Research article

Controlled-release urea reduced nitrogen leaching and improved nitrogen use efficiency and yield of direct-seeded rice

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ABSTRACT

The use of controlled-release urea (CRU) has become one of best management practices for increasing crop yield and improving nitrogen (N) use efficiency (NUE). However, the effects of CRU on direct-seeded rice are not well understood while direct-seeding has gradually replaced transplanting due to increasing labor cost and lack of irrigation water. The objective of this two-year field experiment was to compare the effects of the CRU at four rates (120, 180, 240 and 360 kg N ha^{-1}, CRU1, CRU2, CRU3 and CRU4, respectively) with a conventional urea fertilizer (360 kg N ha^{-1}; U) and a control (no N fertilizer applied; CK) on yield, biomass, NUE of direct-seeded rice and soil nutrients. The results indicated that the successive release rates of N from CRU corresponded well to the N requirements of rice. The use of CRU3 and CRU4 increased rice grain yields by 20.8 and 28.7%, respectively, compared with U. In addition, the NUEs were improved by all CRU treatments compared to the U treatment. Concentrations of NO_3^--N and NH_4^+-N in the soil were increased, especially during the later growth stages of the rice, and the leaching of N was reduced with CRU treatments. In conclusion, applying CRU on direct-seeded rice increased the crops yields and NUE, increased nitrogen availability at the late growth stages, and reduced N leaching.

1. Introduction

In traditional rice production systems, rice seedlings are transplanted, a labor-intensive and high costs process (Pan et al., 2017; Song et al., 2017). It has been the trend to move from traditional rice transplanting to the direct-seeding method in recent years (Tao et al., 2016). Many new types of N fertilizers were developed to meet crop N requirements and increase crop yield and NUE (Fang et al., 2006; Yuan et al., 2016). The CRU has been strongly advocated recently because of the many advantages it brings to various crop systems (Yang et al., 2012a, 2012b; Wang et al., 2016), but not as often in direct-seeded rice systems (Shaviv, 2001; Ye et al., 2013; Zhang et al., 2016). There are also currently no studies on how CRU application influences N levels in the plough layer and N leaching after fertilizer application during the

growth period of direct-seeded rice. Most CRU fertilizers are coated with polymers which slowly release N for plant use (Chen et al., 2018; Zhou et al., 2018), thereby reducing nutrient loss while improving NUE and decreasing groundwater pollution (Yang et al., 2013; Wei et al., 2014; Wang et al., 2015).

The entire growth period of direct-seeded rice lasts about 120 days (Tang et al., 2007; Yang et al., 2012a) and the N needs of rice follow an S-shaped curve during this period of time (Peng et al., 2010; Liu et al., 2016); N demand is low during the nursery and maturity stages, and high from the tillering to milk stages (Golden et al., 2009; Chen et al., 2015; Shi et al., 2017).

To fit the gap of information on using CRUs for direct-seeded rice, a factorial experiment was conducted to compare a newly developed CRU with conventional fertilizer (urea). The specific objectives of this study

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were to 1) determine the beneficial effect of the CRU on yield and NUE of direct-seeded rice, and 2) to examine effect of the CRU on availability of nitrogen in root zone and reduction of nitrate leaching. The findings of this study demonstrate advantage of using the CRU for the production of rice, especially direct-seeded rice.

2. Materials and methods

2.1. Experimental materials

Field experiments were conducted in 2015 and 2016 at Yutai, Shandong Province, China (N35°08′, E116°53′) in a region with a long history of rice cultivation and a typical temperate monsoon climate (Fig. S1A). The soil type is classified as hydromorphic paddy soil, and the main properties of the top-layer soil (0–20 cm) were pH, 8.2 (1:2.5, soil/water); total N, 1.56 g kg^{-1}; available phosphorus, 10.56 mg kg^{-1}; available potassium, 156.32 mg kg^{-1};organic C, 18.75 g kg^{-1}; clay, 18.52%; silt, 72.62%; sand, 8.86%. The soil temperature at a depth of 15 cm ranged from 15 to 33 °C during the rice growing season in 2016 (Fig. S1B).

The rice cultivar used in this study was Runrong11 (*Oryza sativa* L.). The seeds of rice were sown directly in the soil on 17 June 2015 and 15 June 2016 at the rate of 16.5 kg ha^{-1}, and the grain was harvested on 22 October 2015 and 12 October 2016, respectively.

The CRU (42% N) was obtained from Kingenta Ecological Engineering Co., Ltd (Linshu, China). The CRU used for this experiment was coated with thermoplastic resin which was synthesized by recycle plastics (Zhang et al., 2006). Starch and other additives were added during the process of synesis of the resin to improve photodegradability and biodegradability. The N release longevity of CRU in 25 °C water was labeled at four months. Conventional urea, potassium sulfate, diammonium phosphate and monopotassium phosphate were obtained from local fertilizer distributors.

