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Original Article

Effect of coated urea and NPK-fertilizers on spring wheat yield and nitrogen use efficiency

Efeito da ureia revestida e dos fertilizantes NPK na produtividade do trigo de primavera e na eficiência do uso de nitrogênio

V. M. Lapushkin[a]*, A. A. Lapushkina[a] and S. P. Torshin[a]

[a] Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, Moscow, Russian Federation

Abstract

Among the factors that increase the efficiency of mineral fertilizers, due consideration has lately been given to the development and study of fertilizers with various granule coatings. This study is focused on the test of urea and NPK fertilizers, with granules coated with 50 and 100 μm monocalcium phosphate. Two-year greenhouse trials with spring wheat were carried out on soddy-podzolic light loamy soil. Coated fertilizers have proven to be more effective than traditional ones. For instance, using coated urea improved the yield 10-11% compared to conventional fertilizer. At the same time, the weight of one plant increased by 9-11% and the weight of the ear by 10%, the number of grains in the ear was by 4-7% bigger. Similar results were obtained with NPK fertilizer. Providing a thicker coating from 50 to 100 μm significantly increased the efficiency of both urea and NPK fertilizers.

Keywords: coated fertilizers, slow release fertilizers (SRF), controlled release fertilizers (CRF), spring wheat, nutrient use efficiency.

Resumo

Entre os fatores que elevam a eficácia dos fertilizantes minerais, tem-se dado especial atenção recentemente ao desenvolvimento e estudo dos fertilizantes com vários revestimentos granulados. Este estudo se concentra no teste de fertilizantes à base de ureia e NPK, com grânulos revestidos com fosfato monocálcico de 50 e 100 μm.. Ensaios de dois anos em estufa com trigo de primavera foram realizados em solo franco leve podzólico. Os fertilizantes revestidos mostraram-se mais eficazes do que os tradicionais. Por exemplo, o uso de ureia revestida aumentou o rendimento em 10-11% em comparação com o fertilizante convencional. Ao mesmo tempo, o peso de uma planta aumentou em 9-11% e o peso da espiga em 10%, o número de grãos na espiga foi 4-7% maior. Resultados semelhantes foram obtidos com fertilizante NPK. Fornecer um revestimento mais espesso de 50 para 100 μm aumentou significativamente a eficiência dos fertilizantes de ureia e NPK

Palavras-chave: fertilizantes revestidos, fertilizantes de ação lenta, fertilizantes de ação controlada, trigo de primavera, eficácia do uso das substâncias nutritivas.

1. Introduction

As communicated by the International Fertilizer Association (IFA), a steady increase in consumption of mineral fertilizers is predicted throughout the world. If, taking, for example, 2021-2022 the demand in mineral fertilizers comprised 198.2 million tons for 100% of the active substance, then, in 2023 it is expected to increase to 204.0 million tons. Obviously, nitrogen fertilizers play the major role in the world market of agrochemicals, the volume of their annual utilization being approximately 118.0 million tons (Cross, 2021; Cross and Gruère, 2022).

Irrespective of the large volumes of nitrogen fertilizers consumption, the problem of increasing their efficiency is still no less relevant. Nitrogen decline in fertilizers due to denitrification and ammonia release during top fertilizing amide and ammonium fertilizers ignoring their timely placement, and leaching of the nitrate form of nitrogen beyond the root layer of the soil may vary over a wide range occasionally exceeding 50% (Malyavin et al., 2022; Glibert et al., 2006; Howarth, 2008; Yang and Fang, 2015).

One way to get around this problem is the production and use of slow and controlled release fertilizers, which have a number of advantages compared to conventional fertilizers (Lewu et al., 2021; Burzaco et al., 2013; Rudmin et al., 2022):

- Yield gains by increasing the coefficient of fertilizers' nitrogen use efficiency;
- Reducing the negative impact on the environment due to reduced greenhouse gases emission (N_2O, NO_x),

*e-mail: lapushkin@rgau-msha.ru
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contamination of groundwater with nitrates, and eutrophication;

- Single application before sowing reduces financial and labor costs by providing plants with nitrogen throughout the growing season.

