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NITROGEN FERTILIZATION STRATEGIES FOR IMPROVING EFFICIENCY AND YIELD IN MAIZE

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Abstract. *Optimizing nitrogen (N) fertilization is a key factor for achieving high productivity and improving nutrient use efficiency in maize (Zea mays L.). This study investigated the impact of different nitrogen management strategies on grain yield, nitrogen use efficiency (NUE), and selected quality parameters under field conditions. Conventional fertilization based on urea and ammonium nitrate was compared with alternative approaches involving a controlled-release nitrogen fertilizer and a liquid nitrogen fertilizer. The analysis included grain yield, partial nitrogen productivity (PUN), nitrogen concentration in grain and stover, and selected grain quality traits such as thousand kernel weight and protein content. The results showed that controlled-release nitrogen applied during early crop development ensured grain yields comparable to conventional fertilization, while improving nitrogen use efficiency and reducing residual nitrogen in vegetative biomass. Furthermore, this fertilization strategy enhanced nitrogen allocation towards grain formation. In contrast, liquid nitrogen fertilization provided moderate nitrogen efficiency but was associated with lower yields when applied without complementary nitrate-based sources. The obtained results showed that maize response to nitrogen fertilization depended largely on the fertilization strategy and fertilizer type, not only on the total nitrogen rate applied. These findings highlight the importance of fertilizer type and nitrogen management strategy in improving nitrogen use efficiency and sustaining maize productivity under field conditions.*

Keywords*: nitrogen use efficiency; liquid nitrogen fertilizer; controlled-release fertilizer; reduced nitrogen input; sustainable agriculture*

INTRODUCTION

Nitrogen is one of the essential nutrients for maize (*Zea mays L.*) cultivation, directly influencing both grain yield and grain composition. Numerous studies have shown that nitrogen fertilization stimulates vegetative growth, photosynthetic activity, and biomass accumulation, significantly contributing to yield increase (RAUN et al., 1999; CASSMAN et al., 2002; GUO et al., 2022). At the same time, nitrogen availability during the reproductive stages affects protein accumulation in the grain and the balance between protein and starch fractions (HIREL et al., 2007; ANAS et al., 2020).

However, nitrogen use efficiency remains relatively low in many agricultural systems. A significant proportion of the nitrogen applied through fertilization may be lost through leaching, volatilization, or denitrification, reducing fertilization efficiency and contributing to environmental problems (RAUS et al., 2025; GALLOWAY et al., 2008; ROBERTSON et al., 2009). Numerous studies have shown that nitrogen use efficiency tends to decline as nitrogen application rates increase, especially when nitrogen supply exceeds the physiological requirements of the crop (CASSMAN et al., 2002; YOKAMO et al., 2023).

Fertilization efficiency is influenced not only by the total nitrogen rate applied, but also by fertilizer type and application timing. Different nitrogen forms exhibit distinct behavior in soil, affecting nutrient transformation dynamics and nitrogen availability for plants (CUI et al., 2022). In maize cultivation, nitrogen fertilization is commonly split between application at sowing and early vegetative stages, particularly around the 4–6 leaf stage, when nitrogen uptake increases rapidly.

In recent years, controlled-release fertilizers and liquid fertilizers have been considered promising alternatives to conventional fertilization systems based on urea or ammonium nitrate. Controlled-release fertilizers can ensure a gradual nitrogen release, improving synchronization between crop demand and nutrient availability in soil (SHAVIV, 2001; RAUS et al., 2016; BOLOHAN et al., 2023). In contrast, liquid fertilizers can provide rapid nitrogen availability during periods of high crop demand (MILYUTKIN et al., 2022; GOLOTOV et al., 2024). However, the performance of these fertilizers largely depends on pedoclimatic conditions and the fertilization strategy used.

In this context, the objective of the study was to evaluate the effect of different nitrogen fertilization strategies on grain yield, nitrogen use efficiency, and grain quality parameters in maize. The study aimed to compare conventional fertilization systems with strategies based on controlled-release and liquid fertilizers in order to identify solutions capable of improving nitrogen use efficiency without reducing grain yield or crop quality.

MATERIAL AND METHODS

General conditions and experimental site. The experiment was conducted within the Plant Nutrition and Soil Fertility Laboratory of the “Ion Ionescu de la Brad” University of Life Sciences in Iași, at the Ezăreni Research and Student Practical Station (47°07′ N, 27°30′ E), on a plateau with a 3–5% slope and slight north-eastern exposure.

