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Yield Response of Upland Rice as Influenced by Enhanced-Efficiency Nitrogen Fertilizers in the Brazilian Cerrado

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Abstract

Nitrogen (N) fertilizers have their use efficiency adversely affected by the rate and source of N. A two-year field experiment was conducted to examine the yield response of upland rice by using NBPT (urease inhibitor), PCU (polymer-coated urea) and uncoated urea under different N application rates. It was hypothesized that either NPBT or PCU may result in increased yield components of upland rice when compared to conventional urea. The experiment was set up in a randomized block design in a 3 × 4 + 1 factorial scheme, with four replicates. Treatments comprised three sources (conventional uncoated urea, NBPT-treated urea, and polymer-coated urea) and four rates (30, 60, 90 and 120 kg ha^{-1}) of N, in addition to a control treatment (no fertilizer application). Nitrogen fertilizers were applied in two split doses: 50% at the seedling stage, and 50% at the tillering stage (~80 days after planting). The results revealed that the use of enhanced-efficiency N sources increased the productivity and plant height of upland rice crop when compared to conventional urea. As compared to when it is untreated or polymner-coated, treating urea with NBPT resulted in increased 100-grain weight.

Keywords: grain yield, fertilizer efficiency, *Oryza sativa* L.

1. Introduction

Rice (*Oryza sativa* L.) is one of the major food crops for more than 3.5 billion (> 50%) people in the world (CGIAR, 2016). It is a staple food in the diet of many developing countries, particularly in Asia, Latin America and Africa (Fageria et al., 2011). Based on FAO's forecasts for cereal production, 516.8 million tonnes of rice was harvested in 2019, led by China and India (FAO, 2019). Brazil s among the ten largest rice producers worldwide, accounting for 7.2 million tonnes, down 11.7% from the previous year's output because of the reduction in the planted area (FAO, 2019). The traditional methods for cultivating rice are known as upland rice and irrigated lowland rice, which are distinguished by the soil's water availability. Due to lower yield as compared with flooded rice, upland rice contributes less than 40% of total rice production in Brazil (Barbosa Filho & Yamada, 2002).

To produce high grain yields, modern rice cultivars require adequate amount of essential nutrients. Nitrrogen (N) fertilizers are extensively used by farmers to enhance rice crop production, as N is usually the most limiting nutrient except in soils containing high content of organic matter (V. B. Singh & V. K. Singh, 2017). Rice crops use 1 kg of N to produce 68 kg of grain (Witt et al., 1999). Deficiency of N in plants rapidly slows shoot growth and lead to severe nutritional disorders.

Fertilizer N-use efficiency by the crops is typically low. In general, plants assimilate less than 50% of the N applied (Tilman et al., 2002; Dobermann & Cassman, 2004), turning the N losses into a potential source of environment pollution. The supply of to crop plants comes from various sources, including native soil N crop residues, animal manure, and inorganic or mineral fertilizers (Ladha et al., 2005). In the case of rice, N fertilizers have their use efficiency adversely affected by the rate and source of N. Inadequate rate of N fertilizer application, as well as poor N management strategies lead to substantial losses of N due to inherently low N uptake capacity and absence of extensive root system in rice (Sinclair & Rufty, 2012).

The major contributors to N losses in rice systems are nitrification-denitrification, ammonia (NH_3) volatilization (Buresh et al., 2008), and to a less extent, leaching (Linquist et al., 2013). In non-flooded soils, NH_3 volatilization is of primary concern, particularly when N is applied as urea in alkaline soils. Urea is quickly hydrolysed to NH_3 and CO_2 after it is added to the soil, resulting in an increase of the soil pH and NH_4^+ around the fertilizer granule (Francis et al., 2008). Under alkaline conditions, the equilibrium of NH_3-NH_4 is shifted more to NH_3, increasing volatilization losses that lead to lower fertilizer N use efficiencies (Ladha et al., 2005).

Several approaches have been adopted for reducing N losses and enhancing the N use efficiency by the crops. The use of formulated forms of fertilizer containing urease and nitrification inhibitors to reduce NH_3 volatilization from urea hydrolysis has emerged as an effective strategy.

Urease inhibitor NBPT [N-(*n*-butyl) thiophosphorictriamide] has been reported to significantly inhibit the activity of the urease enzyme, which reduces NH_3 volatilization losses due to urea application to rice (Buresh et al. 1988; Norman et al., 2009). Polymer-coated urea (PCU) is another important alternative to uncoated urea for improving N-use efficiency since it synchronizes N release and crop N uptake with minimum side effects (Patil et al. 2010).

