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A practical approach for assessing the efficiency of coated urea on controlling nitrogen availability

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ABSTRACT: We propose an approach for assessing the efficiency of coating materials on controlling nitrogen (N) availability to plants. It is based on the use of coated and soluble urea (UR) applied to corn over 3 growing cycles, as follows: coated UR with longevity of 2 (UR-2m) or 4 months (UR-4m) with application of 900 mg N·pot^{-1} at the beginning of the experiment, soluble UR with a split application of 900 mg N·pot^{-1} (300 mg N·pot^{-1} per growing cycle, UR-3x), soluble UR with a sole application of 900 mg N·pot^{-1} at the beginning of the experiment (UR-1x), and a control treatment. At the end of each growing cycle, shoots were harvested to estimate N provision by the UR by quantifying dry matter (DM) and N uptake. In the first cycle, UR-2m and UR-4m promoted lower plant growth and N accumulation in shoots than UR-1x. However, in the third cycle, higher shoot N uptake and DM production was recorded in UR-4m than in UR-1x. Furthermore, fertilizer contribution for shoot N uptake in UR-4m plants was higher than those in UR-1x and UR-2m at the end of the experiment. Accordingly, consecutive growing cycles combined with forms of soluble UR application were able to characterize the pattern of N release from coated fertilizers, being, thus, a suitable method to evaluate the efficiency of such products. We argue that our practical approach could be used by the industry in fertilizer quality programs and to register fertilizer coating materials by regulatory agencies.

Key words: coating, fertilizer efficiency, nitrogen fertilizer, nutrient uptake.

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As a result of the significant loss of nitrogen (N) following soil fertilizer application, a number of management strategies have been proposed to improve N fertilizer efficiency in agricultural systems (Kraiser et al. 2011; Shamsuzzaman et al. 2016). In this context, the use of coated fertilizers, which control the solubilization of granules and minimize the risks of leaching by reducing the concentration of N in the soil solution, has demonstrated to be an efficient alternative to enhance N recovery by the plants (Shoji et al. 2001; Zvomuya et al. 2003; Han et al. 2009). Coated fertilizers are produced from granules of soluble sources by coating their surfaces with compounds that retard the release of nutrients to the external medium (Pérez-García et al. 2007; Azeem et al. 2014). Such a process is controlled by the difference in water potential between the external environment and the interior of the capsule (Zhang et al. 1994) and also by the type of material, its thickness, and the number of orifices in the coating surface (Shaviv 2001; Azeem et al. 2014).

Since coated fertilizers are a suitable strategy for improving the sustainability of agricultural production by increasing the recovery of N-applied fertilizers (Fan et al. 2004; Morgan et al. 2009), there is a practical need to improve the understanding of how different coating materials influence the dynamics of nutrient release to plants. Indeed, there are uncertainties regarding the time period required for the granules to solubilize, which might contribute to growers less frequently use coated fertilizers (Medina et al. 2008). It could be argued that one of the reasons behind such a limitation is the lack of suitable methods to assess these fertilizers, as the evaluations conducted under laboratory conditions (Shaviv et al. 2003; Liang and Liu 2006) do not take into account the fertilizer interaction with the soil and also the role of plant roots acting as a sink for nutrients. Although studies in the field have been able to demonstrate differences in N provision to plants between coated and soluble fertilizers (Fan et al. 2004; Han et al. 2008), the complexity of factors driving N availability in soils limits the extrapolation of the results. Therefore, pot-based studies arise as a suitable alternative to fertilizer industry and regulatory agencies to evaluate the efficiency of coating materials in controlling the nutrient supply to crop plants.

We accordingly propose a practical approach to characterize the pattern of nutrient release from coated fertilizers compared with a soluble source by using coated urea (UR) with polymers of distinct longevity (2 and 4 months) as a fertilizer model. Our method was based on a practicable evaluation of N availability in the soil over time by quantifying growth and N uptake in plants using sequential shoot harvests during consecutives growing cycles under controlled conditions.

