

MODERN NITROGEN FERTILIZATION STRATEGIES FOR IMPROVING EFFICIENCY AND GRAIN QUALITY IN WINTER WHEAT

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Abstract

*Efficient nitrogen (N) management is essential for improving yield and grain quality in winter wheat (*Triticum aestivum* L.). This study evaluated the effects of different spring-applied nitrogen fertilization strategies on grain yield, nitrogen use efficiency, and quality parameters of winter wheat. Field experiments compared conventional mineral fertilization based on urea (U46) and ammonium nitrate (AN34) with advanced fertilization systems, including a controlled-release nitrogen fertilizer (NS27) and a liquid nitrogen fertilizer (NS19). Grain yield, partial factor productivity of nitrogen (PFP-N), nitrogen content in grain and straw, and quality traits such as thousand-kernel weight, test weight, protein content, and gluten content were assessed. Controlled-release nitrogen applied at the onset of spring regrowth achieved grain yields comparable to conventional fertilization while significantly increasing partial factor productivity of nitrogen (PFP-N) and reducing nitrogen accumulation in straw. Late application of controlled-release nitrogen enhanced grain protein and gluten content without compromising yield. Liquid nitrogen fertilization showed relatively high nitrogen efficiency but resulted in lower yields when not combined with nitrate-based nitrogen sources.*

Key words: controlled-release fertilizer, liquid nitrogen fertilizer, nitrogen fertilization, nitrogen use efficiency, low nitrogen input.

INTRODUCTION

Nitrogen is one of the most important nutrients for cereal crops, playing a key role in both yield formation and grain quality. The application of nitrogen almost doubles the global average wheat yield (Yokamo et al., 2023; Guo et al., 2022). However, nitrogen use efficiency largely depends on the proportion of applied nitrogen that is effectively taken up by plants and contributes to grain production (Ma et al., 2019; Yokamo et al., 2023).

The type of fertilizer used and the method of its application significantly influence nitrogen uptake and utilization by plants and represent a major concern in modern agriculture (Raus et al., 2016; Allart et al., 2023). Under current conditions, research increasingly focuses on improving the efficiency of fertilizer nitrogen use and reducing nitrogen application rates without compromising crop productivity or economic performance (Hirel et al., 2007; Raus et al., 2025; Walsh, 2018).

The key issue for both farmers and researchers are the capacity of crops to convert available nitrogen into agricultural production, which

represents a fundamental indicator of fertilization system performance (Moll et al., 1982; Raun & Johnson, 1999; Govindasamy et al., 2023). Numerous studies have shown that nitrogen use efficiency tends to decline with increasing nitrogen application rates, as plant capacity to absorb and utilize nitrogen becomes limited once nitrogen supply exceeds crop physiological requirements (Cassman et al., 2002; Yokamo et al., 2023). Consequently, optimizing fertilization strategies is essential for maintaining a balance between yield, nutrient use efficiency, and environmental sustainability. In practice, a substantial proportion of applied nitrogen is not utilized by plants and may be lost through processes such as leaching, denitrification, volatilization, or microbial immobilization (Galloway et al., 2008; Guo et al., 2022; Raus et al., 2025; Govindasamy et al., 2023). These processes reduce fertilization efficiency and may contribute to groundwater contamination and greenhouse gas emissions (Robertson & Vitousek, 2009; Raun & Johnson, 1999; Cassman et al., 2002).

Adjusting fertilizer forms, application timing, and fertilization methods can improve the

synchronization between nitrogen availability and crop demand, allowing reductions in total nitrogen input without affecting yield (Yokamo et al., 2023; Congreves et al., 2021). In addition to the total nitrogen rate applied, nitrogen use efficiency is also strongly influenced by the chemical form of the fertilizer and the timing of application during the crop growth cycle.

Different nitrogen forms exhibit distinct behavior in soil, which determines the rate of transformation and nutrient availability for plants. For example, amide nitrogen from urea must undergo hydrolysis in soil before becoming available to plants, whereas nitrate nitrogen can be readily absorbed by roots (Cui et al., 2022). The timing of nitrogen application is equally important because nutrient availability must coincide with critical stages of crop development.