Many researchers have recorded significant increase in grain yield of flood rice due to combined application of either NBPT + urea or PCU + urea over application of urea alone (Dillon et al., 2012; Norman et al., 2009; Pang & Peng 2010; Rogers et al., 2015). However, only a few studies discuss their utility for lowland rice systems. Hence, a two-year field experiment was conducted to examine the yield response of upland rice by using NBPT, PCU and uncoated urea under different N application rates. It was hypothesized that either NPBT or PCU may result in increased yield components of upland rice when compared to conventional urea.

2. Materials and Methods

2.1 Experiment Site

The field experiment was carried out in two growing seasons (2013/14 and 2014/15) in an area (16°35′50″S; 49°16′40″W; 735 m a.s.l.) located in the Agronomy College at the Federal University of Goiás, State of Goiás, Brazil. The local climate is classified as Aw (seasonal tropical savanna), with a humid season from October to April and a dry one from May to September according to the Köppen classification. The average annual precipitation is 1500 mm, and the mean annual temperature is around 22.5 °C. The soil was classified as typic dystrophic Red Latosol (LVd) in the Brazilian Soil Classification System (Santos et al., 2013), which corresponded to an Oxisol in the US Soil Taxonomy System (Soil Survey Staff, 2003). Prior to characterization, soil samples were air dried and sieved through a 2-mm mesh and then analysed following methodologies as proposed by Embrapa (1997, 2009). Some selected chemical properties and particle size distribution of the top-layer soil (0-20 cm) at the beginning of the experiment in 2013 are given in Table 1.

Table 1. Selected chemical properties and particle size distribution of the soil at the experimental site

Chemical analysis									
pH ($CaCl_2$)	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}	H+Al	CEC	V	P	OM
	---------------------------- $cmol_c\ dm^{-3}$ ----------------------------						%	$mg\ dm^{-3}$	$g\ dm^{-3}$
5.58	2.15	1.05	0.312	0	2.63	6.14	57.46	4.88	17.5
Textural analysis									
Sand			Silt				Clay		
---------------------------- $g\ kg^{-1}$ ----------------------------									
450			110				440		

Note. Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted by 1 mol L^{-1} KCl; P and K were extracted by 0.05 mol L^{-1} HCl + 0125 mol L^{-1} H_2SO_4 (Mehlich-1 extractor); H+Al was extracted by 0.5 mol L^{-1} calcium acetate buffered at pH 7; CEC (cation exchange capacity): $\sum$ (K, Ca, Mg)/$\sum$ (K, Ca, Mg, H+Al) × 100; V (base saturation): $\sum$ (K, Ca, Mg)/CEC] × 100; OM (organic matter) was estimated from the organic carbon (C) extracted by the Walkley-Black method. Textual Analysis conducted using the pipette method.

2.1 Experimental Design and Treatments

The experiment was set up in a randomized block design in a 3 × 4 + 1 factorial scheme, with four replicates. Treatments comprised three sources (conventional uncoated urea, NBPT-treated urea, and polymer-coated urea) and four rates (30, 60, 90 and 120 kg ha^{-1}) of N, in addition to a control treatment (no fertilizer application).

2.3. Field Experiment

Field was ploughed at 20 cm depth prior to seeding. Plots consisted of four 5 meters long rows, spaced 0.5 m apart, using the rice cultivar BRS Esmeralda, which has a moderate resistance to major diseases and a certain tolerance to water stress (Castro et al., 2014). Additionally, BRS Esmeralda is a relatively recent upland rice cultivar developed by the breeding program coordinated by the Brazilian Corporation for Agricultural Research (EMBRAPA). The higher performance of BRS Esmeralda compared to other current cultivars is due to its high grain quality, good drought tolerance, high disease resistance and lodging resistance (Colombari Filho et al., 2013). Further, this cultivar has a great stability and adaptability to a large range of soils, climates, and crop management on the Cerrado region, wich may lead to a satisfactory yield performance in this study.

The useful area of the plot was composed of the two central rows, considering the lateral rows as borders. The soil was prepared in both years by one plowing and one disk harrow leveling. The seeds of rice were sown manually 20 cm spaced apart in rows, with two or three seeds per hole. Nitrogen fertilizers were applied in two split doses: 50% at the seedling stage, and 50% at the tillering stage (~80 days after sowing). All treatments received 400 kg ha^{-1} of the formula 00-20-20 as a basal fertilizer to supply phosphorus and potassium. Weed management consisted of hand weeding plots two times during the growing season. Rice was harvested in every growing season at the end of maturing stage (between 103 and 108 d after sowing).