The experiment was conducted in an unshaded greenhouse with an average air temperature ranging between 19 and 35 °C during summer months. We used an Oxisol soil, which was collected at a layer of 0 – 0.25 m, sieved and air-dried. Chemical soil analysis determined according to van Raij et al. (2001) indicated: organic matter = 25 $g \cdot dm^{-3}$; pH $CaCl_2$ 0.01; M = 6.0; P = 40 $mg \cdot dm^{-3}$; K = 3.1; Ca = 59; Mg = 18 and H + Al = 19 $mmol_c \cdot dm^{-3}$. The soil physical characterization was based on Camargo et al. (1986) and revealed the following results: clay = 390, silt = 71 and sand = 539 $g \cdot kg^{-1}$.

Three consecutive growing cycles of corn, each one lasting 40 days, were performed over the experimental period. The pots received 5.5 kg of soil after being mixed with nutrients in the following rates ($mg \cdot pot^{-1}$): 900 P; 600 K; 600 Ca; 300 Mg; 180 S; 10 Zn; 3 Mn; 10 Cu and 1.3 B. At the beginning of the second and third growing cycles, 200 and 300 $mg \cdot pot^{-1}$ of P and K, respectively, were applied at the soil surface in the form of a solution of KH_2PO_4 and KCl. The pots were irrigated daily with deionized water to maintain soil moisture at 85% of the water field capacity.

We used, as a fertilizer model to test the proposed method, UR coated with synthetic polymer (Multicote®, Haifa, Israel) of distinct thicknesses, which determined the contrasting longevities of 2 (UR-2m) and 4 months (UR-4m). The 5 evaluated treatments corresponded to application of 900 mg $N \cdot pot^{-1}$ in different forms (sole or split application) and sources of UR (coated or soluble uncoated), as follows: UR-2m or UR-4m with a sole application of 900 mg $N \cdot pot^{-1}$, soluble UR with a split application of 900 mg $N \cdot pot^{-1}$ (300 mg $N \cdot pot^{-1}$ per growing cycle, UR-3x), soluble UR with a sole application of 900 mg $N \cdot pot^{-1}$ (UR-1x), and a control (no N fertilization). The UR sources were mixed into the entire soil volume of each pot at the beginning of the experiment, except for UR-3x, for which the UR was applied as a solution (300 mg $N \cdot pot^{-1}$) immediately after sowing the corn in the second and third growing cycles. The experimental →

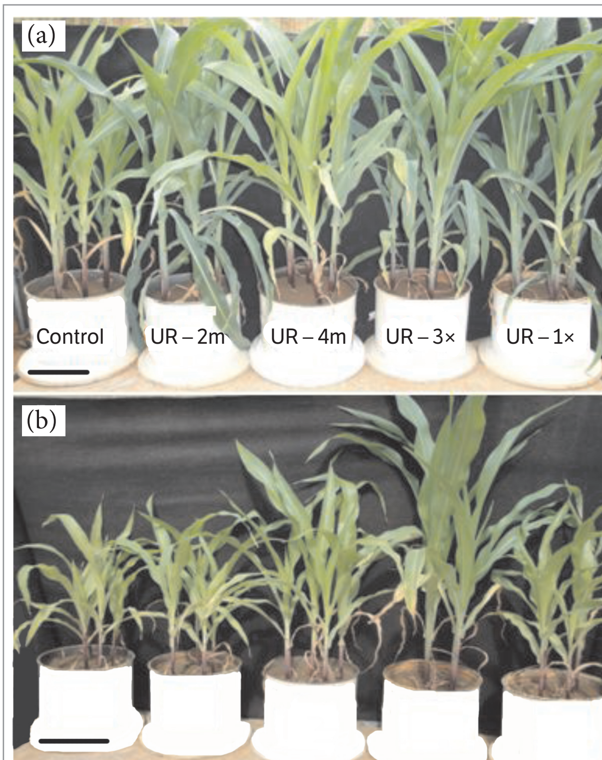
design consisted of randomized blocks with 4 replicates (one 6-L pot with 4 corn plants) totaling 20 pots.

In order to estimate the provision of N fertilizer by UR, the shoots of the plants were cut at soil level at the end of each growing cycle. However, the root system was collected only at the end of the third cycle in order to avoid damage to the coated UR granules during soil sieving. After being harvested, the plant parts were washed and dried at 65 °C for 72 h to further quantify dry matter (DM) production. The N concentration in the plant tissues was determined according to Bataglia et al. (1983), and the accumulation of N in shoots and roots was obtained from the product between the concentration of the nutrient and the respective DM production. The recovery of N applied via UR was estimated in each growing cycle as the difference in shoot N accumulation in the treatments that received UR and the control plants.

