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Prospects for nitrogen fertilization management of corn crops: a review of modern concepts

K. Kuriacha

Article info

Correspondence Author
K. Kuriacha
E-mail:
kateryna.kuriacha@pdau.edu.ua

Poltava State Agrarian University,
Skovoroda Str., 1/3,
Poltava, 36000, Ukraine

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The main purpose of this review was the problem of optimizing nitrogen fertilization of corn crops in the light of recent trends, taking into account the requirements of the ecological and economic approach to the development of cultivation technologies. Based on the review of the research results by Ukrainian and foreign scientists, modern methods of nitrogen fertilization management are described. In particular, this concerns the differentiated application of nitrogen fertilizers using complex organic-mineral fertilizers, which comprise humic compounds, nitrification inhibitors and urease inhibitors. The review draws attention to controversial issues of corn crops' fertilization and contradictions regarding the effectiveness of the use. These include the rate of nitrification of the soil rhizosphere, inhibition of nitrification processes and the effectiveness of the impact on yield formation. The information on the efficacy of using 3, 4-dimethylpyrazole phosphate and thiophosphoric triamide as nitrification inhibitors from economic and environmental points of view is given in the article. A brief analysis of the use of the group of 2-(3, 4-dimethyl-1H-pyrazol-1-yl) isomeric mixture of succinic acid, nitrapyrin or pronitridine is conducted. Attention is paid to the peculiarities of the behavior of nitrification inhibitor substances depending on the properties of soils and climatic factors. The conclusion is made as to the simultaneous use of two strategies – the application of urease inhibitor and nitrification inhibitor. The presented review of scientific sources does not indicate the unanimity of opinions concerning the use of nitrogen inhibitors. Scientists are overwhelmingly inclined to the usefulness of applying inhibitors to reduce greenhouse gas emissions into the atmosphere and the economic efficiency of reducing the rates of nitrogen fertilizers' application, but there are also data on the questionable impact of inhibitors on nitrogen losses into the atmosphere and their impact on yield formation. On the one hand, nitrogen inhibitors can be crucial in reducing nutrient losses and increasing the effectiveness of the use of expensive nitrogen fertilizers and raising plant productivity by 41–79 %, especially when applying stabilized nitrogen fertilizers of increased efficacy. They play an important role in the 4R cultivation concept, which envisages ecological and economic approach to growing crops. On the other hand, while reducing nitrogen losses, they do not increase yields in any way, especially in combination with the use of such fertilizers.

Keywords: corn, fertilization, fertilizers, nitrogen, inhibitors, humin.

Перспективи управління азотним живленням посівів кукурудзи: огляд сучасних концепцій

К. О. Куряча

Полтавський державний аграрний університет,
м. Полтава, Україна

Головною метою цього огляду була проблематика оптимізації азотного живлення посівів кукурудзи у світлі останніх тенденцій з огляду на вимоги еколого-економічного підходу до розробки технологій вирощування. На основі огляду результатів досліджень вітчизняних і закордонних учених описано сучасні методи управління азотним живленням. Зокрема це стосується диференційованого внесення азотних добрив із застосуванням комплексних органо-мінеральних добрив, до складу яких вводять гумінові сполуки, інгібітори нітрифікації та інгібітори уреази. В розвідці приділено увагу дискусійним питанням удобрення посівів кукурудзи та протиріччям стосовно ефективності використання. До таких відносять швидкість нітрифікації ризосфери ґрунту, пригнічення процесів нітрифікації та ефективність впливу на формування урожайності. У статті подано інформацію щодо ефективності застосування як інгібіторів нітрифікації 3,4-диметилпіразолфосфату та тіофосфорного триаміду з економічної та екологічної точок зору. Проведено короткий аналіз використання групи 2-(3,4-диметил-1Н-піразол-1-іл) ізомерної суміші бурштинової кислоти, нітрапірину або пронітридину. Звернено увагу на особливості функціонування речовин інгібіторів нітрифікації залежно від властивостей ґрунтів, кліматичних факторів. Зроблено висновок про одночасне застосування двох стратегій – використання інгібітора уреази та інгібітора нітрифікації. Наведений огляд наукових джерел свідчить про неоднозначність думок щодо використання інгібіторів азоту. Вчені переважно погоджуються з думкою щодо користі застосування інгібіторів для зменшення викидів парникових газів у атмосферу та економічної ефективності від зменшення норм внесення азотних добрив, але існують і дані про сумнівний вплив інгібіторів на втрати азоту в атмосферу й їхній вплив на формування врожайності. З одного боку, інгібітори азоту можуть мати вирішальне значення, зменшуючи втрати поживних речовин та збільшуючи ефективність застосування вартісних азотних добрив і збільшувати продуктивність рослин на 41–79 %, особливо якщо використовувати стабілізовані азотні добрива підвищеної ефективності. Вони відіграють важливу роль у концепції вирощування 4R, яка передбачає еколого-економічний підхід до вирощування сільськогосподарських культур. З іншого боку, зменшуючи втрати азоту, вони жодним чином не збільшують урожайність, до того ж і разом із застосуванням таких добрив.