In winter wheat, nitrogen fertilization is commonly applied in split doses during spring, particularly at the tillering stage, stem elongation, and grain formation stages. This strategy improves nitrogen utilization efficiency and may reduce nutrient losses from the soil-plant system (Ma et al., 2019; Anas et al., 2020; Raus et al., 2016).

The development of modern fertilizers has increasingly focused on improving nitrogen use efficiency and reducing nutrient losses (Ren et al., 2024; Vejan et al., 2021; Raus et al., 2026; Bolohan et al., 2023). Controlled-release fertilizers and liquid fertilizers are currently considered promising alternatives to conventional fertilization systems based on urea or ammonium nitrate (Cui et al., 2022; Jariwala et al., 2022).

Controlled-release fertilizers can ensure a gradual nitrogen release in soil, contributing to improved synchronization between nutrient availability and crop demand throughout the growing season (Shaviv, 2001). Liquid fertilizers, on the other hand, can provide rapid nutrient availability when crop demand is highest and may also be effective under conditions of limited soil moisture (Milyutkin et al., 2022; Raus et al., 2025; Golotov et al., 2024).

However, results reported in the literature regarding the efficiency of these fertilizers are not always consistent. Crop response largely depends on pedoclimatic conditions, soil properties, and fertilization strategies (Raun &

Johnson, 1999; Moll et al., 1982; Raus et al., 2026). Comparative studies evaluating the performance of controlled-release and liquid fertilizers relative to conventional fertilization systems remain limited under many agroecological conditions (Raus et al., 2016).

In this context, evaluating different nitrogen fertilization strategies under field conditions becomes essential for identifying efficient nutrient management solutions.

The main objective of this study was to evaluate the effect of different spring-applied nitrogen fertilization strategies on grain yield, nitrogen use efficiency, and quality parameters of winter wheat. The study aimed to compare conventional mineral fertilization with fertilization systems based on controlled-release and liquid fertilizers in order to identify strategies capable of improving nitrogen use efficiency without compromising grain yield or quality.

The working hypothesis was that the use of controlled-release fertilizers or fertilizers containing both nitrogen and sulfur could improve the synchronization between nitrogen availability and crop physiological demand, leading to more efficient nitrogen utilization and maintaining high yields even under reduced nitrogen application rates. To test this hypothesis, the study evaluated the performance of different spring nitrogen fertilization strategies in winter wheat grown under the excessive continental climatic conditions specific to northeastern Romania by comparing conventional mineral fertilization with fertilization systems based on controlled-release and liquid fertilizers

MATERIALS AND METHODS

a) General conditions and experimental site

The experiment was conducted within the Laboratory of Plant Nutrition and Soil Fertility of the “Ion Ionescu de la Brad” Iași University of Life Sciences, Romania. The experimental field was located at the Ezăreni Research and Student Practice Station (47°07' N, 27°30' E), on a plateau with a slope of 3-5% and a slightly northeastern exposure.

The experimental area is characterized by a temperate continental climate typical of the Moldavian Plain, with relatively warm summers and moderate precipitation. During the 2024-

2025 agricultural year, the rainfall regime was uneven, with total precipitation of approximately 405 mm during the wheat growing season. Autumn conditions favored crop establishment, while spring was characterized by alternating dry periods and episodes of excess rainfall, particularly in May. These climatic conditions were relevant for interpreting nitrogen fertilization efficiency and crop response. The study aimed to evaluate the effect of different spring-applied nitrogen fertilization strategies on grain yield, nitrogen use efficiency (NUE), and selected quality parameters of winter wheat.

b) Soil properties. The main chemical properties of the soil in the 0-20 cm layer are presented in Table 1. The determined values indicate a slightly acidic soil, a moderate content of soil organic carbon, and a relatively high cation exchange capacity. The available phosphorus content falls within the medium range, while available potassium levels are high, reflecting a good fertility status of the experimental soil.