The area is characterized by a temperate-continental climate specific to the Moldavian Plain. During the 2024–2025 agricultural year, weather conditions throughout the vegetation period were marked by uneven rainfall distribution and temperature fluctuations compared to long-term averages.

The study aimed to evaluate the effect of different nitrogen fertilization strategies on grain yield, nitrogen use efficiency (NUE), and grain quality parameters in maize under field conditions.

Soil properties. The chemical properties of the soil in the 0–20 cm layer (Table 1) indicated a slightly acidic soil reaction (pH 6.3), moderate humus content (3.27%), and high cation exchange capacity (26.3 cmolc kg^{-1}), characteristic of a soil with good fertility status.

The content of available phosphorus (P-AL = 17.8 mg kg^{-1}) was classified as low to moderate and may represent a limiting factor under certain conditions, while available potassium (K-AL = 200 mg kg^{-1}) indicated good potassium supply. The nitrogen index (IN = 3.1) reflected a moderate nitrogen supply potential, justifying the application of nitrogen fertilization. Overall, the soil presented good fertility conditions, with possible limitations related mainly to phosphorus availability.

Table 1

Selected chemical properties of the experimental soil (0–20 cm depth)

Depth (cm)	pH (H_2O)	H (%)	CEC (cmolc kg^{-1})	IN	P-AL (mg kg^{-1})	K-AL (mg kg^{-1})
0-20	6.3	3.27	26.3	3.1	17.8	200

(SOC – soil organic carbon; CEC – cation exchange capacity; IN – nitrogen index; P-AL și K-AL determinate prin metoda Egner–Riehm (extractant acetat lactat de amoniu))

Biological material and crop management. The maize crop (*Zea mays L.*) was established in the spring of 2025 using a commercial hybrid adapted to local pedoclimatic conditions. The soil was prepared through conventional tillage operations using a Valtra T190 tractor and Horsch equipment (Tigger and Grubber) for soil loosening and seedbed preparation.

Experimental design and fertilization treatments. The experiment was arranged as a randomized block design with four replications, each experimental plot having an area of 36 m². Nitrogen fertilization strategies differed according to fertilizer type and application timing, as presented in Table 2.

Fertilizers were applied in three stages: before sowing, at sowing, and during the early vegetative stage (4-leaf stage), in order to ensure nitrogen availability during the critical periods of crop growth and development.

Table 2

Experimental treatments and nitrogen application rates at different wheat growth stages

Variant	Fertilizer application rate (kg ha^{-1} / L ha^{-1})			Applied nitrogen (kg N ha^{-1})			
	N1 (Before sowing)	N2 (Sowing)	N3 (4 leaf.)	N1	N2	N3	Total N
V1	-	NP 20-20 (200)	AN34 (200)	-	40	66	106
V2	U46 (150)	NP 20-20 (200)	-	69	51	-	109
V3	-	NP 20-20 (200)	NS27 (200)	-	40	44	88
V4	-	NP 20-20 (200)	NS27 (150)	-	40	33	73
V5	NS27 (150)	NP 20-20 (200)		33	44	-	77
V6	-	NP 20-20 (200)	NS19 (150)/ 50% H_2O)	-	40	28,5	68.5
V7	-	NP 20-20 (200)	NS19 (150)	-	40	28,5	68.5
V8	NS19 (150)	U46 (150)	-	69	28,5	-	97.5
V9	NP-SI25 (200)	U46 (150)	-	69	10	-	79

Characteristics of the fertilizers used. Several nitrogen fertilizers differing in nitrogen form and nutrient composition were used in the experiment. Urea (U46) supplied nitrogen in amide form and required hydrolysis in soil, resulting in a more progressive nitrogen release. Ammonium nitrate (AN34) contained both ammonium and nitrate nitrogen, ensuring rapid nitrogen availability after application.

The NS27 fertilizer, a solid nitrogen and sulfur source, was characterized by a more gradual nutrient release, potentially improving synchronization with crop nitrogen demand. The liquid fertilizer NS19 supplied nitrogen together with sulfur, magnesium, and micronutrients, while its liquid form favored uniform distribution and rapid availability in the active root zone.