The data were subjected to analysis of variance (ANOVA); when the F-test revealed a significant ($p < 0.05$) effect of the evaluated treatments, we compared the means using the Duncan's multiple range test ($p < 0.05$). All analyses were performed with SAS program package (Version 9.2, SAS Institute).

The control treatment exhibited the lowest shoot DM production over the experimental period, except in the comparison with UR-1x in the third growing cycle (Table 1 and Figure 1). This result confirms that the soil was N-limited and, therefore, suitable for evaluating how coating materials affect N availability to plants.

In the first growing cycle, the UR-1x treatment gave the highest shoot DM production, whereas shoot DM of UR-2m plants was higher than that of UR-4m and UR-3x plants (Table 1 and Figure 1). In the second growing cycle, no significant difference was found in shoot DM of corn plants treated with any forms of UR. However, in the third growing cycle, the UR-3x treatment resulted



Control = Absence of fertilization with N;
UR-2m = Coated urea of 2 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1});
UR-4m = Coated urea of 4 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1});
UR-3x = Soluble urea with a split application of 900 mg N·pot^{-1} (300 mg N·pot^{-1} at the beginning of each growing cycle);
UR-1x = Soluble urea with a sole application at the beginning of the experiment (900 mg N·pot^{-1}). Bar = 15.0 cm.

Figure 1. Overview of corn plants growth as affected by source and form of urea application at the end of the first (a) and third (b) growing cycles.

Table 1. Shoot dry matter and root dry matter production (g·pot^{-1}) of corn plants over 3 growing cycles as affected by source and form of urea application.

Treatments	1º cycle	2º cycle	3º cycle	Root DM(1)	Total DM accumulated
	Shoot DM				
Control	25.3 d	4.8 b	5.4 d	11.7 c	47.3 c
UR-2m	35.8 b	18.1 a	7.8 c	18.2 b	79.9 b
UR-4m	31.0 c	17.1 a	12.7 b	27.9 a	88.9 ab
UR-3x	31.0 c	20.4 a	21.4 a	20.0 b	92.7 a
UR-1x	40.2 a	19.6 a	6.7 cd	14.6 bc	81.0 b

The averages followed by the same letters in the same column do not differ by Duncan's test at $p < 0.05$. (1)The results of root dry matter were obtained at the end of the experiment after 3 growing cycles. DM = Dry matter; Control = Absence of fertilization with N; UR-2m = Coated urea of 2 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1}); UR-4m = Coated urea of 4 months with a sole application at the beginning of the experiment (900 mg N ·pot^{-1}); UR-3x = Soluble urea with a split application of 900 mg N·pot^{-1} (300 mg N·pot^{-1} at the beginning of each growing cycle); UR-1x = Soluble urea with a sole application at the beginning of the experiment (900 mg N·pot^{-1}).

in the highest shoot DM production. Additionally, when we compared the sources of coated UR, the shoot DM was 63% higher in the treatment with UR-4m than that with UR-2m. At the end of the experiment, we found the highest root DM production occurring in the UR-4m treatment followed by those amended with UR-3x and UR-2m (Table 1). Concerning total plant DM produced (shoot plus root) during the experimental period, UR-3x had similar values compared to UR-4m but a higher total DM production than UR-1x and UR-2m (Table 1).

In the first growing cycle, the highest and lowest concentrations of N in the shoots were found in UR-1x and control plants, respectively (Table 2). In addition, the use of UR-2m resulted in a greater shoot N concentration than that found in UR-4m and UR-3x plants. In general, the variations in shoot N concentration were much less pronounced in the remaining growing cycles. For the root system, we did not detect any difference in N concentration among the tested treatments at the end of the experiment (Table 2).