2.4 Measurements

At harvest, plots were evaluated for the following yield components: plant height, which consisted in the length of the central culm; number of panicles per linear meter; 100-grain weight, which was randomly evaluated by collecting and weighing 100 fertile spikelets, and corrected to 13% of water content; and the grain yield, which was determined by weighing the harvested grain of each useful plot, corrected to 13% of the water content and converted to kg ha^{-1} as productivity.

2.5 Statistical Analysis

Data from both growing seasons were subjected to an analysis of variance. The statistical model used included sources of variation due to replication, growing season, N source, N rate and the interaction of growing season × N source, growing season × N rate, N source × N rate, and growing season × N source × N rate. For qualitative factors (growing seasons and N sources), the means were compared by the Tukey test at the $P < 0.05$ level when the F test proved significant, whereas the quantitative factors (N rates) were submitted to regression analysis. Sigmaplot 10.0 was used to create figures.

3. Results and Discussion

Statisitical analysis show the differences in plant height, number of panicles, 100-grain weight, and productivity of rice between or among growing seasons, N sources and N rates (Table 2). However, interaction effects of the factors growing season, N sources and N rates on the yield responses of upland rice were not significant ($P >$ 0.05).

Plant height significantly increased with the addition of N rates of all the three N sources (Figure 1). The increase was in a quadratic form when N rates were increased in the range of 0 to 120 kg ha^{-1}, and varied from 83 to 101cm in 2013/14, and from 85 to 102 cm in 2014/15 on average across the N rates regardless of the N sources (Figure 1). When the effect of N rates was analysed for each N source, maximum plant height was obtained with the application of N at a rate of 119 kg ha^{-1} by UU, 102 kg ha^{-1} by PCU, and 81.25 kg ha^{-1} by NBPT in the 2013/14 season. In the 2014/15 season, however, higher rates of UU (180 kg ha^{-1}), PCU (125 kg ha^{-1}) and NBPT (95 kg ha^{-1}) were needed to achieve the maximum height of rice plants. Improvements in plant height with the addition of N in rice grown on Brazilian soils has also been reported by other authors (Fageria & Santos, 2018; Fageria et al., 2011). In our study, the increase in plant height in response to the application of N rates is probably due to enhanced availability of N with all the N sources, thereby indicating that high N inputs inhibited the effect of fertilizers. In a two-growing season experiment with rice plants, Lyu et al. (2015) found the same result on the response of plant height to N sources in both seasons, and they also reported changes in the plant height by application of N up to the highest level of N.

Table 2. Analysis of variance for the yield response of upland rice (cultivar BRS Esmeralda) to the use of untreated and uncoated urea (UU), polymer-coated urea (PCU) and urease inhibitor NBPT-treated urea (NBPT) under different N application rates in two growing seasons

Source	DF	MS			
		PH	NP	100-GW	PROD
Growing season (GS)	1	174.97^{*}	537.63°	0.501^{*}	1739418.80°
N source (S)	2	136.52^{**}	603.33^{Δ}	0.301^{*}	2518689.11^{*}
N rate (R)	4	1086.48^{**}	4790.57^{**}	0.745^{**}	20169969.71^{**}
GS × S	2	16.51^{ns}	100.83^{ns}	0.020^{ns}	187314.74^{ns}
GS × R	4	4.43^{ns}	112.28^{ns}	0.051^{ns}	938235.84^{ns}
S × R	8	40.97^{ns}	69.96^{ns}	0.166^{*}	1293977.53^{ns}
GS × S × R	8	9.31^{ns}	138.23^{ns}	0.031^{ns}	186977.50^{ns}
Residual	87	27.66	138.72	0.064	453841.42
C.V.%		5.56	14.06	9.90	15.61
General mean		94.66	83.78	2.56	4316.23

Note. DF, degrees of freedom; MS, mean square; PH, plant height; NP, number of panicles; 100-GW, 100-grain weight; PROD, productivity. $^{\Delta}$, $^{\circ}$, *, **, ^{ns} significant at the 20, 10, 5 and 1% probability levels and non-significant, respectively.

