://doi.org/10.1016/j.still.2015.03.004.
29. Xia, H.; Song, T.; Wang, L.; Jiang, L.; Zhou, Q.; Wang, W.; Liu, L.; Yang, P.; Zhang, X. Effects of dietary toxic cyanobacteria and ammonia exposure on immune function of blunt snout bream (*Megalabrama amblycephala*). *Fish Shellfish Immunol.* **2018**, *78*, 383–391. https://doi.org/10.1016/j.fsi.2018.04.023.
30. Van Vo, B.; Siddik, M.A.; Fotedar, R.; Chaklader, R.; Foysal, J.; Pham, H.D. Digestibility and water quality investigations on the processed peanut (*Arachis hypogaea*) meal fed barramundi (*Lates calcarifer*) at various inclusion levels. *Aquac. Rep.* **2020**, *18*, 100474. https://doi.org/10.1016/j.aqrep.2020.100474.
31. Guo, L.; Ning, T.; Nie, L.; Li, Z.; Lal, R. Interaction of deep placed controlled-release urea and water retention agent on nitrogen and water use and maize yield. *Eur. J. Agron.* **2016**, *75*, 118–129. https://doi.org/10.1016/j.eja. 2016.01.010.
32. Peng, S.Q.; Zhang, W.; Hou, H.; Wang, H.W.; Chen, A.; Wei, W. Effects of reduction and deep placement of nitrogen fertilizer on rice yield and N2O emissions from double cropping paddy field. *Chin. J. Ecol.* **2019**, *38*, 153–160. https://doi.org/10.13292/j.1000-4890.201901.011.
33. Liu, T.; Fan, D.; Zhang, X.; Chen, J.; Li, C.; Cao, C. Deep placement of nitrogen fertilizers reduces ammonia volatilization and increases nitrogen utilization efficiency in no-tillage paddy fields in central China. *Field Crop. Res.* **2015**, *184*, 80–90. https://doi.org/10.1016/j.fcr.2015.09.011.
34. Freney, J.R.; Leuning, R.; Simpson, J.R.; Denmead, O.T.; Muirhead, W.A. Estimating Ammonia Volatilization From Flooded Rice Fields by Simplified Techniques. *Soil Sci. Soc. Am. J.* **1985**, *49*, 1049–1054. https://doi.org/10.2136/sssaj1985.03615995004900040051x.
35. Zhang, Y.; Liu, H.; Guo, Z.; Zhang, C.; Sheng, J.; Chen, L.; Luo, Y.; Zheng, J. Direct-seeded rice increases nitrogen runoff losses in southeastern China. *Agric. Ecosyst. Environ.* **2018**, *251*, 149–157. https://doi.org/10.1016/j.agee.2017.09.022.
36. Garnett, T.; Conn, V.; Kaiser, B.N. Root based approaches to improving nitrogen use efficiency in plants. *Plant, Cell Environ.* **2009**, *32*, 1272–1283. https://doi.org/10.1111/j.1365-3040.2009.02011.x.
37. Rochette, P.; Angers, D.A.; Chantigny, M.H.; Gasser, M.-O.; Macdonald, J.D.; Pelster, D.; Bertrand, N. Ammonia Volatilization and Nitrogen Retention: How Deep to Incorporate Urea?. *J. Environ. Qual.* **2013**, *42*, 1635–1642. https://doi.org/10.2134/jeq2013.05.0192.
38. Zhang, C.; Che, Y.-P.; Li, Z.-P. Translocation and transformation characteristics of fertilizer nitrogen in paddy soil: A study with simulated soil column. *Chin. J. Appl. Ecol.* **2011**, *22*, 3236–3242.
39. Wu, M.; Li, G.; Li, W.; Liu, J.; Liu, M.; Jiang, C.; Li, Z. Nitrogen Fertilizer Deep Placement for Increased Grain Yield and Nitrogen Recovery Efficiency in Rice Grown in Subtropical China. *Front. Plant Sci.* **2017**, *8*, 1227. https://doi.org/10.3389/fpls.2017.01227.
40. Wang, D.; Chang, Y.; Xu, C.; Wang, Z.; Chen, S.; Chu, G.; Zhang, X. Soil nitrogen distribution and plant nitrogen utilization in direct-seeded rice in response to deep placement of basal fertilizer-nitrogen. *Rice Sci.* **2019**, *26*, 404–415. https://doi.org/10.1016/j.rsci.2018.12.008.
41. Koudjega, K.; Ablede, K.A.; Lawson, I.Y.D.; Abekoe, M.K.; Owusu-Bennoah, E.; Tsatsu, D.K. Reducing Ammonia Volatilization and Improving Nitrogen use Efficiency of Rice at Different Depths of Urea Supergranule Application. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 974–986. https://doi.org/10.1080/00103624.2019.1594880.
