



RESEARCH ARTICLE

Nitrogen release from different polymer-coated urea fertilizers in soil is affected by soil properties

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Abstract

The use of urea as nitrogen (N) fertilizer in agriculture needs to consider environmental, economic and resource conservation aspects because of low N-use efficiency (NUE). Polymer-coated urea (PCU) offers an effective way to improve the NUE of urea and to reduce its environmental trade-offs. However, we lack information on the impact of climate and soil properties on N release from PCU. Therefore, this study was performed to quantify the effects of soil texture, moisture and temperature on the release kinetics of N from PCU. We designed a test system for soil incubation experiments and investigated three fertilizers with different release patterns, five topsoils, three moisture levels and two temperatures over 48 days. We analysed the concentrations of inorganic N (NH_4^+ – N and NO_3^- – N) in the soil and estimated N release rates using the unified Richards model. Soil texture did not change the N release patterns, but release rates varied significantly among the investigated soils. Changes in soil moisture for a given soil had no effect on N release from PCU and urea when fertilizers were incorporated into the soil at conditions supportive of crop growth. Lowering soil temperatures, however, decreased N release rates from PCU by 16%–49% but only in silt loam and not in sandy loam. We conclude that PCU improves the N residence time in soil, but predictions on N release from PCU must be adapted to the prevailing environmental conditions and cannot be generalized across differently textured soils.

KEYWORDS

controlled-release fertilizers, moisture, Richards model, soil texture, temperature

1 | INTRODUCTION

The worldwide consumption of synthetic nitrogen (N) fertilizers amounted to 104 Tg in 2018 (IFA, 2021). Urea is the most frequently used synthetic N fertilizer (47%), because of its high N concentration (46%) and low cost (Fan

et al., 2004; IFA, 2021). However, the N-use efficiency (NUE) from urea by the crops is low, ranging between 30% and 65% of the applied N (Herrera et al., 2016; Hirel et al., 2011; Ladha et al., 2005; Omara et al., 2019). This is because a large proportion of the N from urea is released immediately after application and is not in phase with

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the N uptake of seasonal crops (McKenzie et al., 2007; Trenkel, 2010). The imbalance results in potential N losses of up to 70% for urea applications (Fan et al., 2004; Naz & Sulaiman, 2016), particularly from ammonia (NH_3) volatilization and nitrate (NO_3^-) leaching (Azeem et al., 2014; Blaylock et al., 2005; McKenzie et al., 2007). Consequently, the use of conventional urea as fertilizer causes not only environmental but also economic and resource conservation problems.

The use of a controlled-release technology may offer an effective way to improve the NUE from conventional urea and to reduce its environmental impacts (Chen et al., 2018; Naz & Sulaiman, 2016). The most common controlled-release fertilizers (CRFs) encapsulate urea granules with hydrophobic materials, particularly polymeric ones, to restrict N dissolution rates (Chen et al., 2018; Trenkel, 2010). The coating material acts as physical barrier and controls the N release into the soil solution in three stages: a lag period, followed by a stage of constant N release, and finally by a stage of declining release (Naz & Sulaiman, 2016; Shaviv et al., 2003; Trenkel, 2010). During the initial lag period, water penetrates through the coating membrane and dissolves small fractions of the urea core without any observable N release (Du et al., 2006; Shaviv et al., 2003). The stage of constant release follows when a critical volume of urea-saturated solution has accumulated in the granules, therewith inducing a constant urea transport through the coating material by diffusion (Du et al., 2006; Shaviv et al., 2003). The final decline phase is reached when the solid urea core is dissolved so that the N release rates decrease (Shaviv et al., 2003). Overall, plant-available N is thus released over a prolonged period of time with a higher chance to match the N requirements of crops (Cahill et al., 2010; Shaviv et al., 2003; Trenkel, 2010). Because of diverse polymer properties, it is theoretically possible to adapt N release profiles to individual crop demands (Terlingen et al., 2020). However, the use and entry of PCU into the global fertilizers market is still limited, for example, as the cost of PCU is still two to three times higher than that of conventional urea, despite extensive research during the last five decades. Also, missing regulatory opportunities for registration limited acceptance in European Union.

Several studies have characterized the N release from PCU in the laboratory or their impact on crop growth in the field. When evaluating PCU, it is common practice to measure the N release in water (Shaviv et al., 2003; Trenkel, 2010). A standard method in water is provided, for instance by the ISO 21263:2017. There is, however, no standard method available for the determination of N release in soil. N release curves have been characterized by using models following empirical, semiempirical or

mechanistic approaches (Fujinuma et al., 2009). However, field studies show conflicting results on the effects of PCU. Yields were higher, unchanged or even lower in response to PCU than achieved with conventional urea (Azeem et al., 2014; Blackshaw et al., 2011; Grant et al., 2012; McKenzie et al., 2007). This uncertainty might originate from N release patterns that were predicted from laboratory experiments in water but do not sufficiently account for soil and other environmental parameters. Our current knowledge on the impact of environmental drivers on N release kinetics from PCU and subsequent transformations of inorganic N in soil is still incomplete (Azeem et al., 2014; Chen et al., 2018; Guertal, 2009).

Here, we aimed at first characterizing the typical release patterns of conventional urea and two types of PCU within different release rates. We designed a test system suitable for soil incubations and used a uniform parameterization of the Richards model to describe the inorganic N release from PCU. Second, we determined the influence of soil texture, moisture and temperature on the N release kinetics. We conducted incubation experiments with three fertilizers, five topsoils, three moisture and two temperature levels. During the experiments, we recorded soil respiration and analysed the inorganic N release from PCU fertilizers into soil by determination of plant-available $\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$ concentrations. The experiments were conducted during 48 days to cover the vegetative growth stages of seasonal crops since the majority of N reserves are established in vegetative tissues at pre-anthesis.

2 | MATERIALS AND METHODS

2.1 | Soils and sampling sites

Five soils were selected to cover a wide range of soil textures that are typical for arable topsoils in the temperate climate zone (Table 1). To identify frequent soil textures at German, European and global scales, we used the databases of the Soil Information System FISBo BGR (Fachinformationssystem Boden der BGR; Düwel et al., 2007), the LUCAS project (Land Use and Coverage Area frame Survey; Ballabio et al., 2016) and the GLDAS (Global Land Data Assimilation System; Rodell et al., 2004), respectively. The soils were collected from sampling sites in the German federal states of North Rhine-Westphalia and Rhineland-Palatinate. Topsoil samples were collected from each site at a depth of 0.1–0.3 m to avoid too many plant residues in the sampled soil. The soils were air-dried and homogenized by sieving to <2 mm. The texture of the soils was determined according to FAO (2006), the $\text{pH}_{(\text{CaCl}_2)}$ according to

TABLE 1 Soil properties of the five soils used for the experiments.

Soil texture		Sand (%)	Silt (%)	Clay (%)	SOC (%)	C/N	pH _(CaCl₂)	WHC (%)
SL	Sandy loam	75.5	11.8	12.8	1.3	10.8	5.1	45.7
L	Loam	25.8	48.4	23.9	1.4	10.9	6.0	70.5
SIL	Silt loam	17.3	60.0	20.9	1.6	11.2	6.5	52.5
SiCL	Silty clay loam	13.5	52.5	34.0	1.2	9.6	6.2	61.4
CL	Clay	30.7	18.1	50.2	2.7	9.5	7.0	79.0

Abbreviations: C/N, carbon/nitrogen ratio; SOC, soil organic carbon; WHC, water-holding capacity.

ISO 10390:2005, the soil organic carbon (SOC) concentration and the C/N ratio according to ISO 10694:1995 and ISO 13878:1998, respectively (Table 1). The water-holding capacity (WHC) was determined according to Alef and Nannipieri (1998), by percolating 100 mL of deionized water through 20 g of air-dried soil (with a known residual water content) in duplicate. Samples were allowed to stand overnight (covered by aluminium foil) and the volume of the water stored in the soil was calculated and related to soil dry weight.

