BIO Web of Conferences **238**, 01013 (2026) https://doi.org/10.1051/bioconf/202623801013
ESDCA 2026

Yield of spring wheat under the application of nitrogen fertilizers containing a nitrification inhibitor

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Abstract. The present study assessed the efficacy of nitrogen fertilizers and the nitrification inhibitor 3.4-dimethylpyrazole phosphate (DMPP) in the cultivation of spring wheat (Triticum aestivum L.) on sod-podzolic light loam soil in the Central Non-Chernozem zone of the Russian Federation. A small-plot field experiment was conducted using urea and ammonium nitrate at a rate of 90 kg N ha^{-1}, with and without DMPP, on a phosphorus–potassium background. Plant height, yield components, grain protein and gluten accumulation, nutrient removal, and nitrogen use efficiency (NUE) were evaluated. Nitrogen fertilization significantly increased plant height (by an average of 10 cm), ear length (by 1 cm), 1000-grain weight (by 2.9 g), and the number of grains per ear (by 4). The use of the nitrification inhibitor further enhanced these effects, particularly in combination with urea. Application of DMPP increased grain yield by 19–21% relative to conventional nitrogen fertilizers, primarily due to an increase in the number of grains per ear by an average of 5. Grain protein content increased from 13.6 to 14.1%, whereas gluten content increased from 19.2 to 30.6–33.4%. Moreover, DMPP enhanced plant nitrogen uptake by 21% and increased NUE from 55 to 86%.

1 Introduction

In recent years, the focus of research on nitrogen nutrition systems has shifted from a predominantly yield-oriented approach towards a more comprehensive evaluation that explicitly considers parameters of nitrogen uptake by plants. A key indicator in this context is nitrogen use efficiency, which provides a quantitative measure of the proportion of applied nitrogen that is incorporated into crop growth and development. This metric is widely employed to assess the agronomic and economic effectiveness of mineral fertilizer application, as well as to analyse the environmental consequences associated with their use. Previous studies have demonstrated that, under production-scale field conditions and conventional fertilizer application practices, NUE for nitrogen seldom exceeds 40–60%. Consequently, a substantial share of the applied nitrogen is lost via nitrate leaching and

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denitrification, which reduces economic returns and increases the risk of environmental pollution [1, 2].

In addition to conventional strategies aimed at improving plant nitrogen uptake—such as splitting the total mineral nitrogen rate between basal application and top-dressings at physiologically critical growth stages, or combining different nitrogen fertilizer forms (e.g. using urea for basal application and ammonium nitrate or urea–ammonium nitrate solution as top-dressings)—current research also addresses the optimisation of sowing dates and the consideration of cultivar-specific traits of agricultural crops.

An additional strategy for reducing nitrogen losses involves the production of fertilizers with reduced solubility, such as urea–formaldehyde fertilizers, or the use of various coating materials that create a physical barrier to dissolution, i.e. encapsulated fertilizers. For example, in a wheat experiment [3], the application of polymer-coated urea (PSCU) resulted, first, in a 52% increase in grain yield and, second, in a 25% reduction in the nitrogen rate relative to the recommended dose, compared with conventional urea. In another study [4], when using urea treated with sulfur nanoparticles, the authors reported a 10% increase in grain mass of wheat and rice, as well as an average 30% increase in nitrogen use efficiency from this type of fertilizer.

Chitosan is another compound capable of slowing the dissolution of mineral fertilizers. Coating fertilizer granules with this naturally derived aminopolysaccharide markedly reduced the rate of nutrient release: over the same time period, substantially lower amounts of nitrogen, phosphorus, and potassium were released from encapsulated granules than from conventional (uncoated) fertilizers. Increasing the thickness of the chitosan coating further decreased the dissolution rate: at higher chitosan contents, the release rate of NPK declined, whereas the overall duration of nutrient release increased [5].