Table 1. Chemical properties of the experimental soil

Depth (cm)	pH (H ₂ O)	SOC (%)	CEC (cmolc kg ⁻¹)	NI	P-AL (mg kg ⁻¹)	K-AL (mg kg ⁻¹)
0-20	6.8	1.68	26.3	2.7	45.1	250

SOC - soil organic carbon; CEC - cation exchange capacity; NI - nitrogen index; P-AL and K-AL.

c) Biological material and crop management
Winter wheat (cv. Glosa) was sown on 25 October 2024, with sunflower as the preceding crop, using a seeding rate of 200 kg ha⁻¹. Before sowing, the soil was prepared using conventional tillage practices.

Nitrogen fertilization was applied in spring according to the experimental protocol. During the growing season, plant protection treatments were carried out to control diseases, weeds, and pests using the following products: Doxun (0.8 L ha⁻¹), Prontos (0.12 L ha⁻¹), Systhane C (0.7 L ha⁻¹), and Decis Expert 100 (0.10 and 0.07 L ha⁻¹). The crop was harvested on 15 July 2025.

d) Experimental design and fertilization treatments

The experiment was arranged in a randomized block design with four replications. The area of each experimental plot was 42 m², with a net harvest area of 15 m².

Nitrogen fertilization strategies differed according to fertilizer type and application timing during the main growth stages of winter wheat. The treatment scheme and fertilizer application rates are presented in Table 2.

Table 2. Experimental treatments and nitrogen application rates at different wheat growth stages

Treatment	Fertilizer application rate (kg ha ⁻¹)			Applied nitrogen (kg N ha ⁻¹)			
	N1 (BBCH 21-25)	N2 (BBCH 30-32)	N3 (BBCH 37-41)	N1	N2	N3	Total N
T1	U46 (150)	AN34 (100)	AN34 (100)	69	34	34	137
T2	U46 (150)	AN34 (150)	-	69	51	-	120
T3	NS27 (150)	AN34 (150)	-	40.5	51	-	91.5
T4	U46 (150)	NS27 (150)	-	69	40.5	-	109.5
T5	U46 (150)	AN34 (100)	NS27 (100)	69	34	27	130
T6	U46 (150)	NS19 (150)	-	69	28.5	-	97.5

Fertilizers were applied in three stages during spring, corresponding to the main crop growth stages: N1 - BBCH 21-25 (tillering); N2 - BBCH 30-32 (stem elongation); N3 - BBCH 37-41 (flag leaf emergence)

Total nitrogen rates applied in the experiment ranged from 91.5 to 137 kg N ha⁻¹, depending on the treatment.

e) Characteristics of the fertilizers used

Four nitrogen fertilizers with different chemical forms and nutrient compositions were used in the experiment (Table 3).

Urea (U46) provides nitrogen in amide form and requires hydrolysis in soil before becoming available to plants, resulting in a gradual nitrogen release. Ammonium nitrate (AN34) contains nitrogen in both ammonium and nitrate forms, ensuring rapid nutrient availability after application.

Table 3. Chemical composition and characteristics of nitrogen fertilizers used in the experiment

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	Controlled-release nitrogen-sulfur fertilizer (27% N)	27% N+ SO ₃	Solid (controlled-release)
NS19	Liquid nitrogen-sulfur fertilizer (19% N)	19%N+ 6% SO ₃ + 3% MgO+0.1% Zn+0.1% B+ PHYSIO PRO	Liquid fertilizer

The experimental fertilizer NS27 represents a solid nitrogen-sulfur source characterized by a more gradual nitrogen release and improved synchronization between nutrient availability and crop demand. The liquid fertilizer NS19 supplies nitrogen together with sulfur, magnesium, and micronutrients. Its liquid form promotes uniform distribution and rapid nutrient availability in the active root zone.

f) Soil and plant analysis methods

Soil chemical analyses were performed using standard pedological and agrochemical methods recommended by the National Research and Development Institute for Pedology, Agrochemistry and Environmental Protection (ICPA), described in Romanian methodological literature and complemented by internationally recognized procedures.

Soil pH was determined potentiometrically in a 1:2.5 soil-water suspension.

Soil organic carbon (SOC) was determined using the modified Walkley–Black method.