2.2 | Experimental design and materials

We investigated four treatments comprising an unfertilized control (CON), conventional urea (URE) and two different PCU fertilizers (PCU2, PCU17). The PCU2 fertilizer was coated with a biodegradable polymer and released 80% of its N within 2 days in water. The PCU17 fertilizer was coated with a less permeable and non-biodegradable polymer. The release time was substantially higher, and 17 days were needed to release 80% of its N in water. The fertilizers were provided by EuroChem Agro GmbH. The release time of N from the fertilizers in a water system was also obtained from EuroChem Agro GmbH (data were determined in a modified test system based on ISO 21263:2017). All fertilizers were applied at a rate of 105 mg N per sample (100 g soil), which corresponds to 1.05 g N kg⁻¹. Assuming that the fertilizer covers a layer of 2 cm soil within the Ap horizon with an average bulk density of 1.2 kg dm⁻³, this amount translates into a N fertilization rate of 250 kg N ha⁻¹, which is common for crops such as wheat.

We designed a test system to determine N release from different PCU fertilizers in soil. This allowed us to study the effect of soil texture on N release under conditions that are closer to field conditions than existing standards like the ISO 21263:2017, which describe a procedure for determining the release of nutrients from coated fertilizers into water. For the incubation, we used straight-side, wide-mouth polypropylene jars with a volume of 250 mL (Thermo Fisher Scientific) that are compatible with the respirometer Respicond VIII (Nordgren Innovations AB).

100 g of air-dry soil was placed in sealed jars and incubated in the dark at varying water contents and temperatures, according to the test conditions described in the following sections. The jars were opened every second to third day (depending on soil respiration) to ensure air exchange and to maintain a constant water content by weighing the sample and adding the lost mass of water between two openings (only deionized water was used in the whole experiment). A pre-incubation period of 9 days was set to compensate for the rewetting effect in soil causing a flash increase in the basal respiration and mineralization. After 9 days, the N fertilizers were added to the samples by placing strainer inserts (made of polyvinyl chloride) into the jars. The strainers were filled with approximately one third of the soil and the granules (ensuring that the granules were completely covered by soil). This facilitated the removal of granules but ensured their connection to the soil-water system. The samples were prepared in sets of triplicates, one set for each treatment and extraction day since the entire sample was extracted. The samples sets were randomized and incubated for 0, 1.5, 3, 6, 12, 24 and 48 days in an incubation chamber. The sample sets for extraction day 48 were prepared twice. One was incubated within the incubation chamber and the other one in the respirometer to determine respiration rates of the soils as a measure of microbial activity during the experimental.

2.2.1 | Testing effects of soil texture

The N release from PCU into soils was investigated for five different soil textures incubated at an average temperature of 21°C. As soil texture modifies the water-filled pore space, we tried to incubate the soils in moist state, close to 50% of the WHC. However, the sample preparation including drying and sieving altered the aggregate structures of the soils. As a consequence, the structural stability of the soil was reduced and additional dispersion was observed from adding de-ionized water so that silting and clumping occurred when the experiment was prepared. This would have affected the incubation experiments negatively regarding oxygen level and fertilizer handling. Therefore, the water content was adjusted as close as possible to 50%

of the individual WHC of the soils without visual deterioration of soil structure and thus without affecting soil conditions negatively. Deionized water was added to the soils to achieve the following percentages of WHC: 35% for the sandy loam, 33% for the loam, 45% for the silt loam, 38% for the silty clay loam and 44% for the clay, which corresponded to gravimetric water contents between 22% and 40% w/w. To account for these variations, we tested the effects of soil moisture individually for the given soils and included soil moisture variations as covariate in the subsequent data evaluation. We observed, however, a slight formation of aggregates upon rewetting for the silty clay loam and the clay soil, which was owing to the high clay content of these soils.

2.2.2 | Testing effects of soil moisture

To investigate the influence of soil moisture on N release selectively, soils were incubated at an average temperature of 21°C with three water contents. We selected the silt loam as a medium textured soil with a high WHC and the sandy loam as coarse soil with a low WHC. The permanent wilting points for these soils were 15% (sandy loam) and 25% (silt loam) WHC. For the sandy loam, water contents were set to (a) 22%, (b) 28% and (c) 35% of WHC and for the silt loam to (a) 32%, (b) 38% and (c) 45% of the WHC.

2.2.3 | Testing effects of soil temperature

We conducted an experiment to determine the effect of soil temperature on the N release from PCU. For this purpose, the sandy loam at 35% WHC and the silt loam at 45% WHC (corresponding to gravimetric moisture contents of 25% and 40% w/w, respectively) were incubated at 16°C to be able to compare them with the samples incubated within the first experiment on soil texture at 21°C.

2.3 | Sample extraction and chemical analyses

After incubation, the plant-available N (N_{min}) was determined in the soil samples as sum of the $\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$ concentrations. Before extraction, the granules were manually removed and counted ($n=9$) to ensure complete removal from samples. After homogenization of samples, aliquots of 25 g moist soil were extracted with K_2SO_4 solution (1%) at a soil: solution ratio of 1:8 mainly according to ISO 14256-1:2005. Extracts were filtered (M&N G 261 ¼) and stored at -21°C until further analysis. The inorganic N concentrations ($\text{mg NO}_3^- - \text{NL}^{-1}$ and

$\text{mg NH}_4^- - \text{NL}^{-1}$) in soil extracts were measured according to ISO 14256-2:2005 by continuous flow analysis (CFA) using high-resolution colorimetry and photometric detection (Skalar, San++).

2.4 | Data evaluation and statistics

To determine the net N release from fertilizers, the $\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$ concentrations in the control soil were subtracted from concentrations in soils treated with fertilizers. This was done for each extraction day and fertilizer. The net release was then expressed as percentage of the total N released as inorganic N.

To describe the N release from fertilizers, we applied a unified approach of the Richards model that was introduced by Tjörve and Tjörve (2010) for the assessment of organismal growth. Another parameterization of the Richards model was used by Hara (2000) to characterize N release patterns from PCU at constant temperatures. However, the parameterization according to Hara (2000) was difficult to interpret and compares fertilizers that showed differently shaped release curves (i.e. simple saturation and asymptotic sigmoid curves). We therefore adopted the unified approach for modelling of the N release curves from different fertilizers as it allows for the comparison of parameters between differently shaped curves without the need for a conversion.

The function of the unified Richards model after Tjörve and Tjörve (2010) is given in Equation (1), where $W(t)$ is the value of the released N, A is the upper asymptote (endpoint or maximum of net N release), W_0 is the starting value at time zero, k is the slope at the inflection point (which is the point of maximum N release rate), and d is the shape parameter of the curve (Tjörve & Tjörve, 2010). The point of inflection is given by $(T_{\text{in}}, W_{\text{in}})$ with T_{in} being the time at inflection (time of maximum release rate) and W_{in} being the value of released N at this time which can be calculated by using Equation (2) (Tjörve & Tjörve, 2010).

$$W(t) = A \left(1 + \left(\left(\frac{W_0}{A} \right)^{1-d} - 1 \right) \cdot \exp \left(\frac{-k \cdot t}{d^{1-d}} \right) \right)^{\frac{1}{1-d}} \quad (1)$$

$$W_{\text{in}} = A \cdot d^{\frac{1}{1-d}} \quad (2)$$

To ensure that the release curves are comparable, the W_0 parameter was set to zero for all curves, to provide a fixed starting point. The upper asymptote A was designed to be 100%. The fitting procedure showed, however, that it could not be uniformly set to 100% as the maximum of released N varied considerably among soils and treatments. Therefore, we adapted the endpoint of N release to

individual release curves to avoid the deterioration of parameter estimates. We thus set the endpoints of the curves (for URE and PCU2) to the individual values of maximum released N that were closest to 100% of applied fertilizer N. However, for PCU17 we assumed that the maximum released N amounts measured at the end of incubation were not the endpoints of the curves. Thus, we set the endpoint values of PCU2 also as endpoints of the release curves for PCU17. To account for the different values of the A parameter, we calculated the absolute maximum release rate K (Equation 3) and used this parameter to evaluate release pattern.

$$K = k \cdot A \quad (3)$$

Polymer coatings control the N release from PCU into the soil solution in three stages: lag period, (nearly) constant release and decline phase (Naz & Sulaiman, 2016; Shaviv et al., 2003; Trenkel, 2010). When considering a tangent to a sigmoid curve at the inflection point to be a linear approximation of the growth phase (Passos et al., 2012), its intersections with the upper and lower asymptotes divide the release curve into three segments. These three segments correspond to the three stages of N release from the PCU fertilizers. The intersection of the tangent with the lower asymptote (x -axis) defines the end of the lag period (T_{lag}); the intersection with the upper asymptote (A) corresponds to the beginning of the decline phase (T_{dec} ; Passos et al., 2012; Shoffner & Schnell, 2015). Thus, the lag period extends from day zero (time of application) to T_{lag} , the time of constant release from T_{lag} to T_{dec} and the decline phase from T_{dec} to the endpoints of the curves.