Considerable interest in both scientific and practical agriculture has been directed towards nitrification inhibitors [6]. These compounds help to retain ammonium nitrogen in the soil by delaying its conversion to nitrate, thereby maintaining it for a longer period within the root zone, and they also contribute to reducing emissions of nitrogen oxides to the atmosphere. In field experiments on rice, Ye et al. [7] demonstrated that the application of nitrogen fertilizers containing nitrification and urease inhibitors, compared with conventional urea, increased grain yield by 6–12% and nitrogen use efficiency by 10–25% (relative), while simultaneously reducing nitrate leaching with drainage water and N_2O emissions. The effect was most pronounced when an optimal combination of nitrogen rate and fertilizer form was used, ensuring closer synchronisation between nitrogen supply to the soil and the temporal pattern of crop nitrogen demand.

One of the most extensively studied active compounds in this group is 3,4-dimethylpyrazole phosphate (DMPP). It has been shown that DMPP selectively inhibits the activity of ammonia monooxygenase in ammonium-oxidising bacteria of the genus Nitrosomonas, thereby slowing the conversion of ammonium nitrogen (NH_4^+) to nitrate (NO_3^-), while having virtually no effect on total microbial biomass or on the activity of non-target microbial groups. Field and laboratory experiments have demonstrated that the use of DMPP in nitrogen fertilizers can reduce nitrous oxide emissions by 30–60% and simultaneously increase soil ammonium nitrogen content by 10–30% compared with fertilizers without the inhibitor [8, 9]. Yang et al. [10] reported that the use of nitrification inhibitors (DMPP, DCD, etc.) in cereal crops (including wheat) reduced N_2O emissions by an average of 38%, decreased nitrate leaching from the root zone by 16%, and concurrently increased grain yield by 7% and nitrogen use efficiency (NUE) by 13% relative to the control. Li et al. [11] demonstrated that the application of urea with DMPP in wheat and maize increased yield by 5–15% and NUE by 10–22% relative to conventional urea, while total nitrogen losses were reduced by 25–40%. In experiments with blueberry, the use of DMPP at various concentrations (0,5%, 1%, and 2%) increased soil N-NH_4^+ content and suppressed the conversion of ammonium to nitrate throughout the experimental period, thereby improving plant nutrition: leaf nitrogen content increased by 4–21% and phosphorus content by 10–28%, chlorophyll a and b concentrations increased irrespective of leaf position in the canopy, shoot length increased by 17–35%, and plant dry matter by an average of 33% compared with the control treatment [12].

The aim of this study was to investigate the effect of the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) on the formation of yield components in spring wheat and on the efficiency of two of the most widely used nitrogen fertilizer forms, urea and ammonium nitrate.

2 Materials and methods

The study was conducted in 2023 as a small-plot field experiment at the Field Experimental Station of the Russian State Agrarian University – Moscow Timiryazev Agricultural Academy (RSAU-MTAA) named after K.A. Timiryazev. The soil of the experimental site was a cultivated soddy weakly podzolic soil with a humus content of 2.47%, pH(KCl) 5.9, a high content of available phosphorus (according to Kirsanov) – 203 mg kg^{-1}, a medium content of exchangeable potassium (according to Kirsanov) – 100 mg kg^{-1}, and a very low content of alkali-hydrolysable nitrogen (according to Kornfield) – 95 mg kg^{-1}.

The test crop was spring wheat (Triticum aestivum L.), cv. Lyubava. Nitrogen fertilizers, urea (46% N) and ammonium nitrate (34% N), were applied once before sowing at a rate of 90 kg N ha^{-1}. Prior to application, the nitrogen fertilizers were treated with the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) at a rate of 1.6% of the applied nitrogen dose.

Chemical analyses of plant samples were carried out using standard procedures after wet ashing in sulfuric acid in the presence of selenium. Nitrogen content was determined by the colorimetric indophenol method, phosphorus by the colorimetric molybdate method, and potassium by flame photometry.

Nutrient removal was calculated according to Equation (1):

$$R_{kg\ ha^{-1}} = \frac{Y \times 1000\ \times C \times N_{\%}}{100} \tag{1}$$

where Y is grain yield, t ha^{-1}; 1000 is the conversion factor to kg; C is the conversion coefficient to dry matter; N% is nitrogen content, %.