42. Cao, Y.; Yin, B. Effects of integrated high-efficiency practice versus conventional practice on rice yield and N fate. *Agric. Ecosyst. Environ.* **2015**, *202*, 1–7. https://doi.org/10.1016/j.agee.2015.01.001.

43. Shang, Q.; Gao, C.; Yang, X.; Wu, P.; Ling, N.; Shen, Q.; Guo, S. Ammonia volatilization in Chinese double rice-cropping systems: A 3-year field measurement in long-term fertilizer experiments. *Biol. Fertil. Soils* **2013**, *50*, 715–725. https://doi.org/10.1007/s00374-013-0891-6.
44. Colt, J. Water quality requirements for reuse systems. *Aquac. Eng.* **2006**, *34*, 143–156. https://doi.org/10.1016/j.aquaeng.2005.08.011.
45. Ip, Y.K.; Chew, S.F. Air-breathing and excretory nitrogen metabolism in fishes. *Acta Histochem.* **2018**, *120*, 680–690. https://doi.org/10.1016/j.acthis.2018.08.013.
46. Stormer, J.; Jensen, F.; Rankin, J. Uptake of nitrite, nitrate, and bromide in rainbow trout, (*Oncorhynchus mykiss*): Effects on ionic balance. *Can. J. Fish. Aquat. Sci.* **1996**, *53*, 1943–1950. https://doi.org/10.1139/cjfas-53-9-1943.
47. Pinto, W.; Aragão, C.; Soares, F.; Dinis, M.T.; Conceição, L.E.C. Growth, stress response and free amino acid levels in Senegalese sole (*Solea senegalensis* Kaup 1858) chronically exposed to exogenous ammonia. *Aquac. Res.* **2007**, *38*, 1198–1204. https://doi.org/10.1111/j.1365-2109.2007.01788.x.
48. Ye, Y.; Liang, X.; Chen, Y.; Liu, J.; Gu, J.; Guo, R.; Li, L. Alternate wetting and drying irrigation and controlled-release nitrogen fertilizer in late-season rice. Effects on dry matter accumulation, yield, water and nitrogen use. *Field Crop. Res.* **2013**, *144*, 212–224. https://doi.org/10.1016/j.fcr.2012.12.003.
49. Mei, Y.; Dong, W.; Qiang, W.; Kai, W.; Cui, K.; Huang, J. Dry Matter and Nitrogen Partitioning in Rice Genotypes Varying in Different Nitrogen Harvest Index. *Philipp. J. Crop Sci.* **2011**, *36*, 1–9.
50. Pan, J.; Liu, Y.; Zhong, X.; Lampayan, R.M.; Singleton, G.R.; Huang, N.; Liang, K.; Peng, B.; Tian, K. Grain yield, water productivity and nitrogen use efficiency of rice under different water management and fertilizer-N inputs in South China. *Agric. Water Manag.* **2017**, *184*, 191–200. https://doi.org/10.1016/j.agwat.2017.01.013.
51. Jing, J.; Zhang, F.; Rengel, Z.; Shen, J. Localized fertilization with P plus N elicits an ammonium-dependent enhancement of maize root growth and nutrient uptake. *Field Crop. Res.* **2012**, *133*, 176–185. https://doi.org/10.1016/j.fcr.2012.04.009.
52. Liu, H.; Won, P.L.; Banayo, N.P.; Nie, L.; Peng, S.; Kato, Y. Late-season nitrogen applications improve grain yield and fertilizer-use efficiency of dry direct-seeded rice in the tropics. *Field Crop. Res.* **2019**, *233*, 114–120. https://doi.org/10.1016/j.fcr.2019.01.010.
53. Kapoor, V.; Singh, U.; Patil, S.K.; Magre, H.; Shrivastava, L.K.; Mishra, V.N.; Das, R.O.; Samadhiya, V.K.; Sanabria, J.; Diamond, R. Rice Growth, Grain Yield, and Floodwater Nutrient Dynamics as Affected by Nutrient Placement Method and Rate. *Agron. J.* **2008**, *100*, 526–536. https://doi.org/10.2134/agronj2007.0007.
54. Xiang, J.; Haden, V.R.; Peng, S.; Bouman, B.A.; Huang, J.; Cui, K.; Visperas, R.M.; Zhu, D.; Zhang, Y.; Chen, H. Effect of deep placement of nitrogen fertilizer on growth, yield, and nitrogen uptake of aerobic rice. *Aust. J. Crop Sci.* **2013**, *7*, 870–877.
55. Huda, A.; Gaihre, Y.K.; Islam, M.R.; Singh, U.; Islam, R.; Sanabria, J.; Satter, M.A.; Afroz, H.; Halder, A.; Jahiruddin, M. Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. *Nutr. Cycl. Agroecosyst.* **2016**, *104*, 53–66. https://doi.org/10.1007/s10705-015-9758-6.