We used the Gnuplot version 5.2 software for Windows released 2017 for plotting and fitting the N release curves to the data. To assess model quality, we used the residual standard error (RSE). The mean release rates between the treatments were considered to be significant from another if their 95% confidence interval (CI) did not overlap.

3 | RESULTS

We were able to generate accurate and reproducible data with the test system to characterize the release of N from urea and PCU fertilizers into soil. We calculated the recovery of fertilizer N as the ratio of applied fertilizer N to the measured N content in soil after 48 days (corrected for background N mineralization in the controls). The recovery across all soil textures accounted to $95.6 \pm 11.2\%$ for URE, $99.6 \pm 8.43\%$ for PCU2 and $88.9 \pm 11.1\%$ for PCU17. We assume that the N release from PCU17 was

still incomplete for some soils after 48 days of incubation, yet this did not restrain parameter estimates for PCU17 since the endpoint of the curves (A parameter) was set to the same values as for PCU2. The best results in N recovery for all three fertilizers were achieved in the sit loam soil $100.7 \pm 13.9\%$ for URE, $103.8 \pm 12.1\%$ for PCU2 and $100.5 \pm 9.7\%$ for PCU17. The unified Richards model fitted our experimental data well; the residual standard error (RSE) ranged between 0.69% and 7.85% (Table 2; for a comprehensive list of parameter estimates and errors see Tables S1–S3).

The N release from URE and PCU2 followed the shape of a saturation curve with a fast initial release and no lag period (T_{lag} ; Figure 1a,b, Table 2). On average across all textures, a mean maximum release rate of $21.7 \pm 7.70\%$ day⁻¹ (K) was reached after 2 days (T_{in}) for URE and of $12.2 \pm 2.93\%$ day⁻¹ within 3 days for PCU2 (Table 2). However, the mean release rates were not significantly different between URE and PCU2. For both fertilizers, the period of N release was generally short and 90% of the applied N was released within 2 weeks. The N release from PCU17 showed a different kinetics with a significantly lower mean maximum release rate than for URE and PCU2 (Figure 1, Table 2). The initial N release was delayed by 2 days with a short lag period and mean release rate of $4.0 \pm 0.68\%$ day⁻¹ (Table 2). The release time was extended, and 90% of applied N was released from PCU17 within 42 days. The approximated endpoints of the release curve were outside the experimental period of 48 days. Consequently, the release patterns for conventional urea were different from those of PCU17 while the release profile of PCU2 was similar to that of urea without a coating material.

The N kinetics of URE and PCU2 were mainly determined by the fast release of $\text{NH}_4^+ - \text{N}$ (Figure 2a; for details on PCU2 see Figure S1). After 6–10 days, the $\text{NH}_4^+ - \text{N}$ release decreased. This was a result of nitrification and, consequently, concentrations of $\text{NO}_3^- - \text{N}$ increased (Figure 2c, Figure S1). Since nitrate is a transformation product of ammonia, the cumulative ammonia-N release decreased over the time while the nitrate-N release increases. The finding was different to the release pattern of PCU17, where the $\text{NH}_4^+ - \text{N}$ release was slower and prolonged, resulting in a steady increase in the availability of both $\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$ (Figure 2b,d).

3.1 | Texture effects

The typical release kinetics of URE and PCU2 differed among the examined soil textures (Figure 1, Table 2). The N release rates were slower in the two soils clay and silty clay loam, which was particularly evident within

TABLE 2 Parameter estimates of the Richards model for the inorganic N ($=\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$) release from conventional urea (URE) and two polymer-coated urea fertilizers (PCU2, PCU17) for different topsoil textures, moisture and temperature levels; water content refers to a sample volume of 100 g soil dry weight.

Soil	Temp. (°C)	Moist. (% WHC)	Water content (g)	K (% day ⁻¹)	ASE (% day ⁻¹)	95% CI (% day ⁻¹)	W _{in} (%)	T _{in} (day)	T _{lag} (day)	T _{dec} (day)	RSE (%)
Texture											
URE											
Sandy loam	21	35	16.0	28.1	±3.86	18.2; 38.0	31.0	2.00	0.89	2.46	±4.40
Silt loam	21	45	23.4	29.7	±2.70	22.8; 36.6	37.4	1.56	0.30	3.12	±5.22
Loam	21	33	23.4	22.0	±1.94	17.0; 27.0	24.5	1.51	0.40	4.07	±4.12
Silty clay loam	21	38	23.5	11.0	±0.78	8.99; 13.0	14.6	1.52	0.19	8.24	±4.22
Clay	21	44	34.4	17.5	±1.32	14.1; 20.9	35.8	2.53	0.49	5.06	±2.54
Moisture											
Silt loam	21	38	19.9	27.8	±4.78	16.8; 41.4	34.3	1.53	0.30	3.06	±7.85
Silt loam	21	32	16.7	29.1	±4.16	17.1; 38.5	31.6	1.35	0.26	2.70	±7.83
Temperature											
Sandy loam	16	35	16.0	31.0	±3.30	22.5; 39.5	35.2	2.66	1.52	1.48	±2.27
Silt loam	16	45	23.4	15.3	±1.69	11.0; 19.6	21.4	1.80	0.41	5.79	±5.67
Texture											
PCU2											
Sandy loam	21	35	16.0	15.2	±1.83	10.5; 19.9	31.0	3.58	1.54	4.77	±4.31
Silt loam	21	45	23.4	13.2	±0.70	11.4; 15.0	15.5	1.34	0.16	7.72	±3.43
Loam	21	33	23.4	14.4	±1.09	11.6; 17.2	25.5	2.52	0.74	5.98	±0.97
Silty clay loam	21	38	23.5	8.94	±0.75	7.01; 10.9	24.3	3.83	1.11	9.28	±3.69
Clay	21	44	34.4	9.21	±1.63	5.02; 13.4	21.6	2.97	0.62	10.2	±2.66
Moisture											
Silt loam	21	38	19.9	9.39	±1.68	6.88; 15.5	18.7	2.46	0.46	9.37	±4.00
Silt loam	21	32	16.7	11.2	±0.68	7.64; 11.1	25.6	3.44	1.16	6.84	±5.77
Temperature											
Sandy loam	16	35	16.0	12.3	±0.76	10.4; 14.3	31.7	4.93	2.35	5.21	±1.89
Sandy loam	16	45	23.4	9.50	±0.60	7.96; 11.0	28.0	4.64	1.69	8.28	±2.48
Texture											
PCU17											
Sandy loam	21	35	16.0	3.07	±0.19	2.58; 3.56	21.8	9.20	2.10	29.1	±3.30
Silt loam	21	45	23.4	4.18	±0.33	3.33; 5.03	14.8	3.98	0.44	24.4	±5.07
Loam	21	33	23.4	4.93	±0.19	4.44; 5.42	22.8	6.08	1.47	18.1	±2.27
Silty clay loam	21	38	23.5	4.00	±0.18	3.54; 4.46	22.8	7.68	1.99	21.2	±2.01
Clay	21	44	34.4	3.67	±0.32	2.85; 4.49	25.4	9.55	2.64	24.6	±0.84

TABLE 2 (Continued)

Soil	Temp. (°C)	Moist. (% WHC)	Water content (g)	K (% day ⁻¹)	ASE (% day ⁻¹)	95% CI (% day ⁻¹)	W _{in} (%)	T _{in} (day)	T _{lag} (day)	T _{dec} (day)	RSE (%)
Moisture											
Silt loam	21	38	19.9	3.53	±0.35	3.23; 5.03	24.2	9.69	2.83	23.3	±1.42
Silt loam	21	32	16.7	4.13	±0.11	3.25; 3.81	27.7	11.1	4.37	17.4	±3.02
Temperature											
Sandy loam	16	35	16.0	2.57	±0.23	1.98; 3.16	24.8	13.6	3.95	32.2	±2.27
Silt loam	16	45	23.4	2.15	±0.06	2.00; 2.30	15.5	8.36	1.13	42.9	±1.61

Abbreviations: 95% CI, confidence interval of K; ASE, asymptotic standard error of K; K, absolute maximum release rate; RSE, residual standard error of the fit; T_{dec}, begin of the decline phase; T_{in}, time at inflection; T_{lag}, end of the lag period; W_{in}, N released at inflection.

the first 14 days after application (Figure 1a,b). The release rate from URE was significantly lower in the silty clay loam by nearly three times than in all other textures (Table 2). Also, the release rate from PCU2 was lower in the silty clay loam but only significantly lower than in silt loam or sandy loam (Table 2). For both URE and PCU, release rates were strongly negatively correlated with the clay: sand ratio of the soils (sandy loam = 0.2, loam = 0.9 silt loam = 1.2 clay = 1.6 silty clay loam = 2.5; Figure 3). The correlation for URE was close to be significant ($p = .07$) and for PCU2 it was significant ($p < .05$; Figure 3). However, neither clay nor sand content correlated with the release rates. Instead, we found that the C/N ratio of the soils correlated positively with release rates for URE (Pearson's $r = .89$, $p < .05$) and PCU2 (Pearson's $r = .91$, $p < .05$). No such correlation was found with the overall content of SOC, which was lowest for the silty clay loam and highest for the clay.