There are various ways to produce nitrogen-containing slow release fertilizers (Figure 1). One of the most widespread methods is the use of urease inhibitors (N-(n-butyl) thiophosphoric triamide (NBPT), etc.) and nitrification inhibitors (dicyandiamide, nitrapyrin, 3,4-dimethylpyrazole phosphate (DMPP), etc.), which significantly increase the efficiency of fertilizers by reducing gas nitrogen decline and leaching of nitrates (Burzaco et al., 2013; Yang et al., 2016; Chaopu et al., 2022; Li et al., 2017; Fan et al., 2018).

It is commonly known, that all simple nitrogen fertilizers are highly soluble in water, however, it is also possible to obtain poorly soluble nitrogen fertilizers based on urea polymerization products, such as urea-formaldehyde $(HOCH_2NHC(O)NH)_nCH_2$ or isobutylidenediurea $(CH_3)_2CHCH(NHC(O)NH_2)_2$ and others (Trenkel, 2010; Shaviv, 2001; Chaopu et al., 2022). Low solubility provides for less interaction with the soil solution and lower susceptibility to microbiological transformations (ammonification, nitrification and denitrification), due to which the prolongation effect is accomplished.

A promising way to increase the efficiency of nitrogen fertilizers is to coat them, which means, to apply various coatings to the surface of granules. The advantage of this method is the controlled nutrients release by varying the composition and thickness of the coating. Coatings may be organic or mineral in origin. Various polymers can be classified as organic, namely, polyethylene, polyurethane, phenol-formaldehyde resins, all of them, however, having a serious common drawback, which makes itself felt in case of their prolonged or incomplete decomposition in the soil and leads to unwanted accumulation in the plow layer and environmental pollution. There is an option to use natural biodegradable polymers, such as cellulose, lignin, etc. The issue of decomposition of the coat in the soil is completely eliminated by the use of mineral coatings like elemental sulfur, gypsum, or enclosing the nutrients within a matrix based on natural sorbents like zeolite, glauconite, etc. (Trenkel, 2010; Dharmasena and Prapagar, 2016; Lapushkin et al., 2023; Oertli, 1973; Lambie, 1987; Shoji and Gandeza, 1992).

Various salts seem to be a promising material to be used as granules coating, including those containing nutrients, which allows for additional nutrients for the plant. One example is the proposed monocalcium phosphate coating, which has proven the increased efficiency of various forms of fertilizers (Lapushkin et al., 2023).

2. Materials and Methods

Two-year greenhouse trials were carried out with Lyubava variety spring wheat to determine the effectiveness of coating mineral NPK fertilizers and urea (carbamide). The experiments were conducted in quadruple repetition using Mitscherlich pots containing 5 kg of soddy-podzolic light loamy soil. The soil for research was taken from of 0-20 cm depth, mixed, dried to an air-dry state and sifted.

Table 1 presents the physicochemical characteristics of the soil. The content of organic carbon in the soil was determined by means of photometric by the concentration of Cr^{3+} ions after oxidation of a soil aliquot in sulfuric acid mixed with potassium bichromate. The degree of soil acidity was measured using a pH meter in an extract of 1 M KCl at

Table 1. Soil chemical characteristics.

Soil property	Value
Organic carbon (C) g kg $^{-1}$	14.9
Phosphorus (P) mg kg $^{-1}$	40.2
Potassium (K) mg kg $^{-1}$	131.4
Nitrogen (N) mg kg $^{-1}$	68.0
Cation exchange capacity (CEC) $cmol_c$ kg $^{-1}$	14.8
pH_{KCl}	5.8

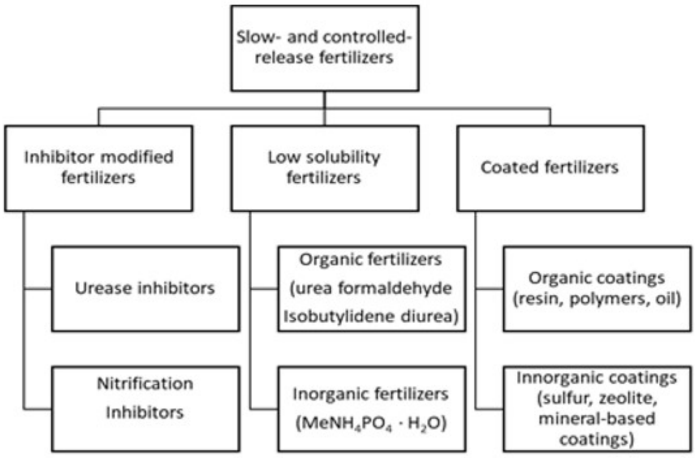

Figure 1. Classification of slow- and controlled-release fertilizers.

a soil-solution ratio of 1:2.5 (Russia, 1985a). The content of labile phosphorus was determined in a 0.2 M HCl extract by the photometric method using ammonium molybdate (Russia, 2011). The concentration of labile potassium was determined using the flame-photometric method in an extract of 0.2 M HCl (Russia, 2011). Nitrogen supply was determined by Cornfield content of alkali-hydrolyzable nitrogen in the soil (Kidin, 2008).