Nitrogen use efficiency (NUE) was calculated according to Equation (2):

$$NUE_{\%} = \frac{RN_{NPK} - RN_{PK}}{D_N} \times 100 \tag{2}$$

где, RN_{NPK} – is nitrogen removal in the treatment with nitrogen fertilizer, kg ha^{-1}; RN_{PK} – is nitrogen removal in the control treatment (without nitrogen), kg ha^{-1}; D_N – is the nitrogen fertilizer rate, kg ha^{-1}.

3 Results and discussion

The results of the study indicated that the application of nitrogen fertilizers and nitrification inhibitors was associated with a tendency towards increased plant height and the formation of larger ears. In treatments with nitrogen application, plant height increased by 3–7 cm and ear length by 9–11 mm, with urea producing taller plants and longer ear s than ammonium nitrate (Fig. 1). The nitrification inhibitor exerted a positive effect on plant linear dimensions only when applied in combination with urea, further increasing plant height and ear length by 3 and 5%, respectively. Comparable increases in plant growth under the combined use of DMPP and urea were reported by Zerulla et al. [8], who observed a 5–10% increase in plant height.

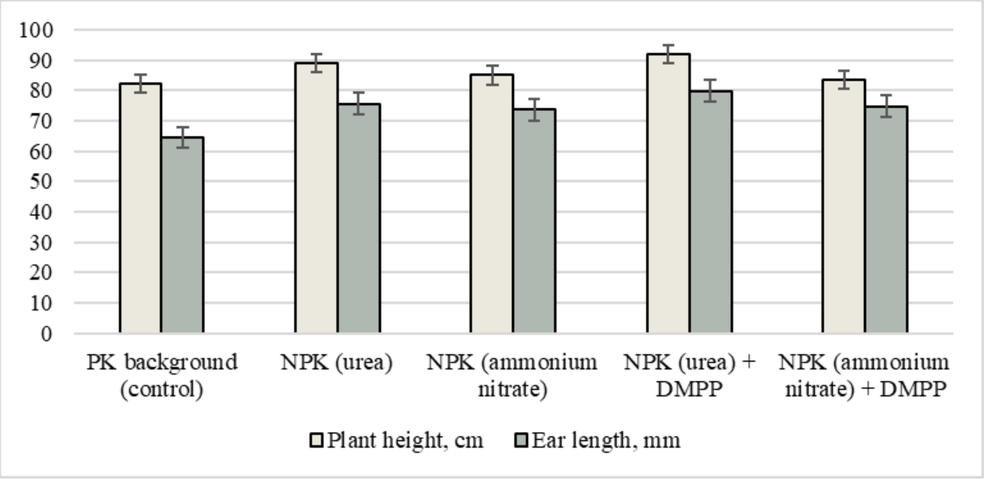

Fig. 1. Effect of nitrogen fertilizers and the nitrification inhibitor on plant growth parameters. Error bars represent LSD_{05}.

The application of both conventional nitrogen fertilizers and those modified with a nitrification inhibitor had a pronounced effect on the formation of yield components in spring wheat. As shown in Fig. 2a, the use of either urea or ammonium nitrate increased single-plant mass by an average of 30%, whereas the incorporation of the nitrification inhibitor increased this parameter by 55%.

Ear mass also increased, by 30% with conventional nitrogen fertilizers and by 53% with fertilizers containing the inhibitor. The effect of agrochemicals was even more pronounced for grain mass per ear. Application of urea and ammonium nitrate increased grain mass per ear by 33%, while the use of fertilizers in combination with DMPP led to a 62% increase. A similar pattern of changes in yield components under DMPP application was reported by Yang et al. [10], who observed average increases of 15–30% in ear mass and grain mass per ear.

The simultaneous increase in plant mass, ear mass, and grain mass per ear indicates that the use of DMPP not only enhances vegetative growth but also improves grain filling by more closely matching the temporal dynamics of mineral nitrogen supply with crop nitrogen demand during critical phases of organogenesis.