Cation exchange capacity (CEC) was calculated as the sum of exchangeable bases (SB) and hydrolytic acidity (Ah), determined by the Kappen method. Base saturation degree was calculated as:

$$V (\%) = (SB / CEC) \times 100.$$

The nitrogen index (NI) was calculated according to Borlan's methodology, using the formula:

$$NI = (\text{Humus} \times V) / 100.$$

Available phosphorus (P-AL) and potassium (K-AL) extracted with ammonium lactate-acetate was determined using the Egner-Riehm method. Phosphorus was measured spectrophotometrically (UV-1700, Shimadzu, Japan), while potassium was determined using flame photometry (Flame Photometer 410, Sherwood, UK).

Grain yield, test weight, and grain moisture at harvest were determined using a Wintersteiger experimental combine equipped with the automated GrainGage HM800 weighing and analysis system. Grain yield was expressed in kg ha⁻¹ and adjusted to a standard grain moisture of 14%.

Thousand-kernel weight (TKW) was determined according to the Romanian standard SR 6123/1999.

Total nitrogen content (Nt) in grain and straw was determined using the Kjeldahl method after sample mineralization. Plant samples were dried, ground, and homogenized prior to analysis.

Grain protein and gluten contents were determined using an automatic analyzer based on near-infrared spectroscopy (NIR) (Infratec 1241 Grain Analyzer, FOSS Analytical, Denmark), a rapid and non-destructive method widely used for evaluating the chemical composition of cereal grains. Analyses were performed on clean and homogenized grain samples, and results were expressed as percentages of dry matter.

g) Calculation of nitrogen use efficiency and quality indicators

To evaluate nitrogen, use efficiency and grain quality, several derived indicators were calculated based on grain yield, nitrogen content, and grain quality parameters.

Partial factor productivity of nitrogen (PFP-N) was calculated as the ratio between grain yield and the total amount of nitrogen applied through fertilization:

$$PFP-N = Y / N_a$$

where: Y represents grain yield (kg ha⁻¹) adjusted to 14% moisture, and N_a represents the total nitrogen applied through fertilization (kg N ha⁻¹).

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

$$N_{\text{grain}} = Y \times (\text{Nt grain} / 100)$$

where: Nt grain represents the total nitrogen content in grain (%).

Protein yield per hectare was calculated based on grain yield and grain protein content:

$$\text{Protein yield} = Y \times (\text{Protein} / 100)$$

To characterize the efficiency of nitrogen translocation to grain, the Nitrogen Harvest Index (NHI) was calculated as:

$$NHI = N_{\text{grain}} / (N_{\text{grain}} + N_{\text{straw}})$$

where: N_{grain} represents nitrogen accumulated in grain (kg ha⁻¹) and N_{straw} represents nitrogen accumulated in straw (kg ha⁻¹).

h) Statistical analysis

Of the experimental data was performed using the mean values obtained from the four replications of each treatment. Differences

between treatments were evaluated using analysis of variance (ANOVA). Mean comparisons were performed using the Duncan multiple range test at a significance level of $p \leq 0.05$. All statistical analyses were carried out using SPSS v.22 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSIONS

a) Grain yield response to nitrogen fertilization strategies

Spring-applied nitrogen fertilization strategies significantly influenced winter wheat grain yield (Table 4). Grain yields obtained in the experiment ranged from 5999 to 6895 kg ha⁻¹. These differences were determined by the total nitrogen rate, the timing of application, and the type of fertilizers used. Previous studies have shown that crop response to nitrogen fertilization largely depends on the synchronization between nitrogen availability and periods of maximum crop demand (Raun & Johnson, 1999; Fageria & Baligar, 2005).