Ключові слова: кукурудза, удобрення, добрива, азот, інгібітори, гумін.

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The role of nitrogen fertilization in corn yield formation is well known. In modern agronomy, the attention is paid to optimizing fertilizers' application in order to improve the efficiency of using expensive nitrogen fertilizers and reducing the harmful effect of nitrogen on the environment.

It is also well known that for growing corn it is expedient to use differentiated nitrogen application or apply complex fertilizers. According to S. M. Kalenska and R. V. Hovenka's data, plastic corn hybrids were able to increase the yield by almost 16 % when using diammonium phosphate at the rate of $N_{22}P_{57}K_{57}$, and additional nitrogen application contributed to further yield increase by 8–18.6 % [1].

The use of complex organic-mineral fertilizers, which include humic compounds, neem oil (*Azadirachta indica*), moringa (*Moringa oleifera*), pomegranate leaves (*Punica granatum*), etc., is quite promising [2, 3]. In the latter case, the coating of carbamide granules with these substances delayed nitrification for up to 30 days, which significantly reduced nitrogen losses and contributed to better plant productivity. Nitrogen losses were reduced from 48 to 2 %.

The greatest concern of scientists is the growing greenhouse effect, which is provoked by emissions of greenhouse gases into the atmosphere, including N_2O and NH_3. The main sources of emissions, in the agronomic aspect, are the use of nitrogen fertilizers, which are also not fully absorbed by plants and, thus, reduce the economic effect. To reduce these negative processes, the use of nitrification inhibitors and urease inhibitors is proposed. Not only the aforementioned plant components or products can be used as inhibitors.

The inhibition of nitrification processes can be achieved by both chemical and natural substances, as well as biological preparations. 3, 4-dimethylpyrazole phosphate is one of the chemicals used as nitrification inhibitors. The use of this inhibitor in combination with UAN-32 at a rate of 300 kg/ha against the background of $N_{32}P_{30}K_{42}$ gave the increase in the yield by 17–19.8 %, i.e. by 1.11–1.68 c/ha, which was quite convincingly demonstrated by field diagnostics using NDVI. The yield capacity also depended to a large extent on the sum of active temperatures [4].

As J. Muller et al. note, the use of urea coated with 3, 4-dimethylpyrazole phosphate at a rate lower by 20 % reduced N_2O emissions by 51 % without reducing the yield capacity [5]. The use of 3, 4-dimethylpyrazole phosphate for two years allowed a 23 % reduction in nitrogen fertilizers' rates in the second year, which gives the prospect of using this substance to reduce nitrogen fertilizers' rates [6].

However, there are less optimistic scenarios of the action of 3, 4-dimethylpyrazole phosphate. For example, in the studies of X.-L. Wang et al., the use of this inhibitor reduced the rate of the soil rhizosphere nitrification, which negatively influenced the growth of corn plants and the effectiveness of their water consumption [7].