The release kinetics for PCU17 were also affected by soil texture but they deviated from those for URE and PCU2 (Figure 1c): the mean release rate of PCU17 was significantly lower in sandy loam than in loam (Table 2). Aside, the release rates in the clayey soils (clay and silty clay loam) were also substantially lower than in the loam but this was only close to be significant at the $p < .05$ level of probability (Table 2). We further found a significant correlation between release rates and the gap between clay and sand content (Pearson's $r = -.88$, $p < .05$). This means that the release rates decreased when the gap or distance between the clay and sand content increased (gaps were: loam = 1.9%, silt loam = 3.6%, clay = 19.5%, silty clay loam = 20.5%, sandy loam = 62.7%). We conclude that release rates of PCU17 were reduced in heavy soils with a very fine texture as well as in light soils with a coarse texture in comparison with soils where no mineral fraction dominates.

As incubations for the different soils were performed at maximum feasible moisture contents, we had to accept some variations in moisture contents between soils (Table 2). Hence, in a first glance, texture effects cannot be separated from texture-induced changes in water-holding capacities. Correlating the K values of N release, however, with soil moisture contents did not reveal any significant relationship for urea and PCU17 (Figure S2). We did observe, however, a significant negative relationship for PCU 2, which explained 53% of the variation of the data ($p < .05$; Figure S2). Hence, soil moisture did likely not control all differences among soils, but might interact with N release rates of specific coating materials. To better understand moisture effects on N release dynamics, we also incubated the same soils with different moisture contents.

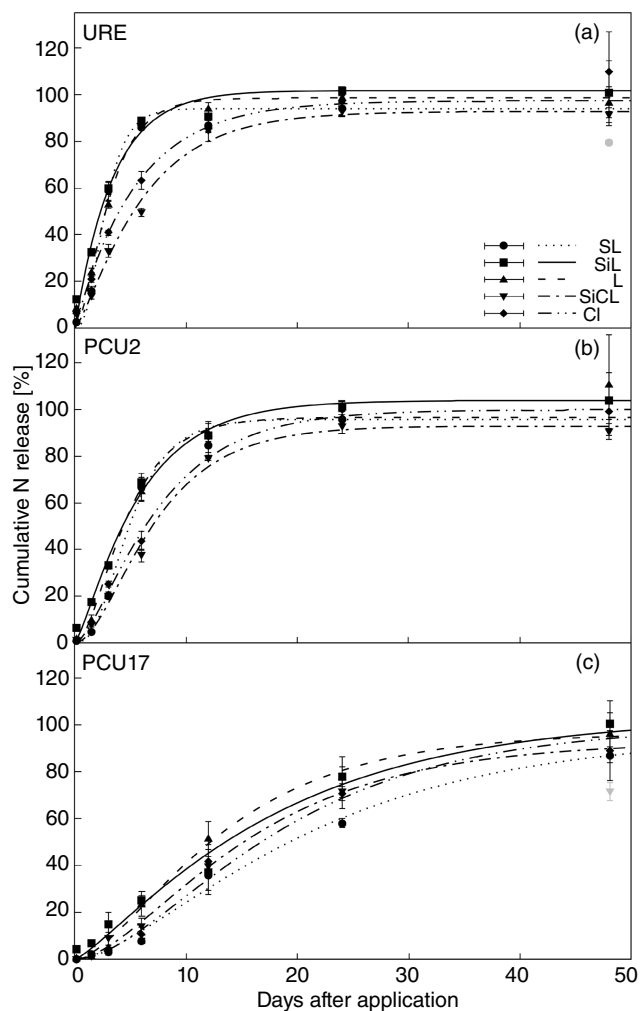


FIGURE 1 Cumulative inorganic N ($=\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$) release from conventional urea (a), the fast-release PCU2 (b) and the slow-release polymer-coated urea PCU17 (c) in differently textured topsoils; given are means of three replicates \pm standard deviation, and lines represent the fitted release curves using unified Richards model; Clay, grey symbols indicate that data were not included for the curve fit; L, loam; SiCL, silty clay loam; SiL, silt loam; SL, sandy loam.

3.2 | Moisture effects

We found that different soil moisture contents did not significantly affect the N release kinetics of urea and PCU in silt loam (Figure 4, Figure S4) and sandy loam (Figures S3 and S5). The release rates were also not significantly affected by soil moisture content within the range of permanent wilting point and 50% of WHC (Table 2, Tables S1–S3). As soil textures had similar variability in WHC than used for the moisture study, these data give support to the above-mentioned suggestion that moisture might also not be the key driver explaining differences in N release rates between soils. Despite this, the release curves of PCU2 and PCU17 were initially delayed, which resulted in an extension of the lag period (Table 2,

Figure 4, Tables S2 and S3). This was evident in the silt loam but not in sandy loam.

3.3 | Temperature effects

Soil temperature affected the N release kinetics from all fertilizers, conventional urea, PCU2 and PCU17 (Figures 5 and 6, Figures S6 and S7). The effect of temperature was significant in the silt loam soil. No temperature effect was apparent or significant in the sandy loam soil (Table 2). Lowering the temperature by 5°C (from 21 to 16°C) resulted in a significant reduction of release rates for all three fertilizers in silt loam (Figure 5). For the URE treatment, the N release rate was reduced by nearly half (Table 2, Figure 5a). For both PCU fertilizers, the release rates decreased by 28% for PCU2 and 49% for PCU17 (Table 2, Figure 5b,c). Moreover, lower temperature caused an extension of the lag period (T_{lag}) for the PCU fertilizers and an increase of the time to inflection (T_{in}) by factor three for PCU2 and two for PCU17 (Table 2). Overall, lowering temperature inhibited the N release from PCU and conventional urea but not across all soil textures.

4 | DISCUSSION

There is yet no standardized method for the reliable determination of N release from PCU into soil (Lawrence et al., 2021; Medina et al., 2014). To date, different laboratory methods have been used to determine N release from coated fertilizers into soil (Medina et al., 2014; Terlingen et al., 2020). A method by Medina et al. (2014) used a soil incubation column leaching technique with sand: soil mixture containing <1% soil (Medina et al., 2014). However, this method is not suitable for the evaluation of the N release into pure soil as it uses leaching technique that would distort N release since $\text{NH}_4^+ - \text{N}$ would be retained on exchange sites in soil. Our results experiments illustrate that the N release from PCU can be determined in pure soil.