Table 4. Grain yield and nitrogen productivity under different fertilization strategies

Treatment	N rate (kg N ha ⁻¹)	Grain yield (kg ha ⁻¹)	PFP-N (kg grain kg ⁻¹ N)
T1	137	6641 ab	49.2 d
T2	120	6895 a	58.2 c
T3	91.5	6878 a	83.4 a
T4	109.5	6320 bc	62.0 b
T5	130	6692 ab	54.0 c
T6	97.5	5999 c	61.5 b

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

Grain yield was highest in treatments T2 (6895 kg ha⁻¹) and T3 (6878 kg ha⁻¹), with no significant differences between them. An important observation is that treatment T3 achieved a yield comparable to that of T2, although the total nitrogen rate applied was lower (91.5 kg N ha⁻¹ compared with 120 kg N ha⁻¹). This result may be attributed to the use of the NS27 fertilizer, characterized by controlled nitrogen release and sulfur content. The gradual release of nitrogen can contribute to maintaining a more stable nitrogen availability in the soil, while sulfur plays an important role in nitrogen metabolism, being directly involved in the synthesis of amino acids and proteins (Scherer, 2001; Salvagiotti et al., 2009).

The results also show that increasing nitrogen application rates does not necessarily lead to proportional yield increases. Numerous studies indicate that once a certain nitrogen supply level is reached, nitrogen use efficiency tends to decline (Cassman et al., 2002; Ladha et al., 2005). This aspect is also illustrated by treatment T1, where the application of 137 kg N ha⁻¹ resulted in a grain yield of 6641 kg ha⁻¹, which was close to that obtained in treatment T5 (6692 kg ha⁻¹). Under these conditions, increasing the nitrogen rate or adding an additional fertilization split did not generate significant yield increases.

The lowest grain yields were recorded in treatments T4 (6320 kg ha⁻¹) and T6 (5999 kg ha⁻¹). In treatment T6, the use of the liquid fertilizer NS19, characterized by rapid nitrogen availability in soil, may result in less favorable synchronization between nitrogen availability and crop demand. In such situations, part of the applied nitrogen may be lost through processes such as volatilization or leaching before being efficiently utilized by plants (Galloway et al., 2008; Robertson & Vitousek, 2009).

This dynamic is also reflected in the values of partial factor productivity of nitrogen (PFP-N), which ranged between 49.2 and 83.4 kg grain kg⁻¹ N. The highest nitrogen use efficiency was observed in treatment T3 (83.4 kg grain kg⁻¹ N), significantly higher than in the other treatments. These findings suggest that fertilization strategies based on moderate nitrogen rates combined with controlled-release fertilizers and sulfur supply can substantially improve nitrogen use efficiency. In this respect, the results obtained are consistent with studies highlighting the role of combined N + S fertilization in maintaining high productivity levels even at reduced nitrogen application rates (Fageria & Baligar, 2005; Scherer, 2001).

b) Nitrogen use efficiency and nitrogen accumulation

The fertilization strategies tested influenced the nitrogen content in both grain and straw, having a direct effect on the total amount of nitrogen accumulated in the plant (Table 5).

Treatment T5 recorded the highest nitrogen content in grain (2.56%), a value significantly higher compared with most of the other treatments. At the same time, the relatively high

values observed in treatments T2 (2.49%), T3 (2.46%), and T6 (2.48%) indicate that the applied fertilization strategies ensured adequate nitrogen availability during the grain formation and filling stages. Previous studies have shown that nitrogen availability during these growth stages plays a decisive role in nitrogen accumulation in grain and in determining grain quality (Fageria & Baligar, 2005; Gooding & Davies, 1997).

Table 5. Nitrogen content and nitrogen accumulation in grain and straw

Treat.	Grain N (%)	Straw N (%)	N accumulated in grain (kg ha ⁻¹)	Nitrogen Harvest Index (NHI)
T1	2.36 c	0.537 ab	157 b	0.81 c
T2	2.49 ab	0.547 ab	172 a	0.82 bc
T3	2.46 ab	0.384 d	169 a	0.86 a
T4	2.41 bc	0.459 bc	152 bc	0.84 ab
T5	2.56 a	0.426 c	171 a	0.86 a
T6	2.48 ab	0.566 a	149 c	0.81 c

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

Regarding the total amount of nitrogen accumulated in grain, the highest values were recorded in treatments T2 (172 kg ha⁻¹), T5 (171 kg ha⁻¹), and T3 (169 kg ha⁻¹), with no statistically significant differences between them. These results reflect both grain yield levels and nitrogen concentration in the grain. In the case of treatments T3 and T5, the higher nitrogen accumulation may be associated with the use of N-S fertilizers, as sulfur plays an important role in nitrogen metabolism and in the synthesis of protein compounds (Scherer, 2001; Salvagiotti et al., 2009).