In these studies, an increase in corn yields by 8.1–21.2 % was also registered. On the whole, it was possible to speak about the effectiveness of using nitrogen inhibitors: 3, 4-dimethylpyrazole phosphate and thiophosphoric triamide from the economic and environmental points of view [8]. Thiophosphoric triamide gave relatively better results concerning nitrogen content in the soil and increased yield capacity [9]. The use of 3, 4-dimethylpyrazole phosphate together with digestate increased plant biomass by almost half – 49 % in the experiments conducted to determine the effectiveness of the combined use of inhibitors with organic fertilizers [10].

Both of the above mentioned nitrification inhibitors can reduce nitrogen emissions into the atmosphere and increase corn yields, but their effect can largely depend on the conditions of the year, the agrochemical characteristics of the soils at the location of application, the term and many other factors [11]. The corn yields increase by 1.85 c/ha was possible, but under high temperatures, the use of such inhibitors may be generally insignificant, not exceeding 4–7 % [12, 13].

Similar data were obtained in the studies with 3, 4-dimethylpyrazol succinic acid. In most cases, lower nitrogen losses of 25 % due to leaching were observed, but no differences in plant development between the variants were observed [14]. In case of using the substance from the same group, 2-(3,4-dimethyl-1H-pyrazol-1-yl) isomeric mixture of succinic acid, a significant decrease in residual nitrogen in fertilizers was observed, although a significant increase in root mass was registered – up to 64 % [15]. In other studies, the effectiveness of the inhibitors' use largely depended on the method of soil cultivation – after plowing, NH_3 emissions decreased by up to 64 %, and in case of no-till – up to 53 % and more [16].

Quite widespread are the studies on determining the effect of nitrapyrin or pronitridine as the nitrification inhibitor, which also significantly softens environmental consequences [17] that are considered by some authors to be almost equivalent in effectiveness. In favorable years, to obtain yields at the level of the use of inhibitors, the rate of UAN had to be increased by 14–19 %. The use of nitrification inhibitors of this group inhibits the activity of microbial enzymes that catalyze the first stage of the transition of ammonium to nitrite. From the ecological point of view, the impact of nitrapyrin on the environment has not yet been studied and it is quite possible that the use of inhibitors has only economic benefits [18].

The use of these preparations is considered to be one of the most effective strategies for applying nitrogen fertilizers due to the possibility of saving them and reducing emissions into the atmosphere. According to the research results by B. Ren et al., the use of nitrapyrin increased the yield capacity by 3.4–5.7 % and compensated the differentiated application of nitrogen fertilizers, and sometimes increased it by 19 % [19].

The addition of inhibitors to organic fertilizers also has its prospects, as it significantly reduced ammonia emissions from the soil by 46 % if cattle manure or straw was used, and the addition of straw was an important element of nitrogen fertilization management [20]. There are also data of the positive effect of applying inhibitors together with poultry manure for plants' phosphorus fertilization management [21].

Pakistan's scientists recorded the data when urea treatment with pronitridine reduced nitrogen emissions into the atmosphere of N_2O by 39–43 %. At the same time, plant biomass, grain yield and total nitrogen uptake increased by 23, 17 and 15 %, respectively [22].

In the experiments of Singh G., Nelson K.A, the use of pronitridine in the fall increased the corn yields by 7 % in a lean year [23]. Other research results indicate the same effect of application in the spring [24], although there is evidence of the need to increase the rates of nitrogen application in the

fall [25]. The autumn application of nitrapyrin increased the NH_4N content by 21–63 % and ensured a higher content of total mineral nitrogen in the spring by 10–19 %, while the spring application increased it by 25 % [26]. It should also be mentioned that nitrification inhibitors can have a positive effect in the years with high precipitation [27].