Experience included the following treatments: T1 - Control (phosphorus and potassium was applied); T2 - Uncoated urea; T3 - Coated urea (50 µm); T4 - Coated urea (100 µm); T5 - Uncoated NPK; T6 - Coated NPK (50 µm); T7 - Coated NPK (100 µm). The rate of application of phosphorus and potassium to all pots was 700 and 650 mg per pot. Nitrogen was applied in T2 - T7 in an amount of 750 mg per pot.

The fertilizer production method involves applying coatings consisting of monocalcium phosphate to the surface of mineral fertilizer granules. The rate of nutrient release is regulated by changing the thickness of the coating. Production technology is protected by patent RU2776275C1 (Russia, 2021).

Coating the fertilizer granules with a monocalcium phosphate ($Ca(H_2PO_4)_2$) increased the phosphorus content of the fertilizer compared to its initial concentration, which was considered when determining fertilizer doses. The actual content of nutrients in the studied fertilizers is presented in Table 2.

Yields is determined by weighing grain and straw dried at 105 °C laboratory heat cabinet was used. Formation of the chemical composition of substances happens after wet mineralization. Plant material aliquot was digested in a sulfuric acid (H_2SO_4) and selenium catalyzer was used. Total nitrogen concentration was determined by the Kjeldahl method (Russia, 1993). The total phosphorus concentration was measured by using the molybdenum blue colorimetric method (Russia, 1997a). And total potassium contain was determined by using flame photometry (Russia, 1997b).

The nutrients uptake was calculated based on the results of chemical analysis, the mass of the main and secondary parts of the crop considered. The efficiency of consuming nitrogen fertilizers by agricultural crops was assessed based on the ratio of the nitrogen fertilizers uptake to its input.

Laboratory experiment to study the intensity of conversion of nitrogen-containing mineral fertilizers was carried out in 3 repetitions according to the following method: the soil was thoroughly crushed, mixed and sifted through a sieve with a mesh size of 2 mm; Soil moisture was determined and the humidity was adjusted to 60% field moisture capacity with distilled water; A sample of fertilizer containing ~5 mg of nitrogen was placed in vessels with a capacity of 200 cm^3 and a sample of soil of 20 g (calculated on dry weight) was added; The containers were kept at a constant temperature of +20 °C. 1, 2, 3, 5, 7, 14, 21, 28 and 35 days after the start of the experiment, the content of ammonium and nitrate nitrogen in the soil was determined (Russia, 1985b, 1986).

Statistical processing of the test results was carried out using one-way analysis of variance in MS Excel.

3. Results and Discussion

The results obtained demonstrate that fertilizers with monocalcium phosphate coated granules contribute to a more uniform supply of nitrogen to wheat plants during the crop season. Table 3 presents data on average for 2020/2022 on the biomass accumulation dynamics and nitrogen supply to wheat plants.

The gradual release of nitrogen from coated fertilizers, synchronized with plant demand, promotes nitrogen assimilation and biomass accumulation by plants, which subsequently increases yield (Shao et al., 2009; Ye et al., 2013). It is known that the period of maximum nitrogen consumption by spring wheat begins in the shoot stage and continues until the paniculation stage. At this time, spring wheat consumes up to 70% of total nitrogen. The data in Table 3 show that during the tillering period, the most intensive wheat plant biomass accumulation occurred in variants where coated urea was used. In comparison with conventional urea, in the variants with its coated form, the dry weight of the tillering period plants was 15-23% higher. Moreover, all studied forms of NPK fertilizers had the same effect on the accumulation of plant dry mass.