An interesting aspect was observed in the nitrogen content of straw. The highest value was recorded in treatment T6 (0.566%), while treatment T3 presented the lowest value (0.384%). A higher nitrogen content in straw at harvest may indicate a lower translocation of nitrogen to the grain during the grain-filling period. The efficiency of this process depends on the plant's ability to redistribute nitrogen from vegetative organs to reproductive organs (Hirel et al., 2007).

The efficiency of nitrogen translocation is also reflected in the values of the Nitrogen Harvest Index (NHI), which ranged between 0.81 and 0.86. The highest values were observed in treatments T3 and T5 (0.86), indicating a greater

proportion of accumulated nitrogen being allocated to grain compared with vegetative biomass. This result suggests a more efficient utilization of nitrogen for grain production, a factor considered essential for achieving high yields and good grain quality (Moll et al., 1982).

A particularly relevant aspect is the performance of treatment T3, which combined high grain yield with high nitrogen accumulation in grain and the highest NHI values while using a reduced nitrogen rate. This result suggests that controlled-release N-S fertilizers can significantly improve nitrogen use efficiency in wheat cultivation.

Overall, the results indicate that fertilization strategies based on moderate nitrogen rates combined with controlled-release fertilizers or sulfur supply can promote nitrogen accumulation in grain and improve nitrogen use efficiency in the plant. These observations are consistent with studies highlighting the role of combined N + S fertilization in optimizing nitrogen metabolism and improving nitrogen use efficiency in cereal crops (Scherer, 2001; Salvagiotti et al., 2009).

c) Effect of nitrogen fertilization on grain quality

The results presented in Table 6 highlight a differentiated impact of fertilization strategies on the physical and technological quality parameters of wheat grain. Regarding the physical characteristics, the thousand kernel weight (TKW) varied within a relatively narrow range (49.6-50.8 g), with no statistically significant differences between treatments.

Table 6. Grain physical and technological quality

Treat.	1000-kernel weight (g)	Test weight (kg hl ⁻¹)	Grain protein (%)	Wet gluten (%)	Protein yield (kg ha ⁻¹)
T1	49.6 a	72.3 a	13.7 c	29.9 c	910 b
T2	50.8 a	72.5 a	15.1 a	35.4 a	1041 a
T3	50.0 a	72.3 a	14.7 ab	33.3 b	1011 a
T4	50.0 a	71.2 a	14.6 b	32.4 b	923 b
T5	50.4 a	71.5 a	15.4 a	35.9 a	1031 a
T6	49.8 a	71.4 a	14.3 b	32.0 b	858 c

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

A similar stability was also observed for hectoliter weight (71.2-72.5 kg hl⁻¹), suggesting that grain bulk density was less influenced by

variations in nitrogen fertilization under the experimental conditions.

In contrast, the chemical parameters showed greater sensitivity to fertilization strategies. The protein content ranged between 13.7% and 15.4%, with the highest values recorded in treatments T5 (15.4%) and T2 (15.1%), significantly higher than in T1 (13.7%). The protein level observed in T3 (14.7%) also indicates that this fertilization strategy ensured adequate nitrogen availability during the period of protein synthesis and accumulation in the grain.

A similar pattern was observed for wet gluten content, which ranged between 29.9% and 35.9%. The highest values were recorded in treatments T5 (35.9%) and T2 (35.4%), exceeding those observed in treatments characterized by lower protein content. The close relationship between protein and gluten content is well documented in the literature, as gluten proteins represent the main structural component of wheat gluten (Gooding & Davies, 1997; Wieser, 2007).

Protein yield per hectare ranged between 858 and 1041 kg ha⁻¹, with the highest values obtained in treatments T2 (1041 kg ha⁻¹), T5 (1031 kg ha⁻¹), and T3 (1011 kg ha⁻¹). The absence of statistically significant differences between these three treatments indicates that total protein production is determined by the interaction between grain yield and grain protein concentration.