Table 3

Experimental treatments and nitrogen application rates at different wheat growth stages

Code	Fertilizer	Key Components	Type
U46	Urea (46% N)	46% as $CO(NH_2)_2$	Solid
AN34	Ammonium nitrate (34% N)	17% NH_4^+ + 17% NO_3^-	Solid
NS27	Nitrogen–sulfur fertilizer (27% N)	27% N+ SO_3	Solid (controlled-release)
NS19	Liquid nitrogen–sulfur fertilizer (19% N)	19N+ 6SO_3+ 3% MgO+0.1% Zn+0.1% B	Liquid fertilizer
NP-SI25	Nitrogen–phosphorus fertilizer (5% N)	5% N + 20% P_2O_5 + silicate-based additives	Solid

The NP-SI25 fertilizer was also included in the experiment. This fertilizer contained high phosphorus concentrations together with silicate-based compounds, which may reduce phosphorus fixation in soil and improve phosphorus uptake by plants.

Soil and plant analysis methods. Soil chemical analyses were performed according to standard ICPA methods, complemented by internationally recognized procedures. Soil reaction (pH) was determined potentiometrically in a soil–water suspension (1:2.5), soil organic carbon (SOC) by the modified Walkley–Black method, and cation exchange capacity (CEC) using standard analytical procedures. The nitrogen index (IN) was calculated based on humus content and soil reaction.

Available phosphorus (P-AL) and potassium (K-AL) were determined using the Egner–Riehm method. Phosphorus concentration was measured spectrophotometrically using a Shimadzu UV-1700 spectrophotometer, while potassium was determined by flame photometry using a Sherwood 410 flame photometer.

Grain yield, test weight, and grain moisture were determined using a Wintersteiger experimental combine equipped with the GrainGage HM800 system. Grain yield values were expressed at the standard moisture content of 14%. Thousand-kernel weight (TKW) was determined according to SR 6123/1999.

Total nitrogen content (Nt) was determined using the Kjeldahl method, while protein content was analyzed by near-infrared spectroscopy (NIR), with results expressed on a dry matter basis.

Calculation of derived indicators related to nitrogen use efficiency and grain quality. Several derived indicators were calculated based on grain yield, nitrogen content, and grain quality parameters in order to evaluate nitrogen use efficiency and production quality.

Partial factor productivity of nitrogen (PFP-N) was calculated as the ratio between grain yield and the total amount of nitrogen applied through fertilization, being expressed as kg grain kg^{-1} N:

$$PFP\text{-}N = Y/Na$$

where Y represents grain yield (kg ha^{-1}), expressed at the standard moisture content of 14%, and N_a represents the total amount of nitrogen applied through fertilization (kg N ha^{-1}).

The amount of nitrogen accumulated in grain (Ngrain) was calculated using the following equation:

$$Ngrain=Yx(Nt\ grain/100)$$

where Ntgrain represents total nitrogen content in grain (%).

Protein yield was determined based on grain yield and grain protein content according to the following relationship:

$$Protein\ yield= Y\times(Protein/100)$$

Starch yield was calculated using grain yield and starch content:

$$Starch\ yield=Y\times(Starch/100)$$

The protein/starch ratio was calculated as: PSR=Protein/Starch

Statistic analysis. Experimental data were analyzed by analysis of variance (ANOVA), and treatment means were compared using Duncan’s multiple range test at $p \leq 0.05$. Significant differences between treatments are indicated by different letters within table columns. Statistical analyses were performed using SPSS v.22 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSIONS

a. Grain yield response to nitrogen fertilization strategies

Grain yield responded differently to the fertilization strategies, without a linear relationship between nitrogen rate and yield level. The highest grain yields were obtained in V2 (8574 kg ha^{-1}, 109 kg N ha^{-1}), V8 (8354 kg ha^{-1}, 97.5 kg N ha^{-1}), and V5 (8320 kg ha^{-1}, 77 kg N ha^{-1}), all belonging to the same statistical group despite the substantial differences in nitrogen input.

The comparison between V2 and V5 highlights that an additional input of approximately 32 kg N ha^{-1} resulted only in a limited yield increase, suggesting proximity to an agronomic efficiency threshold where crop response becomes constrained by other limiting factors (CIAMPITTI et al., 2012). At the same time, the reduced-input variants maintained competitive yields, with V6 reaching 8077 kg ha^{-1} at only 68.5 kg N ha^{-1}.