Notably, a similar pattern for plant hight for all the tested fertilizers was observed in both 2013/14 and 2014/15 growing seasons, except for the conventional untreated urea (UU) in 2014/15, which led to plant height up to 4% lower than those achieved upon application of the enhanced-efficiency N fertilizers (Table 3). This finding confirmed the higher positive effect of polymer-coated urea (PCU) and urease inhibitor NBPT-treated urea (NBPT) on rice growing compared with UU.

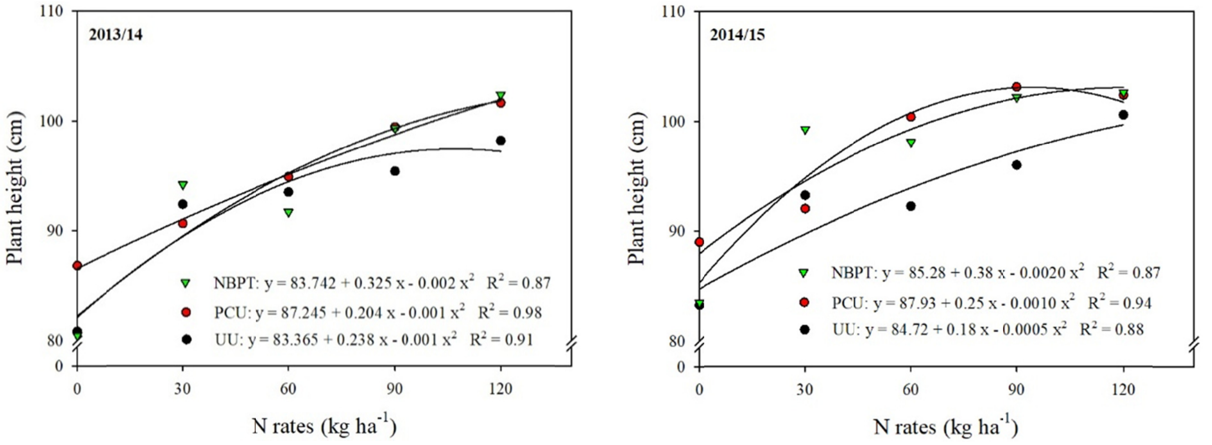

Figure 1. Plant height of upland rice (cultivar BRS Esmeralda) as a function of N rates by untreated and uncoated urea (UU), polymer-coated urea (PCU) and urease inhibitor NBPT-treated urea (NBPT) during 2013/14 and 2014/15 growing seasons

Similar to plant height, the 100-grain weights (100-GW) increased in a quadratic form with the addition of N rates by all N sources in both seasons, varyin from 2.25 to 2.55 g in 2013/14, and from 2.27 to 2.60 g in 2014/15 on average across the N rates regardless of the N sources (Figure 2). When the effect of N rates was analysed for each N source, maximum 100-GW was obtained in 2013/14 with the application of N at a rate of 50 kg ha^{-1} by UU, 69 kg ha^{-1} by PCU, and 110 kg ha^{-1} by NBPT, whereas 26 kg ha^{-1} by UU, 100 kg ha^{-1} by PCU, and 100 kg ha^{-1} by NBPT were needed to achieve the maximum 100-GW in 2014/15. Noteworthy, increasing the N application rates from 0 to 120 kg ha^{-1} did not cause expressive improvements in the rice grain weight despite its significant effect (Table 2). This finding may be attributed to the influence of some limiting factor affecting the rice grain yield, as discussed in more details bellow.

Table 3. Plant height (PH), 100-grain weight (100-GW) and productivity (PROD) of upland rice (cultivar BRS Esmeralda) affected by N fertilizers at the maturing stage during 2013/14 and 2014/15 growing seasons

Treatments	PH	100-GW	PROD
	cm	g	kg ha^{-1}
		2013/14	
UU	92.06 a	2.55 a	3858.50 b
PCU	94.69 a	2.41 a	4318.25 ab
NBPT	93.62 a	2.54 a	4410.75 a
		2014/15	
UU	93.07 b	2.73 a	4229.00 a
PCU	97.40 a	2.52 b	4416.00 a
NBPT	97.15 a	2.64 ab	4664.88 a

Note. UU, uncoated urea; PCU, polymer-coated urea; NBPT, urease inhibitor N-(*n*-butyl) thiophosphorictriamide. Means followed by the same lowercase letters in the columns are not significantly different by the Tukey test at 5% probability level.