The unified Richards model after Tjørve and Tjørve (2010) allowed a prediction of the release of inorganic N from conventional and polymer-coated urea in soil with an acceptable error. Because of its empirical character, it was possible to predict the N release from fertilizers without considering release-affecting mechanisms like enzymatic urease activity or diffusion rates (Fujinuma et al., 2009; Juan et al., 2010; Shaviv et al., 2003). Another parameterization of the Richards model has been used by Hara (2000), who successfully estimated the N release from coated urea fertilizers at constant temperatures. In contrast to the parameterization

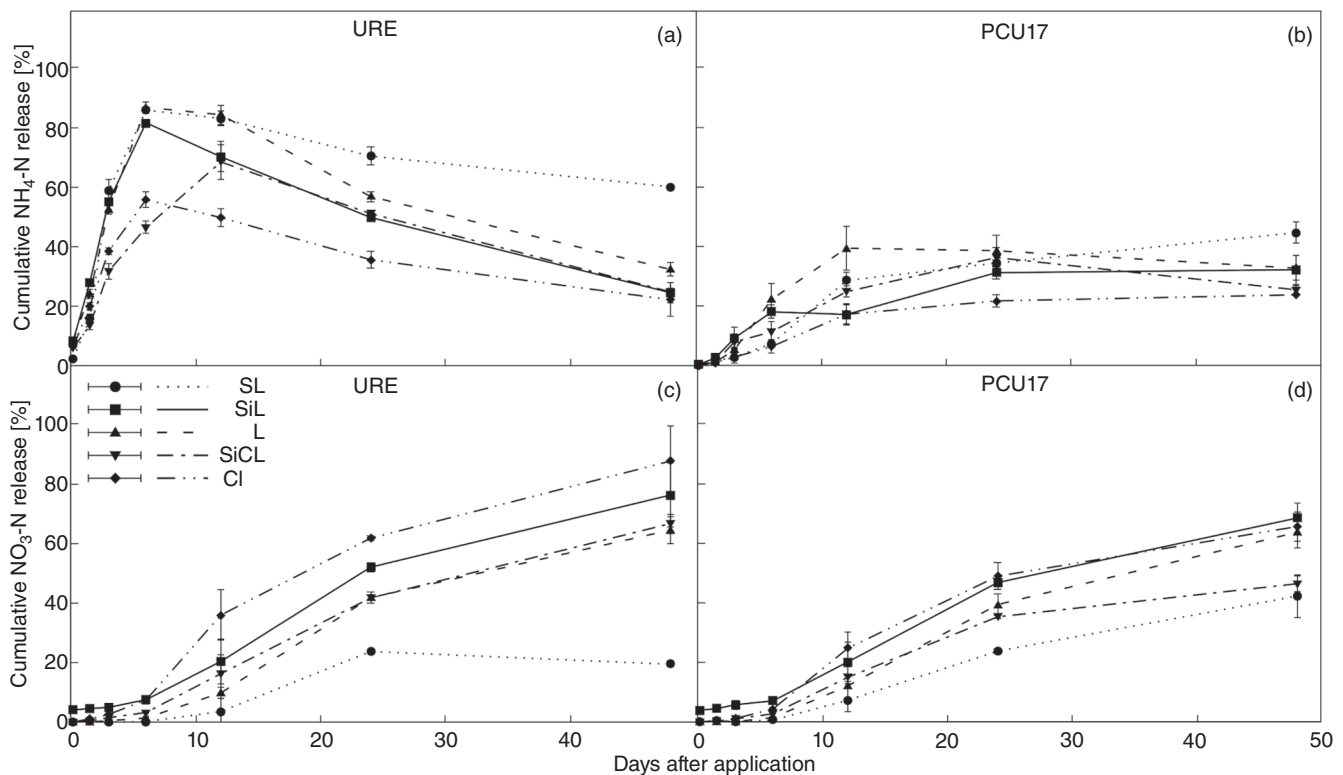
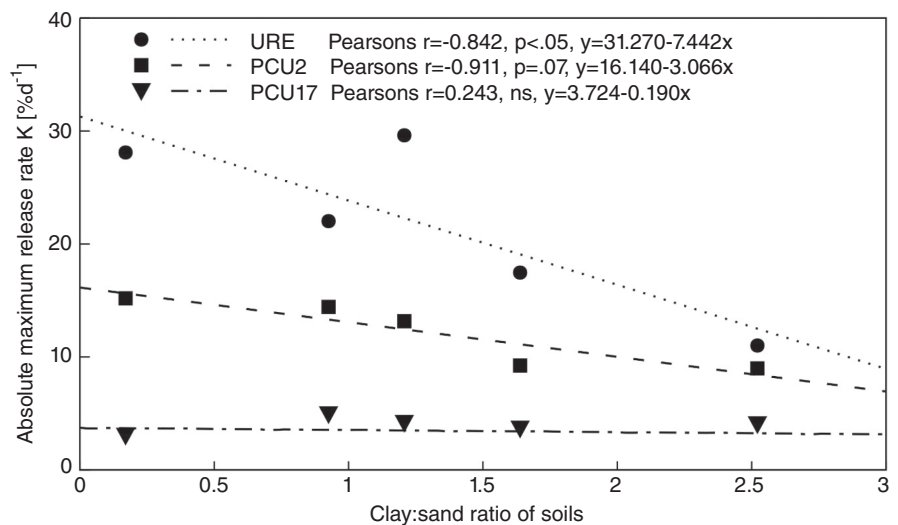


FIGURE 2 Inorganic N release splitted into NH_4^+ – N (a, b) and NO_3^- – N (c, d) from conventional urea (a, c) and the slow-release polymer-coated urea PCU17 (b, d) in differently textured topsoils; given are means of three replicates \pm standard deviation; CL, Clay; L, loam; SiCL, silty clay loam; SiL, silt loam; SL, sandy loam.

FIGURE 3 Correlation of the clay:sand ratios of five differently textured topsoils with absolute maximum release rates (K , calculated from unified Richards model) of conventional urea (URE), the fast-release PCU2 and the slow-release polymer-coated urea PCU17; ns, not significant.



used by Hara, the unified Richards model uses only parameters that control individual shape characteristics that can be compared among different release curves. Furthermore, the unified Richards model allowed separation of the sigmoidal-shaped N release into a lag, growth and plateau phase (Passos et al., 2012; Shoffner & Schnell, 2015). Hence, the unified Richards model is suitable for comparing and assessing the performance of conventional urea and PCUs with different release patterns.

We found that the basic kinetics of N release in soil from URE and PCU2 were similar but significantly different than that of PCU17 (Figure 1). The kinetics of N release for URE and PCU2 followed a saturation curve without lag period but with high release rates, as typical for fast, enzyme-catalysed hydrolysis of urea to ammonium (Juan et al., 2010; Khakural & Alva, 1995). In our experiments, 90% of the applied fertilizer N was hydrolysed after 11 days in the URE, which coincides with earlier reports that the hydrolysis of urea usually takes 1–14 days in soil (Herbst

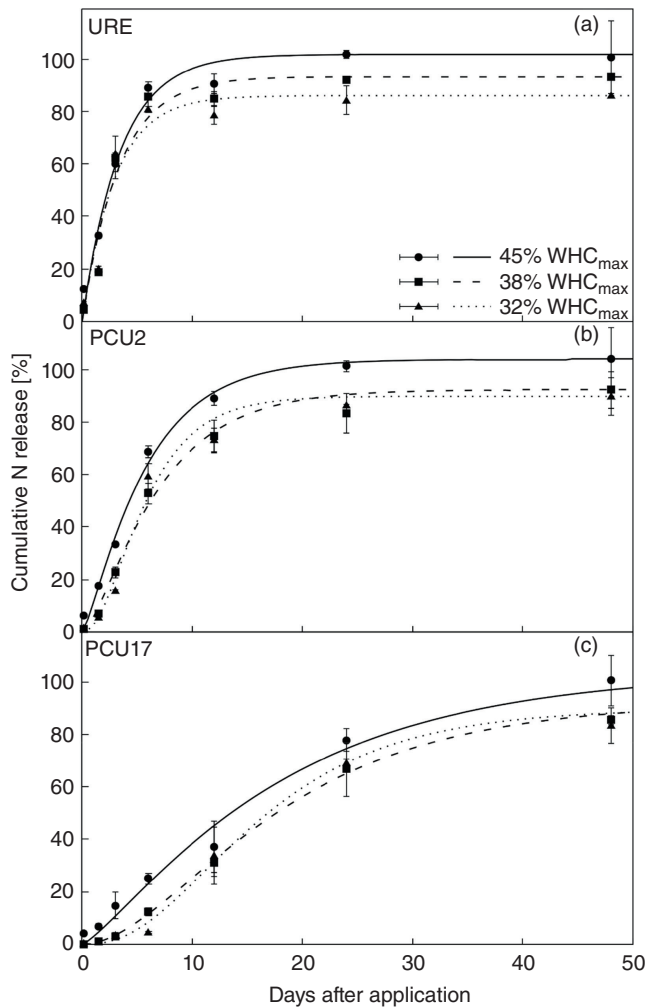


FIGURE 4 Cumulative inorganic N ($=\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$) release from conventional urea (a), the fast-release PCU2 (b) and the slow-release polymer-coated urea PCU17 (c) in a silt loam topsoil at different soil moisture levels; given are means of three replicates \pm standard deviation, and lines represent fitted release curves using unified Richards model.

et al., 2006; Khakural & Alva, 1995). Therefore, we assume that hydrolysis of urea is governing the release of inorganic N from urea and also from PCU2, despite polymer coating of the latter. In contrast, the release profile of PCU17 had a sigmoidal shape with an initially delayed N release and short lag period, typical for fertilizers of which diffusion is the main driver of N release (Shaviv et al., 2003). Such sigmoidal release profiles have been reported to be the most effective in matching the N requirements of crops (McKenzie et al., 2007; Shaviv et al., 2003). This suggests that the retention of N by the coating of PCU2 was not high enough to create release characteristics that were controlled by diffusion while the coating of PCU17 shaped N release in a promising way.