It should be noted that the combined application of DMPP with urea exerted a more pronounced and statistically significant effect on the formation of yield components than its use with ammonium nitrate. When urea was treated with DMPP, single-plant mass, ear mass, and grain mass per ear increased by 35, 27, and 39%, respectively, compared with conventional urea, whereas for ammonium nitrate treated with DMPP these parameters increased by only 6, 9, and 6%, respectively. This difference in the effectiveness of the nitrogen fertilizer forms is likely due to the fact that, in the case of urea, nitrogen is initially present in the ammonium form, which is more strongly affected by the nitrification inhibitor, whereas in ammonium nitrate a substantial proportion of nitrogen is already in the nitrate form and therefore less sensitive to the action of DMPP. As a result, the use of urea with DMPP provides a more prolonged nitrogen supply, which is supported by both field and laboratory studies.

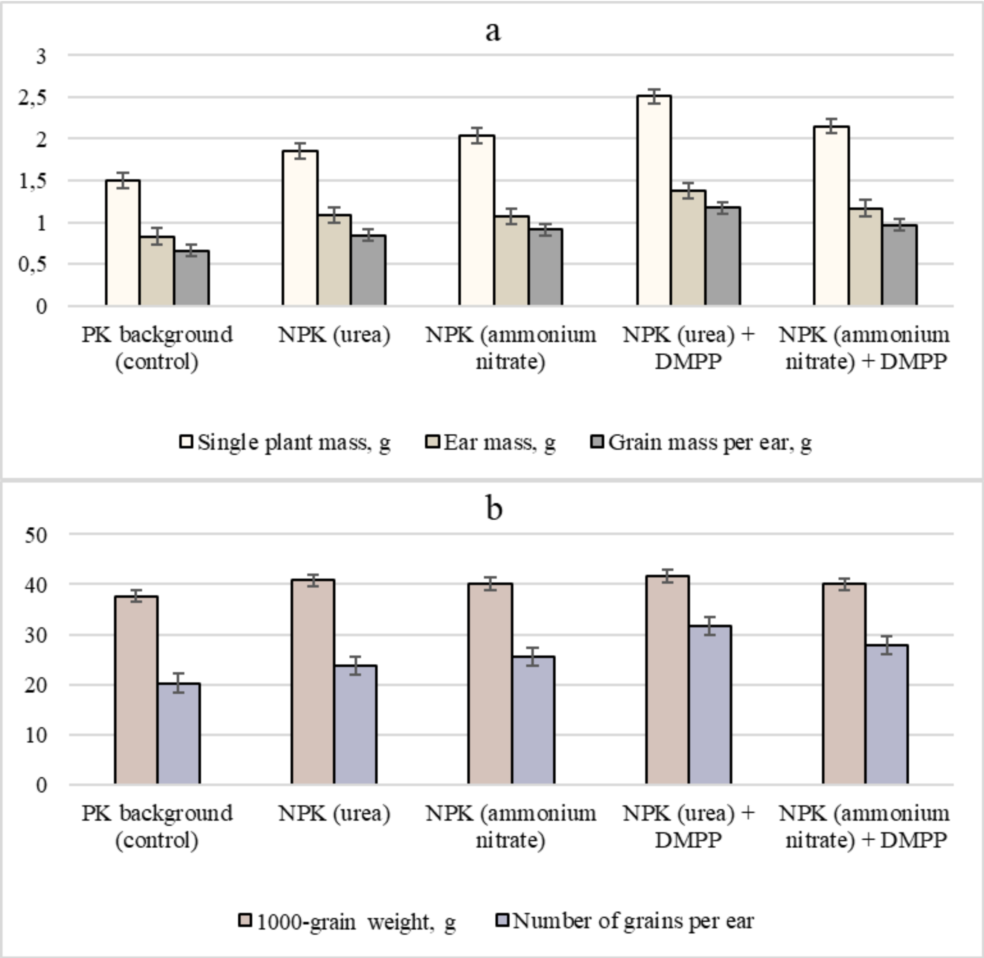

Fig. 2. Yield components of spring wheat. Error bars represent LSD_{05}.

An important indicator influencing cereal grain yield formation is the 1000-grain weight. The results showed that the application of all tested nitrogen fertilizers led to a significant increase in this parameter from 37.6 g to 40.0–41.6 g, irrespective of fertilizer form or the use of the nitrification inhibitor.