All the three N sources produced the same grain weight in 2013/14, but they significantly affected the 100-GW in 2014/15. As such, the highest grain weights in the second rice growing season were recorded in plants fertilized with UU, followed by NBPT and PCU (Table 3). Opposite results reported that slow- or controlled-release urea compared with common urea significantly improved grain yield of maize plants owing to an increase in 1000-grain weight (Yang et al., 2017). In our study, the reason why the highest 100-GW season was found in rice plants treated with UU is unknown, since we expected that the greater plant height recorded in the the 2014/15 season with the PCU and NBPT treatmments would favor the grain weight of rice plants treated with such N sources. However, rice growth and development are mainly affected by water management (Ye te al., 2013; Xu et al., 2018) and according to Heinemann et al. (2011), the water deficit is one of the most important abiotic stress limiting upland rice yield in the Cerrado region of Brazil, where the experiments were carried out. In addition, slow-release fertilizers are highly affected by meteorological conditions in different growing seasons (Guo et al., 2016), and their effects may be weakened by adverse climate changes (Yang et al., 2018).

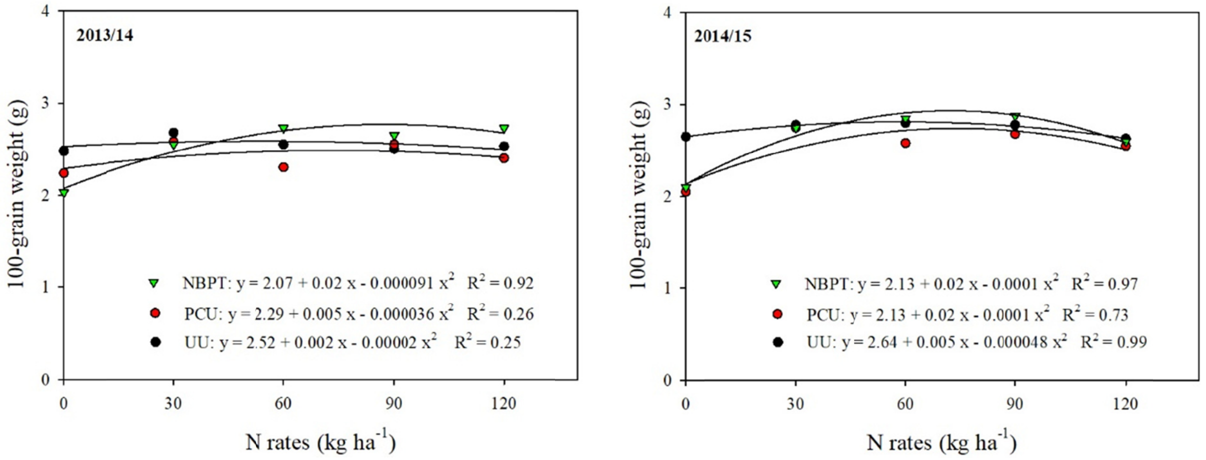

Figure 2. 100-grain weight of upland rice (cultivar BRS Esmeralda) as a function of N rates by untreated and uncoated urea (UU), polymer-coated urea (PCU) and urease inhibitor NBPT-treated urea (NBPT) during 2013/14 and 2014/15 growing seasons

Hence, we speculate that the grain weight of rice plants in our study was dependent on factors other than the N treatments, such as the water availability for the rice crop production. In a field experiment under drip irrigation and varying N rates, Xu et al. (2019) found increased rice grain yield due to an increase in the water and N use efficiency of rice with up to 50% lower N application. Yang et al. (2017) also found inconsistent effects of slow-release fertilizers on field crop production in different rice growing seasons and attributed their findings to the influence of adverse meteorological conditions. In addition, other authors reported that the supply of N has little influence on the weight of 100 grains (Arf et al., 2003; Farinelli et al., 2004; Cazetta et al., 2008; Hernandes et al., 2010; Fidelis et al., 2012), which may also explain the inconsistency in our results.

The rice productivity also increased in a quadratic form with increasing the N rates in both seasons, varying from 2713 to 4764 kg ha^{-1} in 2013/14, and from 2718 to 4640 kg ha^{-1} in 2014/15 kg ha^{-1} on average across the N rates regardless of the N sources (Figure 3). When the effect of N rates was analysed for each N source, maximum productivity was obtained with the application of N at a rate of 94 kg ha^{-1} by UU, 111 kg ha^{-1} by PCU, and 83 kg ha^{-1} by NBPT in the 2013/14 season, whereas 96 kg ha^{-1} by UU, 79 kg ha^{-1} by PCU, 76 kg ha^{-1} by NBPT were needed to achieve the maximum rice productivity in 2014/15.