During the shoot stage, in the variants with the application of coated urea, the plant weight was 10-28% higher compared to conventional fertilizers, and 10% higher when using 100 µm coating thickness NPK fertilizers. During the inflorescence emergence stage, coated urea provided 17-36% of the increase in biomass, and NPK fertilizers with coatings provided 7-11%.

Fertilizers with 100 µm granule coating thickness provided wheat plants with nitrogen during the entire period of its intensive absorption to the fullest extent possible. The advantage of this form of fertilizer became evident even at the shoot stage. The supply of nitrogen

Table 2. Fertilizers chemical H_2SO_4 characteristics.

Fertilizer	Nitrogen (N) %	Phosphorus (P) %	Potassium (K) %
Urea (uncoated)	46	-	-
Urea (coated, 50 µm)	40	3	-
Urea (coated, 100 µm)	35	6	-
NPK (uncoated)	15	7	13
NPK (coated, 50 µm)	14	9	12
NPK (coated, 100 µm)	12	11	10

Table 3. Effect of coated fertilizers on vegetative growth characteristics and nutrients uptake by spring wheat.

Treatments	Plant weight (g)		Nutrients content (%)			Nutrients uptake (mg per plant)		
	Fresh matter	Dry matter	N	P	K	N	P	K
Tillering								
T_1 - Control (PK)	1.14	0.13	3.1	1.1	4.3	4.0	1.5	5.6
T_2 - Urea	1.13	0.13	5.2	1.0	4.2	6.6	1.3	5.4
T_3 - Coated urea (50 µm)	1.32	0.15	5.3	1.0	4.3	8.0	1.5	6.6
T_4 - Coated urea (100 µm)	1.31	0.16	5.3	0.8	4.2	8.4	1.3	6.6
T_5 - NPK	1.35	0.18	4.7	0.9	4.3	8.3	1.6	7.6
T_6 - Coated NPK (50 µm)	1.33	0.16	5.6	1.0	4.7	9.2	1.6	7.7
T_7 - Coated NPK (100 µm)	1.41	0.18	5.0	1.0	4.1	8.9	1.8	7.3
LSD $_{(P=0,05)}$	NS	0.04	0.3	NS	NS	1.5	NS	1.7
Stem elongation								
T_1 - Control (PK)	3.10	0.52	1.5	0.7	2.7	8.1	3.9	14.0
T_2 - Urea	5.90	0.81	3.5	0.6	3.1	28.2	5.2	25.1
T_3 - Coated urea (50 µm)	5.51	0.89	3.1	0.6	2.8	28.0	5.6	25.1
T_4 - Coated urea (100 µm)	6.51	1.04	3.7	0.7	3.0	37.9	6.9	30.9
T_5 - NPK	5.38	0.87	3.4	0.7	3.1	29.8	6.1	27.3
T_6 - Coated NPK (50 µm)	5.91	0.84	3.6	0.7	2.9	29.9	6.3	24.2
T_7 - Coated NPK (100 µm)	6.25	0.96	3.6	0.7	3.2	34.8	6.6	30.7
LSD $_{(P=0,05)}$	0.45	0.09	0.3	NS	0.4	3.2	1.2	4.2
Inflorescence emergence								
T_1 - Control (PK)	3.21	0.90	0.8	0.5	1.5	7.1	4.9	13.5
T_2 - Urea	7.22	1.77	1.5	0.5	1.5	26.1	8.2	27.1
T_3 - Coated urea (50 µm)	9.50	2.41	1.7	0.4	1.5	40.8	10.6	36.1
T_4 - Coated urea (100 µm)	8.70	2.07	1.9	0.5	1.5	39.8	9.9	31.0
T_5 - NPK	8.25	1.89	1.6	0.5	1.8	29.9	9.9	34.5
T_6 - Coated NPK (50 µm)	8.97	2.02	1.7	0.6	1.7	34.4	11.5	34.2
T_7 - Coated NPK (100 µm)	8.67	2.09	1.8	0.5	1.7	36.6	10.8	35.0
LSD $_{(P=0,05)}$	0.97	0.29	0.2	NS	NS	7.0	2.1	7.8

LSD = least significant difference; NS = not significant.

to plants in experimental variants T-4 and T-7 during the shoot stage and paniculation-blooming stage of wheat plants was higher compared to other variants where nitrogen fertilizers were used.

The results of the yield formula recording, given in Table 4, show that all the studied fertilizers had a significant effect on the formation of elements of the spring wheat yield formula.