At the same time, there are also alternative results to the above presented ones, which indicate the absence of a positive effect from the use of nitrification inhibitors on the formation of yield and its quality. Based on 1,248 observations, R. Cook et al. found that the effectiveness of the use of inhibitors can be influenced by soil and climatic factors, methods of cultivation technologies and many others, which, however, does not deny the prospects for the use of inhibitors [28]. According to Omonode R.A, Vyn T.J, nitrapyrin did not increase corn yields, but reduced cumulative seasonal N_2O emissions [29].

An important role in the use of nitrification inhibitors is played by weather factors that also influence the terms of conducting technological operations, including sowing and applying inhibitors. Late treatment with nitrapyrin contributed to an increase in such indicators as the length and diameter of the corn ear, the number of rows in it, grains, but did not affect the formation of thousand-kernel weight [30]. According to G. Guardia et al. nitrogen inhibitors did not affect grain yields in case of rainy conditions, but may affect nitrogen content [31].

There is insufficient information on the behavior peculiarities of nitrification inhibitors' substances depending on soil properties, although a positive effect on reducing NH_3 and N_2O evaporation was registered on black soils; positive results were also obtained on poorly drained clay soils. The use of nitrapyrin turned out to be effective in V5 phase of corn development, increasing its yield capacity by 1.5 t/ha at the same time reducing N_2O emissions [32].

In the works of Ukrainian scientists, it was noted that the use of Stabiluren 30 inhibitor with Aminomax and Aidamin fertilizers and Stim Organic destructor, 2 l/ha used for foliar application in the period of 15 leaves – flowering, assisted in enlarging the leaf area. The use of this method in the milky ripeness phase did not give positive results. The effect of the nitrogen inhibitor on grain quality indicators, in particular protein content, was not observed [33]. In the conditions of Poltava region, the use of nitrification inhibitor based on 1H-pyrazole, 3, 4-dimethylphosphate (DMPP) delayed the release of nitrogen, which contributed to a decrease in the use of machinery and had a positive impact on the distribution of nitrogen in the soil – the content of ammonium nitrogen exceeded the control variant by 38–85 % [34].

In the studies by C.F Drury et al., B. Ren et al. with urea on the variants with the use of urease inhibitors, ammonia losses were reduced by 64 %, but N_2O emissions increased by 30 %. Thus, it was concluded that the simultaneous use of two strategies – the application of urease inhibitor and nitrification inhibitor – was effective. In this case, corn yield increased by 19 %, significantly reducing greenhouse gas emissions [35, 36]. The so-called dual strategy may also be effective in case of the use of cattle manure.

The use of the nitrification inhibitor dicyandiamide and 1, 2, 4-triazole reduced the soil nitrate nitrogen content by 7–32 % and increased the ammonium nitrogen content by 10-59 %. Dicyandiamide contributes to an increase in the mineral nitrogen content in the soil in 30 days after sowing [37]. The application of this substance together with pig manure did not increase corn yields in case of zero tillage, in contrast to the effect on wheat. This was apparently connected with the time of fertilizer application [38]. When this substance was used as a coating for urea granules, N_2O-N emissions into the atmosphere were reduced by 75 % [39].

In warm, humid climates, the use of dicyandiamide together with pig manure can be very effective in reducing nitrogen emissions into the atmosphere and better managing phosphorous nutrition of plants [40]. The application of digestate as an organic component for plant nutrition also requires the use of inhibitors that can reduce nitrogen losses by two to four times and become a valuable replacement of mineral fertilizers [41]. Dicyandiamide had little impact on yield formation and its use probably had environmental advantages. However, in humid conditions, nitrogen emissions can be high, regardless of the use of the substance, and the impact of the preparation on the yields was not observed. As it can be seen, this somewhat contradicts the previously presented material on the expediency of applying dicyandiamide in humid conditions.

According to M. Ahmed et al., the use of dicyandiamide contributed to better nitrogen assimilation effectiveness and an increase in corn yield capacity by 15–20 % compared to the variants in which untreated urea was used [42].