A relevant result was the similarity between V3 (7565 kg ha^{-1}, 88 kg N ha^{-1}) and V4 (7564 kg ha^{-1}, 73 kg N ha^{-1}), indicating that part of the additional nitrogen applied was not efficiently utilized, possibly due to nitrogen losses or inadequate synchronization with periods of intensive nutrient uptake.

In maize, nitrogen demand increases rapidly during vegetative development, while excessive or very early nitrogen availability may favor nutrient losses through leaching or volatilization, particularly under uneven rainfall conditions. In contrast, fertilizers ensuring gradual nutrient release or more uniform nitrogen distribution may improve nitrogen utilization efficiency (RAUN et al., 1999; HIREL et al., 2007; ZHANG et al., 2023; IKEDA et al., 2014).

Variant V1 (7487 kg ha^{-1}, 106 kg N ha^{-1}), which recorded one of the lowest yields despite a relatively high nitrogen rate, further confirmed that crop response depended not only on the amount of nitrogen applied, but also on the dynamics of nitrogen availability in soil.

The results emphasize the importance of synchronization between nitrogen availability and crop demand for maintaining grain yield and optimizing nitrogen use efficiency (RAUN et al., 1999; FAGERIA et al., 2005). Grain yield reflected the interaction between nitrogen input and nitrogen utilization efficiency. Fertilization strategies providing better synchronization between nitrogen supply and crop demand were able to maintain high productivity even at reduced nitrogen rates, an aspect considered essential for optimizing nitrogen management in agricultural systems (RAUS et al., 2016; SCHERER, 2001; SALVAGIOTTI et al., 2009).

Table 4

Grain yield and nitrogen productivity under different fertilization strategies

Variant	N rate (kg N ha^{-1})	Grain yield (kg ha^{-1})	PFP-N (kg grain kg^{-1} N)
V1	106	7487 c	70,6 d
V2	109	8574 a	78,7 d
V3	88	7565 b	86,0 c
V4	73	7564 b	103,6 ab
V5	77	8320 a	108,0 ab
V6	68	8077 ab	118,8 a
V7	68	7746 b	113,9 a
V8	97,5	8354 a	85,7 c
V9	79	7781 b	98,5 b

Values followed by different letters within a column differ significantly at $p \leq 0.05$ according to Duncan's multiple range test

b. Nitrogen use efficiency and nitrogen accumulation

Nitrogen use efficiency indicators and nitrogen accumulation in grain revealed clear differences between fertilization strategies that were not always reflected at the yield level (MOLL et al., 1982). Grain nitrogen content varied within a relatively narrow range (1.32–1.42%), with the highest values recorded in V2 and V9 (1.42%), followed by V5 (1.40%) and V8 (1.39%), while the lowest values were observed in V1 and V7 (1.32%). Although these variations were relatively small, they indicated a slight increase with higher nitrogen input, but did not fully explain the differences in total nitrogen accumulation.

Nitrogen accumulated in grain ranged from 99 kg ha^{-1} in V1 to 122 kg ha^{-1} in V2, while high values were also recorded in V5 and V8 (116 kg ha^{-1}). However, these values reflected the combined effect of grain yield and grain nitrogen concentration. For example, V6 accumulated 110 kg ha^{-1} at a nitrogen rate of only 68.5 kg N ha^{-1}, approaching the variants with higher nitrogen input and suggesting improved nitrogen uptake and translocation efficiency toward the grain.

The differences became more evident when considering the ratio between accumulated and applied nitrogen, which ranged from 0.93 in V1 to 1.62 in V6. High values observed in V6 (1.62), V5 (1.51), and V7 (1.50) indicated more efficient nitrogen utilization under reduced nitrogen input, whereas V2 (1.12), despite its high yield and nitrogen accumulation, showed lower nitrogen recovery efficiency.

This type of response suggests that under moderate nitrogen rates combined with better synchronized nutrient availability, a larger proportion of the applied nitrogen is recovered in the grain (MOLL et al., 1982). In contrast, under high nitrogen inputs, a greater fraction of nitrogen may remain unused or be lost through leaching, volatilization, or immobilization, depending on environmental conditions and nitrogen form (RAUN et al., 1999; CASSMAN et al., 2002).