The crop yield increase when applying nitrogen ranged from 8.7 to 16.4 g/pot, while the effect of coated fertilizers proved to be more pronounced. Given the crop yield increase with uncoated fertilizers comprised 8.7-14.3 g/pot, this figure amounts to 10.0-16.4 when using coated fertilizers.

On average, over two years of coated urea studies, the yield was 10-11% higher against conventional fertilizer (Figure 2). Research by Chalk et al. (2015) shows that coated urea increases yield and reduces fertilizer nitrogen losses by better synchronizing nitrogen availability with plant demand. At the same time, the weight of one plant increased by 9-11%, the weight of one ear increased by 10%, the number of grains in the ear increased by 4-7%.

In addition, using the coated urea led to formation of more filled grains in spring wheat plants, as evidenced by data on the weight of 1000 grains, which was 5-6% higher in comparison with the option where the plain form of urea was used. Increasing the coating thickness from 50 to 100 µm posed no affect on the change in the elements of the yield formula.

The 50 µm coating thickness NPK fertilizer insignificantly increased the yield by 2%, while increasing the coating thickness to 100 µm provided a 9% increase in yield against the uncoated fertilizer. The crop yield increase in the variants with the coated fertilizers was achieved to a

Table 4. Effect of coated fertilizers on vegetative growth and yield characteristics of spring wheat during 2020/2022 seasons.

Treatments	Weight dry matter (g)					Number of grains in ear
	Plant	Grain	Straw	Ear	1000 grain	
2020						
T_1 - Control (PK)	15.1	4.9	10.2	0.4	29.1	10.5
T_2 - Urea	34.2	13.6	20.6	1.0	36.0	22.5
T_3 - Coated urea (50 µm)	38.3	16.0	22.3	1.2	35.0	27.0
T_4 - Coated urea (100 µm)	39.0	15.3	23.6	1.1	34.5	24.7
T_5 - NPK	38.1	15.4	22.7	1.1	36.3	23.4
T_6 - Coated NPK (50 µm)	38.2	14.9	23.3	1.0	35.9	23.4
T_7 - Coated NPK (100 µm)	42.3	17.3	25.0	1.1	35.9	25.5
LSD $_{(P=0,05)}$	2.6	0.8	1.9	0.2	3.9	3.1
2022						
T_1 - Control (PK)	26.7	11.4	15.4	0.7	33.4	17.1
T_2 - Urea	53.2	25.7	27.5	1.6	40.1	32.0
T_3 - Coated urea (50 µm)	59.9	27.4	32.5	1.7	41.1	33.5
T_4 - Coated urea (100 µm)	58.1	27.8	30.4	1.7	42.6	32.8
T_5 - NPK	55.0	25.4	29.7	1.6	40.4	31.5
T_6 - Coated NPK (50 µm)	57.1	26.7	30.3	1.7	40.8	32.8
T_7 - Coated NPK (100 µm)	58.6	27.2	31.5	1.7	41.1	33.1
LSD $_{(P=0,05)}$	3.9	1.6	2.9	0.1	1.9	2.6

LSD = least significant difference.

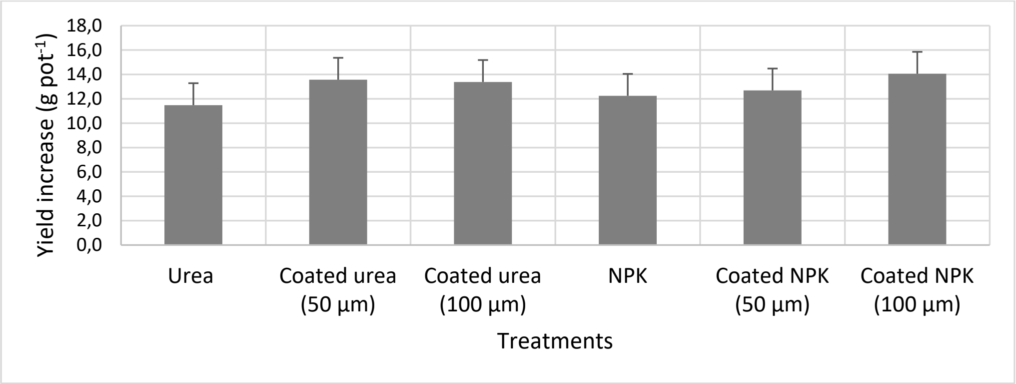

Figure 2. Yield increase from N-treatments over 0 N-treatment (LSD $_{(P=0.05)}$ = 1.8 g).

greater extent due to an increase in the ear grain content. There was also a tendency towards an increase in the weight of 1000 seeds (Figures 3 and 4).