In the studies by Brazilian scientists, it was observed that adding a nitrification inhibitor to urea increased nitrogen losses as a result of NH_3-N evaporation by up to 46 %, although when ammonium sulfate or ammonium nitrate with the addition of an inhibitor was used, these losses were reduced by 54–80 % [43].

The use of N-(n-butyl) thiophosphoric triamide with urea at concentrations of 20, 26.7 and 30 % reduced the total ammonia loss because of evaporation by 35.4–81.9 %, 77.3–87.4 % and 59.1–83.3 % within 20 days after nitrogen application, while the yields increased by 12.9–34.8 %, 18.7–19.9 % and 14.6–41.1 %, respectively. It is mentioned that the use of inhibitors is effective in technologies when fertilizers are surface applied. The use of this inhibitor with UAN contributed to an increase in corn yields by 16.6 % [44].

The use of inhibitors is a promising method for reducing greenhouse gas emissions into the atmosphere and increasing crop yields. However, as it is noted by A.A Pawlick et al., no fertilizers applied with urease inhibitors reduced NO_3-N leaching [45]. But long-term and large-scale studies are necessary to find the patterns and mechanisms of nitrogen inhibitors' action.

The time of nitrogen fertilizers' application plays an important role. When urease inhibitors were used with fertilizers before sowing, ammonia losses were reduced by 34–99 % and this increased grain yield capacity by 83 % compared to the unfertilized control variant, and in other studies, NH_3-N losses were reduced by 46–80 %. As it was previously mentioned, the use of nitrogen inhibitors can contribute to a decrease in the frequency of nitrogen fertilizers' applications, since a single application of nitrogen-sulfur fertilizer with nitrogen inhibitors contributed to a growth in corn yields by 21.8 % [46, 47]. It has also been observed that nitrogen inhibitors are more effective when used for lower nitrogen fertilizers' rates [48].

To improve the efficacy of nitrogen fertilization management, various types of organic substances are also used – bio-char, humic acids and their salts or, for example, some plants – *Brassica juncea*, coarse litter for livestock, etc. The use of bio-char is effective for improving the physical properties of the soil – hydraulic conductivity, structure, bulk density, porosity and electrical conductivity [49]. Even herbicides based on glyphosate can have an inhibitory effect [50]. It should be taken into account that the correct application of various organic fertilizers contributes to the growth of the number of usefull microorganisms in the soil, capable of retaining various forms of nitrogen without the use of chemical inhibitors.

The use of urea in combination with potassium humate was able to increase the yields of corn grain by 7–30.5 %, and also contributed to the accumulation of vegetative mass, on the basis of which conclusions were drawn about the high effectiveness of urea treated with potassium humate. The suspensions of humic and fulvic acids made it possible to obtain an increase in corn yields while simultaneously reducing the rates of nitrogen fertilizers [51].

The above presented review of scientific sources indicates that the opinions on the use of nitrogen inhibitors are different. The majority of scientists are inclined to the usefulness of applying inhibitors to reduce greenhouse gas emissions into the atmosphere and the economic efficiency of reducing nitrogen fertilizers' application rates, but there are also data of the doubtful effect of inhibitors on nitrogen losses into the atmosphere and their impact on yield formation [52].

On the one hand, nitrogen inhibitors can be crucial in reducing nutrient losses and raising the efficacy of applying expensive nitrogen fertilizers and increasing plant productivity by 41–79 %, especially when using stabilized nitrogen fertilizers of increased effectiveness [53–56]. They play an important role in the 4R cultivation concept, which envisages the ecological and economic approach to crop cultivation. On the other hand, while reducing nitrogen losses, they do not increase yield in any way [57], moreover, in combination with the use of such fertilizers [58].

In light of the fact that nitrogen fertilizers are very important for yields increase, their widespread use has global impacts. They have become the main source of nitrous oxide and its various oxides' emissions into the atmosphere therefore it is considered that a significant reduction in this negative phenomenon can be achieved through the use of urease and nitrification inhibitors [59].