Variant V1 illustrated a relatively inefficient use of nitrogen, with 99 kg ha^{-1} accumulated in grain at an application rate of 106 kg N ha^{-1} (ratio 0.93), probably due to poor synchronization between nitrogen availability and crop demand or increased nitrogen losses during periods of excess moisture. In contrast, the high values recorded in V6 and V7 highlighted the importance of fertilizer form and nitrogen distribution in soil. Liquid fertilizer application or fertilization systems favoring a more uniform nutrient distribution may improve nitrogen contact with the active root zone and reduce nutrient losses (HIREL et al., 2007).

Table 5

Grain yield and nitrogen productivity under different fertilization strategies

Var.	Grain N (%)	N accumulated in grain (kg ha^{-1})	Grain N accumulation per unit of applied N (kg N grain kg^{-1} N applied)	Protein yield (kg ha^{-1})
V1	1.32 bc	99 c	0.93	5398 c
V2	1.42 a	122 a	1.12	6199 a
V3	1.33 b	101 b	1.14	5424 b
V4	1.35 b	102 b	1.40	5499 b
V5	1.40 a	116 a	1.51	6048 a
V6	1.36 b	110 ab	1.62	5872 ab
V7	1.32 bc	102 b	1.50	5647 b
V8	1.39 ab	116 a	1.19	6023 a
V9	1.42 a	110 b	1.40	5618 b

Values followed by different letters within a column differ significantly at $p \leq 0.05$ according to Duncan's multiple range test

Protein yield followed a similar trend to nitrogen accumulation, varying between 5398 kg ha⁻¹ in V1 and 6199 kg ha⁻¹ in V2, although the differences were smaller than those observed for nitrogen efficiency indicators. For instance, V6 reached 5872 kg ha⁻¹, remaining close to the highest-yielding variants, which indicates that nitrogen transfer toward the grain can be maintained even under lower nitrogen rates.

Overall, nitrogen use efficiency appeared to depend less on the total amount of nitrogen applied and more on the capacity of the fertilization system to ensure efficient nitrogen uptake and translocation toward the grain (CHEN et al., 2024; LI et al., 2024). Strategies that reduced nitrogen input while improving nitrogen synchronization and availability allowed greater nitrogen recovery in the harvested product and more efficient resource utilization (HIREL et al., 2007; RAUS et al., 2016; RAUS et al., 2025).

c. Effect of nitrogen fertilization on grain quality

Grain quality parameters showed lower variability than grain yield and nitrogen use efficiency indicators, suggesting that fertilization mainly influenced production level rather than the physical structure of the grain.

Thousand-kernel weight (TKW) ranged from 294 g in V3 to 314 g in V4, while relatively high values were also recorded in V2 (311 g) and V8 (312 g). The differences did not follow a clear pattern in relation to nitrogen rate. For example, V4 (73 kg N ha⁻¹) recorded the highest TKW, whereas V3 (88 kg N ha⁻¹) showed one of the lowest values. This behavior suggests that TKW was influenced mainly by conditions during grain filling rather than by fertilization level (BORRÁS et al., 2004).

Test weight varied within a narrow range, from 70.4 kg hl⁻¹ in V6 to 72.8 kg hl⁻¹ in V1, without a clear relationship with fertilization strategy. This indicates a stronger influence of genetic background and grain maturation conditions on this parameter (EGLI, 2006).

Protein content ranged between 8.1% in V3 and 8.8% in V2 and V9, indicating a slight increase with higher nitrogen input. Lower values observed in V3 and V7 (8.1–8.2%) supported this tendency, although the amplitude of variation remained relatively limited, suggesting a relatively stable physiological control of grain composition (CIAMPITTI & VYN, 2012).

Starch content remained highly stable (71.7–72.9%), with no significant differences between treatments, while the starch/protein ratio remained nearly constant (0.11–0.12). These results indicate that fertilization mainly affected the amount of accumulated compounds rather than the compositional structure of the grain.