The improved nutritional status of wheat plants achieved by coated fertilizers is confirmed by data on the basic nutrients uptaken by the yield (Table 5). In comparison with the conventional form of urea, in variants with the considered coated urea, the total uptake was higher for nitrogen by 14-20%, phosphorus by 11%, potassium by 4-10%. Coating the surface of NPK fertilizer granules contributed to an increase in nitrogen uptake by 9-12% and phosphorus by 14-19% and did not affect potassium consumption. In general, there was a tendency towards greated nutrients uptake in proportion to an increase in the granule coating thickness.

Coated fertilizers proved to be significantly more effective than conventional forms, as evidenced by the values of the recovery efficiency of applied N (RE_N, %).

Nutrients uptake and fertilizer N recovery efficiency calculation (Equations 1 and 2):

$$Nutrient\ uptake = \frac{Nutrient\ concentration\ in\ plant\,(\%) \times weight\ of\ dry\ metter\,(mg)}{100} \tag{1}$$

$$RE_N = \frac{N_{uptake}^{\text{in N treatment}} - N_{uptake}^{\text{in 0 N treatment}}}{N_{rate}} \times 100 \tag{2}$$

Table 5. Effect of coated fertilizers on nutrients uptake by spring wheat.

Treatments	Nutrients uptake (mg)									RE_N
	Grain			Straw			Total uptake			
	N	P	K	N	P	K	N	P	K	%
T_1 - Control (PK)	146	36	28	33	16	222	179	52	250	-
T_2 - Urea	484	85	66	124	19	392	608	104	458	57
T_3 - Coated urea (50 µm)	551	98	79	142	18	424	693	115	503	68
T_4 - Coated urea (100 µm)	563	97	73	164	18	405	727	115	478	73
T_5 - NPK	481	80	73	109	21	450	589	101	523	55
T_6 - Coated NPK (50 µm)	509	91	74	133	24	426	643	115	499	62
T_7 - Coated NPK (100 µm)	528	97	68	135	23	470	662	120	538	64
LSD $_{(P=0,05)}$	40	17	6	20	7	78	57	22	83	8

LSD = least significant difference.

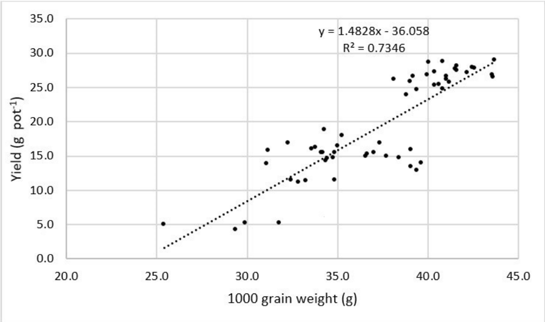

Figure 3. The relationship between yield and weight of 1000 grains (mean of two seasons).

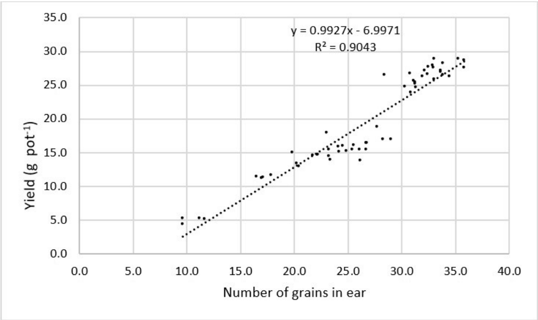

Figure 4. The relationship between yield and the number of grains per ear (mean of two seasons).

Fertilizer granules coated with calcium phosphate added to the carbamide nitrogen use efficiency by 11-16%, and NPK fertilizer by 7-9%. Also notable, that fertilizer use efficiency increased ratably to increasing granule coating thickness. This finding is consistent with another researchers. A pot study by Kamekawa et al. (1990) showed that plant N-NH_4^+ recovery was enhanced by applying fertilizer in the coated form (60%) rather than uncoated (40%). Also Acquaye and Inubushi (2004) shows on two soil types the N recovery averaged 74% when coated urea was applyied compared with an average of 39% for urea.