A much more effective decrease in nitrogen emissions into the atmosphere can be achieved by combining the use of nitrogen inhibitors with soil cultivation methods [29, 57] or fertigation. In terms of obtaining a high yield, urea with an inhibitor gave high results in only one of the three research years.

Recently, Ukrainian farmers have been resorting to using anhydrous ammonia in their fields, but there are a number of cautions when using this fertilizer, because of the high nutrient losses. In the studies by W. Neels et al. it was found that the sources of nitrogen supply played a significant role in the yield formation and the amount of losses. The retention of NH_4 + –N in the soil on anhydrous ammonia was by 340 % higher compared to urea. The inhibitor ensured the similar indicator at the level of 14–50 % [60].

Nitrogen inhibitors can play an important role in improving the efficacy of phosphorus fertilizers' use. Delaying the process of nitrification probably results in phosphorus release and its better utilization by 29 % [61, 62], and sometimes also contributes to better magnesium use indicators. The use of inhibitors with simultaneous use of sulfur containing fertilizers also favors the assimilation of this important nutrient element, increasing not only the yields but also the protein content in the grain [46].

Thus, the issue of effective nitrogen management is a global challenge. Despite more than 50 years of the experience in using nitrogen inhibitors in crop growing, there are opposite opinions and views on the effectiveness of their use. Meta-analyses of the data indicate both the positive role of these preparations in the yield formation and the neutrality of their use or even the negative impact. Some sources emphasize the prospects of applying them as a promising method to reduce the negative influence from the use of mineral nitrogen fertilizers however it is not always possible to achieve the effect even from the combined application of inhibitors with fertilizers of increased efficacy.

The absence of the positive effect from the use of nitrogen inhibitors with fertilizers may be connected with soils peculiarities, weather conditions, and, moreover, there may even be a complete absence of any agronomic advantages. Many scientists emphasize the need for long-term studies to clarify as many nuances of the use of such substances as possible. Interpreting the conclusions of D. Fan et al., obtained as a result of meta-regression and multivariate data analyses [63], it can be concluded about the probable result of using nitrogen inhibitors. This probabilistic effect may largely depend on changes in weather conditions or time of fertilizer' application and it may also happen that even the use of highly effective new fertilizers may not lead to an increase in yields.

Conclusions

The main purpose of this review was the problem of optimizing nitrogen fertilization of corn crops in the light of recent trends, taking into account the requirements of the ecological and economic approach to the development of cultivation technologies.

The use of nitrogen inhibitors is a promising direction of research and production testing. The effectiveness of inhibitors from the theoretical point of view is scientifically substantiated. However, in the process of conducting field experiments, the results are often obtained that are difficult to interpret clearly. In Ukraine, the use of inhibitors is still a relatively new topic. The complexity of conducting research is often associated with the absence of specialized machinery for field studies. In the author's opinion, it is necessary to continue the investigation in long-term experimental programs.

The relevance of correcting nitrogen nutrition and developing its effective management is especially important in the context of climate change, especially since the use of nitrogen fertilizers may be one of the factors of these changes. Thus, this direction contains an important environmental aspect in terms of reducing greenhouse gas emissions, including nitrogen oxides and ammonia. The analysis of literary sources indicates a predominantly considerable effect of inhibitors on reducing nitrogen losses.

The generalization of the literature data indicates a variety of statements and results of the experimental data on the effect of urease or nitrification inhibitors on increasing the yields. According to the published materials, both a significant increase in yield capacity and neutrality of the effect of such substances were recorded. In some publications, the data on the negative effect of inhibitors on corn yields can be found.

In Ukraine, the topic of using nitrogen inhibitors is relatively new. Taking into account the soil and climatic diversity of our country's territory, it is expedient to form long-term research programs to establish the peculiarities of using nitrogen inhibitors in production conditions, where modern machines for using inhibitors with various types of fertilizers are available.

Conflict of interest

The authors state that there is no conflict of interest.

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ORCID
K. Kuriacha https://orcid.org/0009-0008-4665-9835