2.2. Experimental design

The experiment included a control (no N fertilizer), four rates of CRUs [120 kg N ha^{-1} (CRU1), 180 kg N ha^{-1} (CRU2), 240 kg N ha^{-1} (CRU3) and 360 kg N ha^{-1} (CRU4)] and conventional urea (U) at 360 kg N ha^{-1} with three replicates in a randomized block design. All treatments except the control received 90 kg P$_2$O$_5$ ha^{-1} as diammonium phosphate and 90 kg K$_2$O ha^{-1} as potassium sulfate prior to rice planting while the control plots received monopotassium phosphate and potassium sulfate as the basal fertilizers for same amounts of P and K. The conventional urea was split into 25% as basal fertilization, then 25% each at 20, 30 and 50 days after sowing as top dressing. The treatments of CRUs included diammonium phosphate as the starter (90 kg P$_2$O$_5$ ha^{-1} and 35 kg N ha^{-1}) and CRU as the basal fertilization. Experimental plot size was 6.00 × 3.33 m (20 m^2). Plots were separated by a ridge which was 40 cm wide and 35–40 cm high. There were 14 rows in each plot along with the rectangular width with 25 cm row spacing and a 4 cm marginal row.

2.3. Sampling and analytical methods

Soil samples and soil water samples of three depths were collected at five growth stages: seedling (20d), tillering (30d), panicle initiation (50d), milk (80d) and maturity (120d). Three soil samples in every growth stage were collected randomly from each plot at 0–20 cm. After being air-dried, ground and sieved (2.0 mm and 0.25 mm), the soil samples were extracted with 0.01 mol L^{-1} CaCl$_2$ for analyses of NO$_3^-$-N and NH$_4^+$-N using the AA3-A001-02E Auto-analyzer (Bran-Luebbe, Norderstedt, Germany) (Zhang et al., 2016).

Plant samples were gathered randomly from each plot by cutting the aboveground portion at 20, 30, 50, 80 and 120 d after seeding. Plants and grains were dried by an oven, then weighed, ground and sieved (100 mesh sieve). The Automated Chemistry Analyzer (AMS Smartchem 200, Italy) was used to test the N concentrations of plants and grains (Zhang et al., 2016). The biomass and grain yields of rice were measured by hand from the sampling plot (1 m^2). The aboveground plant N uptake was measured following the methods reported by Yang et al. (2012a). Total apparent NUE was calculated using the formula reported by Devkota et al. (2013).

Two water samplers were installed for each plot to gather the water samples from the root zone (at 20 cm soil depth) and below (at 80 cm depth), and water was extracted using a suction lysimeter from the water sampler to a 50 mL plastic centrifuge tube (Fig. S2). The flooding water was collected in 50 mL plastic centrifuge tubes from five sites randomly and mixed together in a plastic bottle in each experimental plot. Water samples were analyzed for NO$_3^-$-N and NH$_4^+$-N with the same methods as the soil samples (Yang et al., 2012a).

The release curve of CRU was tested both in laboratory and field conditions with methods described by Geng et al. (2015). A soil temperature recorder was buried in the soil at a depth of 15 cm. The surface morphologies of the CRU at two stages of nutrient release were analyzed using a scanning electron microscope (SEM, SU8010 EDS: Model 550i, Japan).

2.4. Data statistical analysis

The Statistical Analysis System package version 9.2 (2010, SAS Institute, Cary, NC) was used for the standard analysis of variance (ANOVA) and Duncan's test ($P < 0.05$).

3. Results

3.1. Release characteristics of CRU

The N nutrient release curve of CRU exhibited a steady release rate in 25 °C water, with 80.3% of supplemental N released within 120 days. Nitrogen release characteristics under the paddy field condition were slightly faster (Fig. 2), with 83.6% of N released in 120 days. The release of fertilizer was mainly concentrated in the first 90 days. In the soil, the N release rate was 21.4, 30.6, 22.7 and 9.0% on the first, second, third and last 30 days, respectively. Similar results were found in water.

After nutrient released completely in water at 25 °C, the microstructures of coating shells were characterized by SEM. Surface of the coating shell became rough and micro-holes were observed at 150 days after initiation of the release (Fig. 1).

3.2. Effects of soil N concentration under different treatments

Compared with CK treatments, the concentrations of NO$_3^-$-N in all N treatments were significantly increased at the soil depth of 0–20 cm during the two growing seasons (Table 1). At the seedling, tillering and panicle initiation stages, concentrations of NO$_3^-$-N and NH$_4^+$-N in soil treated with U and CRUs were not significantly different. The different N rates of the CRU significantly affected the mean concentrations of NO$_3^-$-N in both milk and maturity stages, and the mean concentrations of NH$_4^+$-N in maturity stage. NO$_3^-$-N concentration of CRU4 was the largest in the milk and maturity stages, NO$_3^-$-N and NH$_4^+$-N concentrations of U and CRU1 were not significantly different. There was no difference among all the treatments for NH$_4^+$-N concentration apart for the maturity stage.

3.3. Concentrations of NO$_3^-$-N and NH$_4^+$-N in soil water samples

Concentrations of NO$_3^-$-N and NH$_4^+$-N in soil water were similar for samples collected in 2015 and 2016 (Table 2). NO$_3^-$-N and NH$_4^+$-N concentrations in water samples both flooding and below (80 cm depth) zone in U treatment were significantly higher than those in CRU