Our results showed that release rates of URE and PCU2 were lower in silty clay loam and significantly

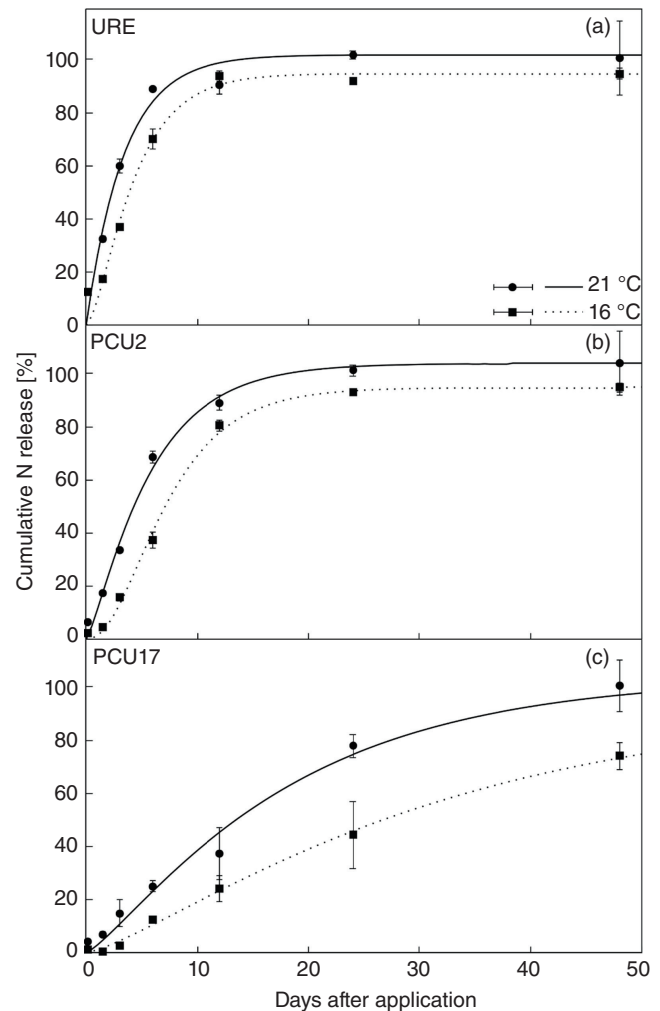


FIGURE 5 Cumulative inorganic N ($=\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$) release from conventional urea (a), the fast-release PCU2 (b) and the slow-release polymer-coated urea PCU17 (c) in a silt loam topsoil at different temperature levels; given are means of three replicates \pm standard deviation, and lines represent fitted release curves using unified Richards model.

correlated with the clay: sand ratio of the soils for PCU2 (Figure 1a,b). However, earlier studies reported a faster hydrolysis of urea in clay loam than in sandy loam (Yadav et al., 1987; Zantua et al., 1977). This effect was attributed not only to clay content but it was assumed that hydrolysis of urea is greater in fine-textured soils because of higher SOC concentration, cation exchange capacity (CEC) and pH value (Yadav et al., 1987; Zantua et al., 1977).

In our experiment, the silty clay loam had the lowest SOC concentration (1.2%). It likely reduced hydrolysis to NH_4^+ since urease activity is known to relate closely to SOC concentration (Dharmakeerthi & Thenabadu, 1996; Zantua et al., 1977). However, the clay soil exhibited low release rates, despite having the highest SOC concentration (2.7%). We did not find a significant correlation between SOC and N release rates. Instead, we found that the

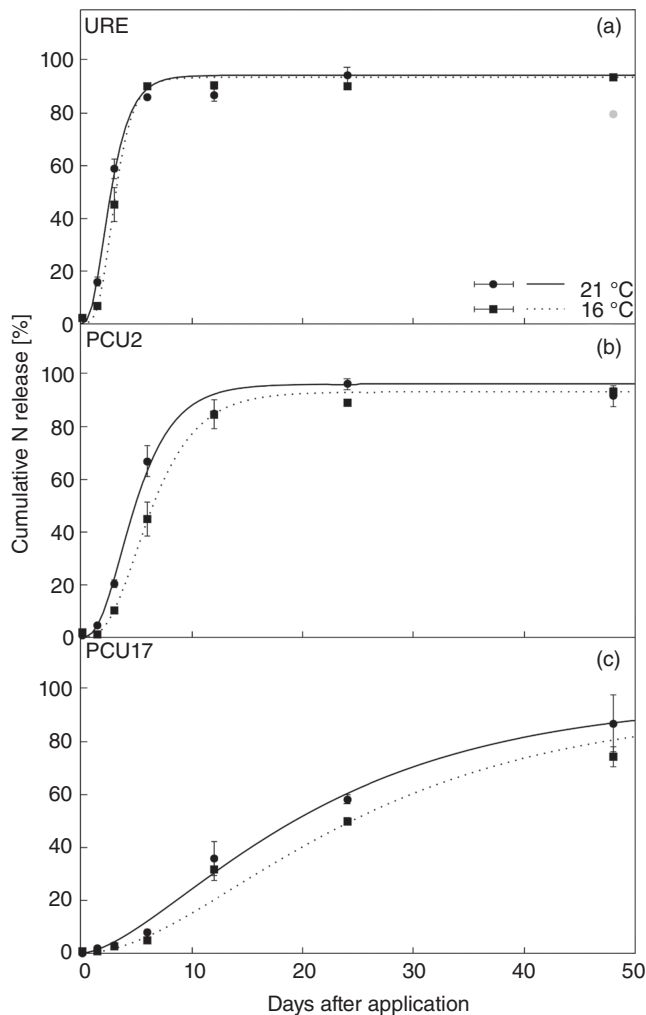


FIGURE 6 Cumulative inorganic N ($=\text{NH}_4^+ - \text{N}$ and $\text{NO}_3^- - \text{N}$) release from conventional urea (a), the fast-release PCU2 (b) and the slow-release polymer-coated urea PCU17 (c) in a sandy loam topsoil at different temperature levels; given are means of three replicates \pm standard deviation, and lines represent fitted release curves using unified Richards model; grey symbols indicate that data were not included for curve.

C/N ratio of the soils correlated positively with N release rates of urea and PCU2. This was in apparent contrast to reports where the C/N ratio correlated negatively with the urease activity (Mavi & Singh, 2007). It is likely that relationships to C/N ratio were caused by enzyme activity.

According to a review by Dharmakeerthi and Thenabadu (1996), soil properties can lead to different impacts on urease activity, which may show both negative or positive correlations to soil-water content. Here, water content did not influence N release rates significantly for a given soil, thus supporting to the assumption that it might also not control differences among the differently textured sites. When plotting release rates for all soils against water content, we found a moderate negative relation between moisture content and release rates for PCU2 ($r = -.73$,

$p = .025$, Figure S2). This relation was not confirmed for PCU17. There is no reason to assume that increasing water content might limit diffusion rates, thus giving rise to the assumption that this relationship, if it was causal at all, might be affected by other factors like oxygen availability, which, however, should not be specific for PCU2. In any case, we cannot fully discount an interaction of moisture content and PCU properties on N release rates, but differences were small compared with the effects of different temperatures.

The N release rates for PCU17 were reduced when either a high clay or sand content dominated soil texture (Figure 1c). As these soils had different WHC, this reduction occurred at both highest and lowest water content, thus substantiating the above-mentioned statement of a lacking (linear) effect of soil moisture on N release from PCU 17. We are also not aware of parabolic relationships reported in the literature. However, the finding is at least partly in line with earlier studies that suggested that N release rates from PCU were higher in soils rich in clay or SOC compared with sandy soils that are poor in SOC (Cahill et al., 2010; Golden et al., 2011; Medina et al., 2014). In particular, initial N release has been found to be faster in clay than in silt- or sandy loam soil while cumulative N release was not affected (Golden et al., 2011; Medina et al., 2014). The low N release rates in our clay soils do not corroborate with these findings. Possibly, the formation of aggregates upon rewetting the swelling soil interfered with the connection of fertilizer granules to soil water, thus slowing down diffusion rates.