The second key yield component that can substantially affect grain productivity is the number of grains per ear. It was found that the application of conventional urea and ammonium nitrate increased the number of grains per ear by an average of 3.5 and 5.3 grains, respectively. The use of fertilizers in combination with nitrification inhibitors had a much stronger effect on grain set, increasing the number of grains per ear by 11.4 and 7.6 grains, respectively. It should be noted that the previously observed pattern of greater effectiveness of DMPP when applied with urea than with ammonium nitrate was retained. In the treatment with DMPP-treated urea, the additional increase in the number of grains per ear was 33%, whereas in the treatment with DMPP-treated ammonium nitrate it was only 9%. Similar data were reported by Wu et al. [13], who showed that the combined application of DMPP and biochar increased the number of grains per ear in wheat by 25–

40%. The increase in ear grain set in the DMPP treatments may be associated with improved functional activity of the reproductive organs and more optimal timing of nitrogen supply during flowering and the onset of heading, when the final number of grains is determined.

As shown in Fig. 3, all mineral fertilizer treatments had a pronounced effect on increasing spring wheat grain yield. Yield increments from the application of ammonium nitrate and urea were 1.51 and 1.88 t ha^{-1}, respectively. The use of the nitrification inhibitor resulted in an additional significant yield increase of 19–21%. Comparable yield gains (5–25%) from the use of DMPP and DCD have been reported in the studies by Yang et al. [10].

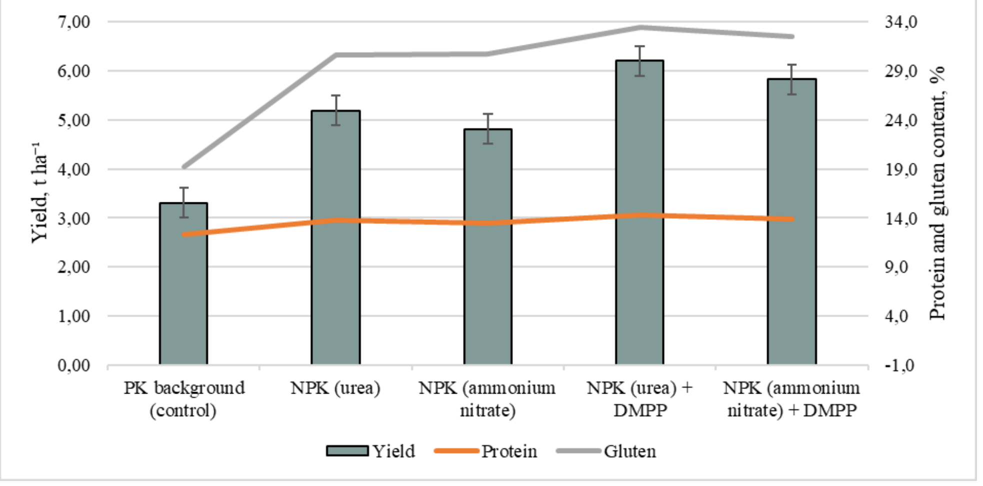

Fig. 3. Yield and quality of spring wheat. Error bars represent LSD_{05}.

The yield increase obtained with nitrogen fertilization was accompanied by an improvement in the main quality parameters of spring wheat grain. In treatments with conventional nitrogen fertilizers, grain protein content was 1,2–1,5% higher than in the control and ranged from 13,5 to 13,8%. The use of the nitrification inhibitor further increased protein content by an additional 0,3–0,5%. Similar findings were reported by Li et al. [14], who showed that the application of stabilized nitrogen fertilizers increased grain protein content in maize by 0,4–0,6%.

Nitrogen fertilization exerted an even stronger effect on grain gluten content. In the control treatment, gluten content was only 19,2%, whereas the application of various nitrogen fertilizer forms increased this value to 30,6–33,4%. It should be noted that the use of the nitrification inhibitor resulted in a further increase in grain gluten content by 1,8–2,8 %.

Based on the results of the chemical analysis of the harvested yield, nutrient removal with the main and by-products was calculated (Table 1). As indicated by the data obtained, total nutrient uptake was closely correlated with grain yield, and the highest nutrient removal was observed in treatments where nitrogen fertilizers were applied in combination with the nitrification inhibitor.