Shoot N accumulation was the lowest and the highest in the control and UR-1x plants, respectively, during the first growing cycle (Table 3). Furthermore, when we compared the 2 sources of coated UR, we observed a greater accumulation of N in the UR-2m shoots than in the UR-4m shoots. However, in the second growing cycle, with respect to shoot N content, we only detected differences between UR treatments and no N fertilization, regardless of the source and form of fertilization. In the last growing cycle, the effect of a split application of UR and the use of coated UR were more pronounced, being found in the following order: UR-3x > UR-4m > UR-2m > UR-1x = control. In the root system at the end of the experiment, the UR-4m plants exhibited the highest accumulation of N and the UR-1x and control plants, the lowest (Table 3). Treatment UR-1x presented the greatest total N accumulated (shoot plus →

Table 2. Concentration of nitrogen (g·kg^{-1}) in the shoot and root system of corn plants over 3 growing cycles as affected by source and form of urea application.

Treatments	1º cycle	2º cycle	3º cycle	Root system[1]
	Shoot			
Control	9.2 d	10.6 b	8.9 bc	11.2 a
UR-2m	17.8 b	11.9 ab	9.1 bc	11.4 a
UR-4m	11.8 c	13.4 a	9.4 b	12.5 a
UR-3x	12.1 c	10.7 b	11.3 a	11.1 a
UR-1x	19.5 a	10.6 b	8.1 c	11.2 a

The averages followed by the same letters in the same column do not differ by Duncan's test at $p < 0.05$. [1]The results of root N concentration were determined at the end of the experiment after 3 growing cycles. Control = Absence of fertilization with N; UR-2m = Coated urea of 2 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1}); UR-4m = Coated urea of 4 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1}); UR-3x = Soluble urea with a split application of 900 mg N·pot^{-1} (300 mg N·pot^{-1} at the beginning of each growing cycle); UR-1x = Soluble urea with a sole application at the beginning of the experiment (900 mg N·pot^{-1}).

Table 3. Accumulation of nitrogen (mg·pot^{-1}) in the shoot and in the root system of corn plants over 3 growing cycles as affected by source and form of urea application.

Treatments	1º cycle	2º cycle	3º cycle	Root system[1]	Total N accumulated
	Shoot				
Control	230.4 d	50.5 b	48.9 d	130.9 c	460.7 c
UR-2m	635.7 b	215.4 a	71.4 c	207.7 b	1,130.3 ab
UR-4m	365.8 c	229.5 a	119.1 b	349.9 a	1,063.2 b
UR-3x	375.5 c	219.3 a	240.9 a	218.7 b	1,054.3 b
UR-1x	783.6 a	207.8 a	53.9 d	163.4 c	1,209.1 a

The averages followed by the same letters in the same column do not differ by Duncan's test at $p < 0.05$. [1]The results of root N accumulation were obtained at the end of the experiment after 3 growing cycles. Control = Absence of fertilization with N; UR-2m = Coated urea of 2 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1}); UR-4m = Coated urea of 4 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1}); UR-3x = Soluble urea with a split application of 900 mg N·pot^{-1} (300 mg N·pot^{-1} at the beginning of each growing cycle); UR-1x = Soluble urea with a sole application at the beginning of the experiment (900 mg N·pot^{-1}).

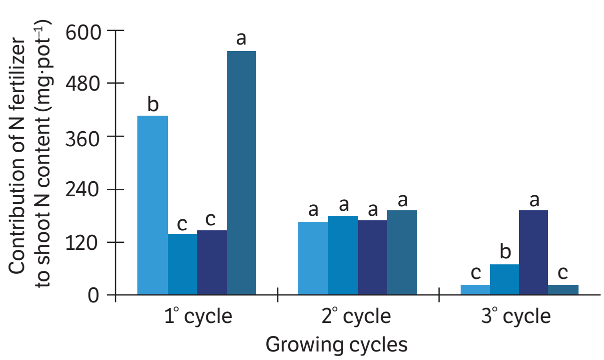
root) at the end of the experiment, excepted when it was compared with UR-2m (Table 3).