Overall, the results show that nitrogen fertilization primarily influences the technological quality parameters of wheat grain, particularly protein and gluten content, while the physical grain characteristics remain relatively stable. These observations are consistent with studies indicating that nitrogen availability during the grain filling period is a key factor determining protein accumulation and the technological quality of wheat (Gooding & Davies, 1997; Triboi et al., 2003).

d) Relationships between nitrogen fertilization, yield and grain quality

The integrated analysis of the experimental data shows that the relationship between nitrogen fertilization, grain yield, and the technological quality of wheat does not depend exclusively on

the total amount of nitrogen applied. Although nitrogen rate remains an important factor, the fertilizer form and the timing of application decisively influence how this element is utilized by the plant.

Under the experimental conditions analyzed, treatments T2 and T3 achieved the highest grain yields. However, the comparison between these two treatments highlights important differences in terms of nitrogen use efficiency. Treatment T3, in which the NS27 fertilizer was applied at the N1 stage, achieved a yield comparable to that of T2, although it used a lower total nitrogen rate. At the same time, this treatment was characterized by high values of efficiency indicators and of the Nitrogen Harvest Index (NHI), suggesting a more efficient redistribution of nitrogen toward the grain.

An important factor that may explain this behavior is the use of controlled-release N–S fertilizers. These fertilizers can ensure a more stable nitrogen availability in the soil and a better synchronization between nutrient supply and crop physiological demand. In addition, the presence of sulfur contributes to improved nitrogen metabolism, as the synthesis of amino acids and proteins depends on the simultaneous availability of nitrogen and sulfur (Scherer, 2001; Salvagiotti et al., 2009).

Regarding grain quality, the highest values of protein and gluten content were recorded in treatments T5 and T2. In particular, treatment T5, in which the NS27 fertilizer was applied at the N3 stage, favored protein accumulation in the grain. This result confirms the important role of nitrogen availability during the grain filling period in determining the technological quality of wheat (Gooding & Davies, 1997; Triboi et al., 2003).

In contrast, treatment T6, based on the use of the liquid fertilizer NS19, showed relatively good nitrogen use efficiency, but grain yield was lower compared with the other treatments. This result suggests that liquid fertilizers characterized by rapid nitrogen availability may require supplementation with other nitrogen sources in order to sustain high yield levels during the later growth stages.

Overall, the results indicate that fertilization strategies including controlled-release N–S fertilizers can improve nitrogen use efficiency

while maintaining high levels of both grain yield and grain quality. At the same time, these strategies may allow a reduction in total nitrogen application rates, which is important for the development of more efficient and sustainable agricultural systems (Raun & Johnson, 1999; Fageria & Baligar, 2005).

CONCLUSIONS

The results of this study show that the response of winter wheat to nitrogen fertilization does not depend only on the total nitrogen rate applied, but also on the fertilizer form and the timing of application during the main growth stages.

The application of the controlled-release fertilizer NS27 at the tillering stage (T3) allowed the achievement of grain yields comparable to those obtained with conventional fertilization based on urea and ammonium nitrate, despite the lower total nitrogen rate applied. In this treatment, the highest values of partial factor productivity of nitrogen (PFP-N) and nitrogen harvest index (NHI) were recorded, indicating a more efficient use of nitrogen.

In contrast, the application of NS27 at the flag leaf stage (T5) was associated with the highest protein and gluten contents, highlighting the important role of nitrogen availability during the grain filling period in determining grain quality. The liquid fertilizer NS19 showed relatively good nitrogen use efficiency; however, grain yield was lower compared with the other fertilization strategies, suggesting that liquid fertilizers characterized by rapid nitrogen availability may require combination with other nitrogen sources in order to sustain high yield levels.

Overall, the results indicate that controlled-release N-S fertilizers may represent an effective strategy for optimizing nitrogen fertilization in winter wheat, contributing to improved nitrogen use efficiency and maintaining high grain yield and grain quality depending on the timing of application.

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