Table 1. Nutrient removal and nitrogen use efficiency of fertilizers.

Treatment	Nutrient removal						NUE
	kg ha⁻¹			kg t⁻¹			
	N	P	K	N	P	K	%
PK background (control)	79	17	46	24	5	14	-
NPK (urea)	137	30	77	26	6	12	63.9
NPK (ammonium nitrate)	121	31	76	25	6	13	46.6
NPK (urea) + DMPP	161	36	93	26	6	13	90.6
NPK (ammonium nitrate) + DMPP	153	34	94	26	6	13	81.2

NUE was strongly affected by fertilizer form and the use of the nitrification inhibitor. The nitrogen use efficiency of amide nitrogen was higher than that of ammonium nitrate and amounted to 64% versus 47%. The application of DMPP substantially enhanced nitrogen utilization by plants, increasing NUE to 81% and 91% when used in combination with ammonium nitrate and urea, respectively.

Soil mineral nutrition diagnostics showed that, at the heading stage, plant nitrogen supply was markedly higher in treatments with the nitrification inhibitor (Table 2). DMPP promoted the retention of ammonium nitrogen in the soil over an extended period, which presumably reduced nitrate losses through leaching and denitrification and resulted in higher contents of mineral nitrogen forms. When DMPP was applied together with urea, the soil ammonium nitrogen content reached 36 mg kg^{-1}, i.e. 23 mg kg^{-1} higher than under conventional urea. In the treatment with ammonium nitrate plus DMPP, soil ammonium nitrogen content was substantially lower, at 21 mg kg^{-1}, which is attributable to the fact that only half of the nitrogen in this fertilizer is present in ammonium form.

A strong correlation was observed between soil mineral nitrogen content and grain yield, as evidenced by the pairwise linear correlation coefficients (r = 0.72–0.80). The closest relationships were found between yield and soil ammonium nitrogen (r = 0.79) and between yield and total mineral nitrogen (r = 0.80).

Table 2. Soil mineral nitrogen content at heading stage, mg kg^{-1}

Treatment	N-NH_4^-	N-NO_3^-	Nmin
PK background (control)	10	9	19
NPK (urea)	13	10	22
NPK (ammonium nitrate)	17	8	25
NPK (urea) + DMPP	36	13	49
NPK (ammonium nitrate) + DMPP	21	11	32
r*	0.79	0.72	0.80

*r – linear correlation coefficient between soil mineral nitrogen content and spring wheat grain yield

4 Conclusion

Thus, the present study showed that the use of the nitrification inhibitor DMPP led to higher soil contents of mineral nitrogen forms, particularly ammonium nitrogen, which contributed to a 19–21% increase in spring wheat grain yield compared with treatments receiving nitrogen fertilizers without the inhibitor. At the heading stage, a marked increase in soil ammonium and total mineral nitrogen contents was observed in the DMPP treatments (up to 49 mg kg^{-1} versus 22 mg kg^{-1} without DMPP). A close positive relationship between soil mineral nitrogen supply and grain yield (r = 0,72–0,80) was established, confirming the key role of improved nitrogen nutrition in the realization of yield potential.

The improved nitrogen supply was accompanied by an increase in nitrogen use efficiency from 47–64% to 81–91% and by higher nitrogen removal with the harvested yield, indicating more complete uptake of applied nitrogen and the formation of more vigorous and productive plants. Yield gains were mainly associated with improved yield components, particularly an increase in the number of grains per ear (33% more grains when DMPP was applied together with urea) and an increase in grain mass per ear. In parallel with yield increases, nitrogen fertilization enhanced grain protein and gluten contents, while the use of the nitrification inhibitor further raised these parameters by 0,3–0,5 and 1,8–2,8 percentage points, respectively. Under the influence of DMPP, nitrogen use efficiency increased by 27% when urea was used and by 35% when ammonium nitrate was applied, which together accounts for the observed yield increase and improvement in grain quality.

Acknowledgments

This study was funded by the special project of University development "Strategic academic leadership program 'Priority 2030'".

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