A pilot laboratory experiment to assess the intensity of conversion of fertilizer amide nitrogen in soil revealed that using monocalcium phosphate coated urea granules stably slows down the processes of ammonification and nitrification of nitrogen (Figures 5 and 6).

For instance, the variant with plain urea spotted the ammonium form of the added amide nitrogen in amount of 57% even on the second day of composting, 65% on the third day, and 68% on the fifth day, which indicates an intensive process of soil hydrolysis under the influence of urease. At the same time, in the variants with coated urea, the N-NH_4^+ content on the second day was only 14-23% of the total added, on the third day it was 39-59%, and only on the fifth day it reached the level of the plain fertilizer at 61-67% (Figure 5).

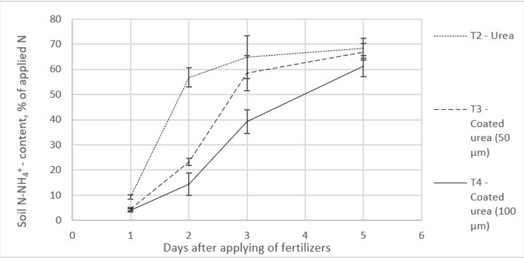

Figure 5. The intensity of ammonification of urea depending on the thickness of the coating. Error bars represent ± standard error of the mean (n=4).

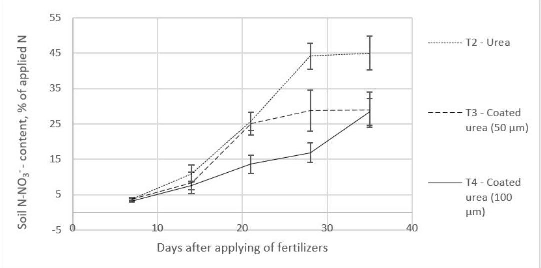

Figure 6. The intensity of nitrification of urea depending on the thickness of the coating. Error bars represent ± standard error of the mean (n=4).

The effect of inhibiting the ammonification process increased markedly with increasing granule coating thickness. A 50 μm coating significantly reduced the intensity of ammonification during the first two days of the experiment. In turn, 100 μm coating thickness suggests the prolongation of urea hydrolysis up to 5 days (Figure 5). Thus, monocalcium phosphate urea coating enables increasing the efficiency of fertilizer by reducing possible gas ammonia nitrogen decline in case of untimely application of fertilizers.

On top of that, coating the urea granules with calcium phosphate promoted a traceable slowdown in the nitrification process. Figure 6 shows that the most intense nitrification of urea nitrogen is visible on the 14th day of composting and continues up to 4 weeks, after which a plateau is observed.

Nitrogen oxidation in plain urea apparently proceeds with greater intensity and reaches a maximum on the 30th day, demonstrating 45% of total added. At the same time, in variants with slow release urea the $N\text{-}NO_3^-$ content is significantly lower and amounts to 20-28% of total added nitrogen. Meanwhile, a 100 μm thickness coating effectively slowed down the process of nitrogen nitrification, making it more uniform and extended over time, reducing nitrogen losses and increasing the efficiency of fertilizers.

Thus, coated fertilizers supply nitrogen and provide nutrition to crops for a longer period. This finding is consistent with Curitiba Espindula et al. (2013), ammonification and nitrification of coated fertilizers occurs more slowly, retaining nitrogen in the soil and will help plants absorb nitrogen, which will subsequently significantly improve growth and increase productivity.

4. Conclusions

Therefore, two-year greenhouse trials on soddy-podzolic soil showed that the monocalcium phosphate-coated mineral NPK fertilizer and urea granules increased the yield of spring wheat, and the thickness of the coating significantly influenced the biomass accumulation. With 100 μm coating thickness, the wheat yield was higher compared to options with 50 μm granule coating thickness. The form of coated fertilizers (urea and NPK fertilizers) had no significant effect on the yield data. It is telling that the soil fertilized with 50 and especially 100 μm coating urea accumulated considerably less ammonium and nitrate nitrogen against the soil in which uncoated fertilizers were applied.

The results of the experiments indicate a striking potential for reducing nitrogen decline from coated fertilizers and thereby ensure more efficient use of nutrients by plants.

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