Increasing soil moisture in a given soil did not significantly influence N release rates from URE, PCU2 and PCU17 (Figure 4). Soil water is essential for the dissolution and diffusion of urea and for hydrolysis by urease (Ibrahim et al., 1984; Ransom et al., 2020), but water is not a limiting factor at contents above the permanent wilting point (Cahill et al., 2010; Ibrahim et al., 1984; Lunt & Oertli, 1962). Yet, a lower soil moisture extended the lag period for N release from PCU17. Similar findings were reported by Golden et al. (2011) who found a lower initial N release (during the first 5 days) at lower moisture levels. However, this does not affect the fitting of N release rates, as this is an independent fitting parameter. Under real-world conditions one might have to add the lag time to the N release rates to assess true N availability; yet, differences in lag time were short and small compared with the effects of soil temperature on N release.

The N release rates for URE, PCU2 and PCU17 decreased with decreasing temperature in the silt loam but release rates did not significantly change in sandy loam soil (Figure 5, Figure S5). We attribute the temperature effect on URE to slower hydrolysis of urea since the urease activity increases with temperature from 10° to 40°C

(Dharmakeerthi & Thenabadu, 1996; Golden et al., 2011). Within our experiment, N release from PCU in silt loam proceeded more rapidly with increasing incubation temperature, which agrees with other findings (Golden et al., 2011; Medina et al., 2014; Trolove et al., 2019). In general, the diffusion rate increases with temperature (and decreases with temperature); thus, diffusion of dissolved urea through the coating membrane into soil solution depends highly on temperature (Golden et al., 2011; Medina et al., 2014; Ransom et al., 2020). Moreover, faster hydrolysis of PCU-derived urea at higher temperatures allows for the establishment of a steeper concentration gradient, enhancing diffusion out of the PCU granules (Carson & Ozores-Hampton, 2013; Golden et al., 2011). Accordingly, lower temperatures can slow down N release, since the released N may accumulate around the PCU granules (Lunt & Oertli, 1962). We therefore assume that in the silt loam, temperature reduced both the diffusion rate and the concentration gradient, because of hydrolysis causing a decrease in release rates.

Our data did not point at a significant deceleration of N release with declining temperature in the sandy loam soil (Figure 6). As in the URE treatment, hydrolysis of urea was not affected by temperature in the sandy loam (Figure 6a), we discount the possibility that hydrolysis rate was main factor also affecting the temperature dependency in the PCU materials (Figure 6b,c). Likely, the temperature-induced reduction of diffusion rates after hydrolysis was not sufficient to significantly change concentration gradients and therewith total N release rates from PCU materials in the sandy soils.

5 | CONCLUSION

The laboratory test system enabled a reliable determination of N release from PCU and urea into pure soil. Further, the uniform Richards model provided a good approximation of the inorganic N release, yielding quantitative parameters to evaluate and compare N release kinetics. Consequently, this test system provides a basis for establishing a standard method that is closer to real environmental conditions than previous methods.

We found that the N release patterns were similar for conventional urea and PCU2 and that both followed a saturation curve with high release rates. Hence, the retention of N by PCU2 was sufficient high enough to create real controlled-release characteristics. In contrast, the N release pattern from PCU17 was sigmoidal, supporting controlled N release over a prolonged period of time.

Soil texture did not change the underlying N release patterns, but release rates significantly varied among the investigated soils. We could not separate the effect of texture

from other related soil properties; however, our results showed that N release from PCU was impaired in fine-textured heavy soils or light and sandy ones. Soil moisture did not affect the N release from PCU and conventional urea in a given soil, although we cannot fully discount the possibility of moisture interactions with PCU types across different soils. Also, water tension is inherently different in soils of different textures, which could not be considered here. In contrast, temperature exhibited a clear and stronger effect on N release rates, which declined as temperatures decreased in silt loam but not in sandy loam soil at given moisture content. We conclude that soil properties such as texture or those correlated with texture such as SOC concentration, C/N ratio or water tension modulate climatic effects on N use efficiency of PCU-treated soils, making soil an essential factor for the further development of PCU fertilizers.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

- Alef, K., & Nannipieri, P. (1998). *Methods in applied soil microbiology and biochemistry* (2nd ed.). Academic Press.
- Azeem, B., KuShaari, K., Man, Z. B., Basit, A., & Thanh, T. H. (2014). Review on materials & methods to produce controlled release coated urea fertilizer. *Journal of Controlled Release*, *181*, 11–21. <https://doi.org/10.1016/j.jconrel.2014.02.020>
- Ballabio, C., Panagos, P., & Monatanarella, L. (2016). Mapping top-soil physical properties at European scale using the LUCAS database. *Geoderma*, *261*, 110–123. <https://doi.org/10.1016/j.geoderma.2015.07.006>
- Blackshaw, R. E., Hao, X., Harker, K. N., O'Donovan, J. T., Johnson, E. N., & Vera, C. L. (2011). Barley productivity response to polymer-coated urea in a no-till production system. *Agronomy*