The rice productivity was higher under the application of NBPT-treated urea and polymer-coated urea in comparison with the application of untreated and uncoated urea in the 2013/14 season, but no difference among N sources was observed in the 2014/15 season (Table 3). Previous studies also reported higher positive effects of controlled-release urea over conventional urea on rice crop yield (Lyu et al., 2015; Zhang et al., 2018).

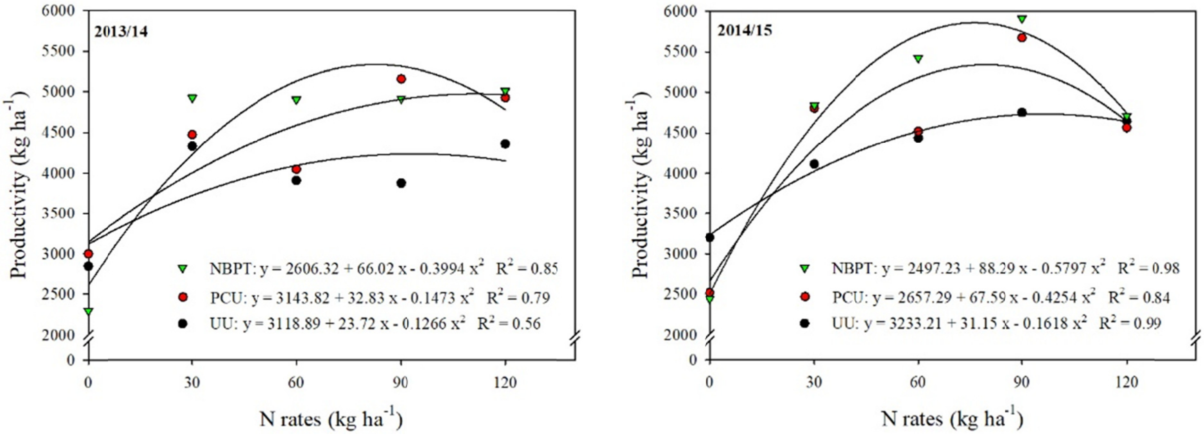

Figure 3. Productivity of upland rice (cultivar BRS Esmeralda) as a function of N rates by untreated and uncoated urea (UU), polymer-coated urea (PCU) and urease inhibitor NBPT-treated urea (NBPT) during 2013/14 and 2014/15 growing seasons

Better rice growth and production with NBPT and PCU treatments verified in our study may be attributed to the greater available N in the soil as a result of the higher N use efficiency of grain promoted by these sources. Recent reviews have been published on the mechanism of actions of enhanced efficiency fertilizers such as those used in this study (Singh, 2016; Cantarela et al., 2018). In summary, polymer-coated urea (PCU), which is produced by coating urea granules with function materials (i.e., sulphur, polyethylene, stach, and paraffin), can alleviate N loss mainly via physical obstacle caused by the functional materials coated on the surface of urea granules (Gao et al., 2015). On the other hand, the stabilized urea amended with urease inhibitor such as NBPT (N-(n-butyl)thiophosphoric triamide) can reduce NH_3 emission and increase fertilizer N retention (Li et al., 2015). Therefore, PCU and NBPT as enhanced-efficiency N fertilizers have potential to increase the N availability in the soil and benefit the crop yield (Zhang et al., 2018).

The overall trend of the 2-yr experiments indicated that the difference in rice productivities verified only in 2013/14 was due to the effective N supply by the NBPT and PCU compared with the UU. However, given the environmental conditions that possibly affected the crop growth in the second year, no differences of N sources on rice productivities were verified in 2014/15.

Noteworthy, the absorption of N by rice plants is more pronounced in two stages throughout the cycle: at the beginning of tillering and floral primordium. In our study, the application of the basal (10-30 kg ha^{-1}) and cover (20-70 kg ha^{-1}) fertilizations at the time of sowing and tillering, respectively, as recommended by Embrapa (2009) may also have contributed to the absence of a higher significant difference between the N sources for rice productivity.

4. Conclusion

The use of enhanced-efficiency N sources increased the productivity and plant height of upland rice crop when compared to conventional urea.

As compared to when it is untreated or polymner-coated, treating urea with NBPT resulted in increased 100-grain weight.

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