The estimated contribution of the fertilizers to N accumulation in the corn shoots revealed a significant effect of the UR sources (Figure 2). For instance, in the first growing cycle, the fertilizer contribution to the N accumulated in the corn shoots was lower for UR-4m and UR-3x plants compared with the UR-2m and UR-1x plants. Conversely, by the last growing cycle, the highest fertilizer contribution was obtained with the UR-3x plants; furthermore, the value found with UR-4m was higher than with both UR-1x and UR-2m plants. Based on the amount of N (900 mg N·pot^{-1}) added in a sole application and the contribution of N fertilizer to shoot N content (Figure 2), the apparent recovery of N fertilizer in the first, second, and third cycles corresponded, respectively, to: 45; 18; and 3% for UR-2m; 15; 20 and 8% for UR-4m and 62; 22 and 2% for UR-1x.

The use of coated N fertilizers has been advocated as an important management strategy to improve N use efficiency in agricultural systems, since they might minimize the risks of N losses and, therefore, increase plant nutrient uptake (Drost et al. 2002; Chen et al. 2008; Hyatt et al. 2010; Carson et al. 2014). However, achieving this goal depends on the capability of the coating material to control the release of nutrients to the plants after soil application. Therefore, a critical step before coated N fertilizers are recommended for field plants is to determine how the coating material influences the release of nutrients. In this context, we conducted our study aiming to establish a practical approach to evaluate the efficiency of coated N fertilizers in controlling the solubilization of granules and nutrient availability to plants. A UR coated with synthetic polymer was used as a fertilizer model to answer the following question: Can a coated fertilizer modify the dynamics of N release to plants compared with a soluble source? We accordingly defined our treatments to compare the growth and N uptake of corn plants over time that received either coated or soluble UR.

According to the obtained results, it was clearly demonstrated that the approach presented here was able to characterize the role played by coated UR on modulating the dynamics of N solubilization from the granules and the N available to plants compared with uncoated UR. For instance, the coated UR released more N than the untreated soil did but less than the UR-1x treatment after 40 days of fertilizer application, as suggested by the higher growth, shoot N concentration, and accumulation of UR-1x plants. Furthermore, there was also a higher contribution of N fertilizer for the nutrient accumulated in the shoots of UR-1x plants compared with UR-4m and UR-2m plants during the first growing cycle. Therefore, our results confirmed that coating the granules with synthetic polymers has a positive effect on increasing the residual effect of soil-applied N fertilizers (Cabrera 1997; Dou and Alva 1998). In terms of a more specific comparison between the coated UR sources, we observed that the coating longevity also influenced N availability to the plants. In the last growing cycle, the highest values of DM production, N concentration, and shoot accumulation occurred for the UR-4m treatment compared to the UR-2m one. This reflected a longer residual effect for the former source, which is most likely due to differences in the coating thickness (Byung-Su et al. 1996; Azeem et al. 2014).

In conclusion, the treatments proposed in our study (i.e. a combination of consecutive growing cycles of corn with either a sole or split application of a soluble fertilizer source) coupled with the quantification of both shoot growth and N accumulation in a crop with early growth



UR-2m = Coated urea of 2 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1});
UR-4m = Coated urea of 4 months with a sole application at the beginning of the experiment (900 mg N·pot^{-1});
UR-3x = Soluble urea with a split application of 900 mg N·pot^{-1} (300 mg N·pot^{-1} at the beginning of each growing cycle);
UR-1x = Soluble urea with a sole application at the beginning of the experiment (900 mg N·pot^{-1}).
Columns followed by the same letters within a growing cycle do not differ by Duncan's test at $p < 0.05$.

Figure 2. Estimated contribution of nitrogen (N) fertilizer to the total amount of nutrient accumulated in the shoots of corn in 3 growing cycles.

vigor were adequate to differentiate N release from coated and soluble fertilizer sources over time. We accordingly propose that such practicable procedures could be used to evaluate the efficiency with which coated N fertilizers control nutrient availability to plants. We also argue that the proposed method is suitable for adoption by the industry in their fertilizer quality program and for registering fertilizer coating materials by regulatory agencies, even though some adjustments (i.e. number of growing cycles) might be necessary depending on the longevity of the coating material. Indeed, to the best of our knowledge, this research is the first proposal toward the implementation of standardized procedures to evaluate the quality of soil-applied coated N fertilizers in Brazil. Therefore, it might also contribute to provide information to direct further studies on this issue and to improve recommendations for the use of coated fertilizers by growers.

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