- Journal*, 103(4), 1100–1105. <https://doi.org/10.2134/agronj2010.0494>
- Blaylock, A., Kaufmann, J., & Dowbenko, R. (2005). Nitrogen fertilizer technologies. *Western Nutrient Management*, 6, 8–13.
- Cahill, S., Osmond, D., & Israel, D. (2010). Nitrogen release from coated urea fertilizers in different soils. *Communications in Soil Science and Plant Analysis*, 41(10), 1245–1256. <https://doi.org/10.1080/00103621003721437>
- Carson, L. C., & Ozores-Hampton, M. (2013). Factors affecting nutrient availability, placement, rate, and application timing of controlled-release fertilizers for Florida vegetable production using seepage irrigation. *HortTechnology*, 23(5), 553–562. <https://doi.org/10.21273/HORTTECH.23.5.553>
- Chen, J., Lü, S., Zhang, Z., Zhao, X., Li, X., Ning, P., & Liu, M. (2018). Environmentally friendly fertilizers: A review of materials used and their effects on the environment. *Science of the Total Environment*, 613–614, 829–839. <https://doi.org/10.1016/j.scitotenv.2017.09.186>
- Dharmakeerthi, R. S., & Thenabadu, M. W. (1996). Urease activity in soils: A review. *Journal of the National Science Foundation of Sri Lanka*, 24(3), 159. <https://doi.org/10.4038/jnsfsr.v24i3.5548>
- Du, C., Zhou, J., & Shaviv, A. (2006). Release characteristics of nutrients from polymer-coated compound controlled-release fertilizers. *Journal of Polymers and the Environment*, 14(3), 223–230. <https://doi.org/10.1007/s10924-006-0025-4>
- Düwel, O., Siebner, C. S., Utermann, J., & Krone, F. (2007). *Bodenarten der Böden Deutschlands*. Bericht über die länderübergreifende Auswertungen von Punktinformationen im FISBoBGR.
- Fan, X., Li, F., Liu, F., & Kumar, D. (2004). Fertilization with a new type of coated urea: Evaluation for nitrogen efficiency and yield in winter wheat. *Journal of Plant Nutrition*, 27(5), 853–865. <https://doi.org/10.1081/PLN-120030675>
- Food and Agriculture Organization of the United Nations (FAO). (2006). *Guidelines for soil descriptin* (4th ed.). FAO.
- Fujinuma, R., Balster, N. J., & Norman, J. M. (2009). An improved model of nitrogen release for surface-applied controlled-release fertilizer. *Soil Science Society of America Journal*, 73(6), 2043–2050. <https://doi.org/10.2136/sssaj2009.0085>
- Golden, B., Slaton, N., Norman, R., Gbur, E., & Wilson, C. (2011). Nitrogen release from environmentally smart nitrogen fertilizer as influenced by soil series, temperature, moisture, and incubation method. *Communications in Soil Science and Plant Analysis*, 42(15), 1809–1824. <https://doi.org/10.1080/00103624.2011.587568>
- Grant, C. A., Wu, R., Selles, F., Harker, K. N., Clayton, G. W., Bittman, S., Zebarth, B. J., & Lupwayi, N. Z. (2012). Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. *Field Crops Research*, 127, 170–180. <https://doi.org/10.1016/j.fcr.2011.11.002>
- Guertal, E. A. (2009). Slow-release nitrogen fertilizers in vegetable production: A review. *HortTechnology*, 19(1), 16–19. <https://doi.org/10.21273/HORTSCI.19.1.16>
- Hara, Y. (2000). Application of the Richards function to nitrogen release from coated urea at a constant temperature and relationships among the calculated parameters. *Journal of Soil Science and Plant Nutrition*, 46(3), 683–691. <https://doi.org/10.1080/00380768.2000.10409133>
- Herbst, F., Gans, W., Merbach, W., Schuster, C., & Michel, H.-J. (2006). Stickstoffumsatz nach Harnstoffdüngung mit einem Ureaseinhibitor. *Archives of Agronomy and Soil Science*, 52(4), 451–459. <https://doi.org/10.1080/03650340600649849>
- Herrera, J., Rubio, G., Häner, L., Delgado, J., Lucho-Constantino, C., Islas-Valdez, S., & Pellet, D. (2016). Emerging and established technologies to increase nitrogen use efficiency of cereals. *Agronomy*, 6(2), 25. <https://doi.org/10.3390/agronomy6020025>
- Hirel, B., Tétu, T., Lea, P. J., & Dubois, F. (2011). Improving nitrogen use efficiency in crops for sustainable agriculture. *Sustainability*, 3(9), 1452–1485. <https://doi.org/10.3390/su3091452>
- Ibrahim, M. E., Awadalla, E. A., El-Din, M. M. B., & Kassim, A. S. (1984). Effect of rate of urea application and soil moisture on the behaviour of urea in soil. *Zeitschrift für Pflanzenernährung Und Bodenkunde*, 147(2), 177–186. <https://doi.org/10.1002/jpln.19841470206>
- International Fertilizer Industry Association (IFA). (2021). *Databases, total N consumptions*. <https://www.ifastat.org/databases/plant-nutrition>
- ISO 10390:2005. *Soil quality – Determination of pH*.
- ISO 10694:1995. *Soil quality – Determination of organic and total carbon after dry combustion (elementary analysis)*.
- ISO 13878:1998. *Soil quality – Determination of total nitrogen content by dry combustion (elemental analysis)*.
- ISO 14256-1:2005. *Soil quality – Determination of nitrate, nitrite and ammonium in field-moist soils by extraction with potassium chloride solution – Part 1: Manual method*.
- ISO 14256-2:2005. *Soil quality – Determination of nitrate, nitrite and ammonium in field-moist soils by extraction with potassium chloride solution – Part 2: Automated method with segmented flow analysis*.
- ISO 21263:2017. *Slow-release fertilizers – Determination of the release of the nutrients – Method for coated fertilizers*.
- Juan, Y. H., Chen, Z. H., Chen, L. J., Wu, Z. J., Wang, R., Sun, W. T., & Zhang, Y. L. (2010). Kinetic and thermodynamic behaviors of soil urease as affected by urease inhibitors. *Revista de la Ciencia del Suelo y Nutrición Vegetal*, 10(1), 1–11. <https://doi.org/10.4067/S0718-27912010000100001>
- Khakural, B. R., & Alva, A. K. (1995). Hydrolysis of urea in two sandy soils under citrus production as influenced by rate and depth of placement. *Communications in Soil Science and Plant Analysis*, 26(13–14), 2143–2456. <https://doi.org/10.1080/00103629509369435>
- Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy*, 87, 85–156. [https://doi.org/10.1016/S0065-2113\(05\)87003-8](https://doi.org/10.1016/S0065-2113(05)87003-8)
- Lawrencia, D., Wong, S. K., Low, D. Y. S., Goh, B. H., Goh, J. K., Ruktanonchai, U. R., Soottitantawat, A., Lee, L. H., & Tang, S. Y. (2021). Controlled-release fertilizers: A review on coating materials and mechanism of release. *Plants*, 10(2), 238. <https://doi.org/10.3390/plants10020238>
- Lunt, O. R., & Oertli, J. J. (1962). Controlled release of fertilizer minerals by encapsulating membranes: II. Efficiency of recovery, influence of soil moisture, mode of application, and other considerations related to use. *Soil Science Society of America Journal*, 26(6), 584–587. <https://doi.org/10.2136/sssaj1962.03615995002600060020x>
- Mavi, M. S., & Singh, B. (2007). Influence of crop residues and organic manures on the hydrolysis of urea in a typical haplustept. *Arid Land Research and Management*, 21(4), 305–313. <https://doi.org/10.1080/15324980701603466>

- McKenzie, R. H., Bremer, E., Middleton, A. B., Pfiffner, P. G., & Dowbenko, R. E. (2007). Controlled-release urea for winter wheat in southern Alberta. *Canadian Journal of Soil Science*, 87(1), 85–91. <https://doi.org/10.4141/S06-055>
- Medina, L. C., Sartain, J. B., Obreza, T. A., Hall, W. L., & Thiex, N. J. (2014). Evaluation of a soil incubation method to characterize nitrogen release patterns of slow- and controlled-release fertilizers. *Journal of AOAC International*, 97(3), 643–660. <https://doi.org/10.5740/jaoacint.13-065>
- Naz, M. Y., & Sulaiman, S. A. (2016). Slow release coating remedy for nitrogen loss from conventional urea: A review. *Journal of Controlled Release*, 225, 109–120. <https://doi.org/10.1016/j.jconrel.2016.01.037>
- Omara, P., Aula, L., Oyebiyi, F., & Raun, W. R. (2019). World cereal nitrogen use efficiency trends: Review and current knowledge. *Agrosystems, Geosciences & Environment*, 2(1), 1–8. <https://doi.org/10.2134/age2018.10.0045>
- Passos, J. R. D. S., Pinho, S. Z. D., Carvalho, L. R. D., & Mischan, M. M. (2012). Critical points in logistic growth curves and treatment comparisons. *Science in Agriculture*, 69(5), 308–312. <https://doi.org/10.1590/S0103-90162012000500004>
- Ransom, C. J., Jolley, V. D., Blair, T. A., Sutton, L. E., & Hopkins, B. G. (2020). Nitrogen release rates from slow- and controlled-release fertilizers influenced by placement and temperature. *PLoS One*, 15, e0234544. <https://doi.org/10.1371/journal.pone.0234544>
- Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D., & Toll, D. (2004). The global land data assimilation system. *Bulletin of the American Meteorological Society*, 85(3), 381–394. <https://doi.org/10.1175/BAMS-85-3-381>
- Shaviv, A., Raban, S., & Zaidel, E. (2003). Modeling controlled nutrient release from polymer coated fertilizers: Diffusion release from single granules. *Environmental Science & Technology*, 37(10), 2251–2256. <https://doi.org/10.1021/es011462v>
- Shoffner, S. K., & Schnell, S. (2015). *Estimation of the lag time in a subsequent monomer addition model for fibril elongation*.
- Terlingen, J., Hojjatie, M., & Carney, F. (2020). *Review of analytical methods for slow- and controlled-release fertilizers*. Hg. v. International Fertilizer Industry Association (IFA), 08.01.21.
- Tjørve, E., & Tjørve, K. M. C. (2010). A unified approach to the Richards-model family for use in growth analyses: Why we need only two model forms. *Journal of Theoretical Biology*, 267(3), 417–425. <https://doi.org/10.1016/j.jtbi.2010.09.008>
- Trenkel, M. E. (2010). *Slow- and controlled-release and stabilized fertilizers. An option for enhancing nutrient use efficiency in agriculture*. International Fertilizer Industry Association (IFA). https://www.fertilizer.org/images/Library_Downloads/2010_Trenkel_slow%20release%20book.pdf
- Trolove, S., Wijeyekoon, S., & Tan, Y. (2019). Effect of temperature on the rate of nitrogen release from a controlled release fertilizer. In L. D. Currie & C. L. Christensen (Eds.), *Nutrient loss mitigations for compliance in agriculture*. Occasional report, No. 32. Fertiliser and Lime Research Centre, Massey University.
- Yadav, D. S., Kumar, V., Singh, M., & Relan, P. S. (1987). Effect of temperature and moisture on kinetics of urea hydrolysis and nitrification. *Soil Research*, 25(2), 185. <https://doi.org/10.1071/sr9870185>
- Zantua, M. I., Dumenil, L. C., & Bremner, J. M. (1977). Relationships between soil urease activity and other soil properties. *Soil Science Society of America Journal*, 41(2), 350–352. <https://doi.org/10.2136/sssaj1977.03615995004100020036x>

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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