Table 6

Grain yield and nitrogen productivity under different fertilization strategies

Var.	1000-kernel weight (g)	Test weight (kg hl⁻¹)	Grain protein (%)	Starch (%)	Starch/ Protein ratio
V1	301 ab	72,8 a	8,4 b	72,1 a	0.12
V2	311 a	71,5 b	8,8 a	72,3 a	0.12
V3	294 b	71,8 b	8,1 c	71,7 a	0.11
V4	314 a	71,6 b	8,4 b	72,7 a	0.12
V5	305 ab	71,8 b	8,6 b	72,7 a	0.12
V6	304 ab	70,4 c	8,5 b	72,7 a	0.12
V7	302 ab	71,8 b	8,2 c	72,9 a	0.11
V8	312 a	71,9 b	8,7 a	72,1 a	0.12
V9	294 c	71,7 b	8,8 a	72,2 a	0.12

Values followed by different letters within a column differ significantly at $p \leq 0.05$ according to Duncan's multiple range test

Overall, nitrogen fertilization had a moderate influence on grain quality. Physical grain parameters remained relatively stable, while the observed changes in protein content were limited, suggesting that fertilization strategies had a stronger effect on grain yield and nitrogen use efficiency than on grain quality itself (GOODING & DAVIES, 1997; Triboi et al., 2003).

d. Relationships between nitrogen fertilization, yield and grain quality

The integrated analysis of fertilization, grain yield, and grain quality showed that these components were interconnected, but did not evolve proportionally. High-yielding variants such as V2, V5, and V8 also recorded higher protein content and nitrogen accumulation in grain, although the differences in protein concentration remained relatively small. Protein content varied within a narrow range (8.1–8.8%), while starch content and the starch/protein ratio remained highly stable, suggesting that fertilization mainly affected the amount of accumulated compounds rather than grain compositional structure (GOODING & DAVIES, 1997; WIESER, 2007; CIAMPITTI & VYN, 2012).

The relationship between grain yield and nitrogen accumulation was more evident. Variants V2, V5, and V8 combined high grain yield with high nitrogen accumulation, whereas V6 accumulated 110 kg N ha^{-1} despite receiving only 68.5 kg N ha^{-1}, indicating improved nitrogen use efficiency. Similar responses under moderate nitrogen input have also been reported by MOLL et al. (1982) and HIREL et al. (2007).

Differences between treatments became clearer when nitrogen efficiency indicators were considered. Although V2 achieved the highest grain yield and nitrogen accumulation, it showed lower efficiency values than V5 and V6. This result suggests that increasing nitrogen rates did not automatically improve nitrogen utilization. Under moderate and better synchronized nitrogen supply, a larger proportion of nitrogen was recovered in the grain, while under high nitrogen inputs, part of the applied nitrogen remained unused or was lost from the system (CASSMAN et al., 2002; RAUN et al., 1999).

Nitrogen partitioning within the plant also contributed to these differences. Under better synchronized nitrogen availability, a larger proportion of nitrogen was directed toward grain formation, whereas under high nitrogen rates, part of the nitrogen remained in vegetative tissues or was lost before translocation occurred (GOODING et al., 1997; TRIBOI et al., 2003).

Overall, the results indicate that crop performance depended more on nitrogen use efficiency and nitrogen availability synchronization than on the total nitrogen rate applied. Fertilization strategies that improved nitrogen availability during periods of maximum crop demand maintained high grain yield while ensuring more efficient nitrogen utilization (HIREL et al., 2007; LADHA et al., 2005; CASSMAN et al., 2002, BOLOHAN et al., 2023).

CONCLUSIONS

The obtained results showed that maize response to nitrogen fertilization depended largely on the fertilization strategy and fertilizer type, not only on the total nitrogen rate applied. Variants V2, V5, and V8 achieved the highest grain yields, although under different nitrogen input levels, highlighting important differences in efficiency between fertilization systems.

Variant V5, based on the NS27 fertilizer applied before sowing, achieved grain yields comparable to conventional fertilization despite the lower total nitrogen rate. At the same time, this variant recorded high values of PFP-N and nitrogen accumulated in the grain, suggesting a more efficient utilization of the applied nitrogen.

The variants fertilized with the liquid product NS19 showed the highest nitrogen use efficiency values, although grain yields remained lower compared to the highest-yielding variants. In contrast, conventional systems based on urea and ammonium nitrate ensured high yields, but required higher nitrogen rates and showed lower nitrogen use efficiency.

Grain quality parameters showed smaller variations than grain yield and nitrogen efficiency indicators, suggesting that fertilization mainly influenced dry matter accumulation in the grain rather than its compositional structure.

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