

Article

The Impact of Nitrogen Fertilization on the Yield and Quality of Spring and Facultative Wheat Under Different Spring Sowing Dates

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Abstract

This study aimed to investigate the effects of different nitrogen (N) fertilizer rates and sowing dates on grain yield, protein content, grain N uptake, and nitrogen recovery efficiency (NRE) in spring and facultative wheat (*Triticum aestivum* L.) cultivated in northwestern and central Romania from 2018 to 2020. The experiment was designed as a split-split plot study with two spring sowing dates (SDs): an optimal date (1–15 March) and a delayed date (postponed by two weeks). All treatments received a basal autumn fertilizer supplying 36 kg N ha⁻¹ and 92 kg P ha⁻¹. In spring, three N treatments were evaluated: no additional N (N₃₆), 72 kg N ha⁻¹ (N₁₀₈), and 105 kg N ha⁻¹ (N₁₄₁), with the supplementary N top-dressed at the booting stage. The results showed that delayed sowing significantly altered grain N uptake dynamics and reduced NRE, even under standard fertilization regimes. Specifically, delayed sowing reduced grain yield by 7.52% to 28.39% compared to optimal sowing, while adverse climatic interactions in delayed setups reduced the mean NRE to as low as 16.43%. These findings indicate that conventional N application strategies may be suboptimal under variable sowing conditions and highlight the importance of adaptive N management to improve both agronomic performance and environmental sustainability.

Keywords: spring and facultative wheat; sowing date; nitrogen fertilization; grain yield; protein content; grain N uptake; NRE

1. Introduction

Common wheat (*Triticum aestivum* L.) is one of the world's most important cereal crops, providing a major source of calories and protein for the human population. In Romania, wheat represents the predominant grain, occupying approximately 26–28% of the cultivated arable land and nearly 40% of the total cereal-growing area [1]. According to national statistics, wheat was cultivated on 2.27 million ha in 2024, producing 9.29 million t of grain with an average yield of 4091 kg ha⁻¹ [2]. This cereal is cultivated in winter, spring, and facultative forms, which differ primarily in their vernalization requirements [3]. Although winter wheat occupies most of the cultivated area, spring and facultative wheat have attracted increasing interest due to their potential to adapt to highly variable climatic conditions.

An increase of 1 °C in global temperature is estimated to reduce global wheat production by approximately 4.1–6.4% [4,5]. Recent studies indicate that, in temperate

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regions, climate warming is expected to shorten the wheat growing period by accelerating phenological development, primarily owing to rising temperatures, which reduce the duration of vegetative growth and grain filling [6–11]. These conditions can result in insufficient vernalization of winter wheat, leading to significant yield losses [7]. Consequently, agricultural research must consistently enhance crop varieties [12–14] and agronomic practices to ensure reliable, high-quality grain yields [11]. Given the importance of wheat as a staple food crop, identifying suitable genetic materials and optimizing sowing conditions for individual genotypes are essential. Cultivation strategies should therefore be tailored to site-specific environmental conditions. In this context, increased emphasis should be placed on the production of facultative and spring wheat, which exhibit reduced or absent vernalization requirements and may offer enhanced adaptability to highly variable climatic circumstances [15]. As a novel initiative, field trials on facultative and winter wheat were established for the first time at the Agricultural Research and Development Station Turda (ARDS Turda) in autumn 2017, followed by trials on facultative and spring wheat in the subsequent spring [16]. The present study reports selected results from the spring and facultative wheat experiments.

Timely sowing and optimal N fertilization are particularly critical agronomic practices in wheat management, as they exert a substantial impact on grain quality and yield. Under spring sowing conditions, the optimal time for planting is considered to be as early as possible, including during favorable winter intervals. This approach aims to promote tillering and ensure the successful completion of the early stages of organogenesis under moderate temperature conditions [17]. Although wheat exhibits considerable ecological plasticity, delayed spring sowing may result in several adverse effects, including reduced tillering, a lower number of spikes m^{-2} [18], decreased plant height, and a shortened period to heading and maturity [19,20]. Late sowing can also reduce spike length [21], the number of grains per spike, thousand-kernel weight [18,21], and hectoliter weight [21]. Furthermore, delayed sowing often leads to substantial yield reductions [19,20,22,23] while increasing grain protein content [21,22]. Recent studies have investigated the adaptation of spring and facultative wheat genotypes to climate variability by evaluating their performance under contrasting SDs and environmental conditions [14,24,25]. These findings suggest that adjusting the SD alone is insufficient to maintain productivity under climate change and should be complemented by the use of germplasm adapted to environmental stress. Frantová et al. (2025) [25] demonstrated substantial genotypic variation in root morphology and stress responses among spring wheat genotypes carrying distinct vernalization (*VRN*) alleles, indicating that genotypes with facultative growth habits may provide enhanced resilience to climatic variability.

To maximize wheat production and quality, environmental conditions play a crucial role in dictating the optimal N fertilization rate. Various crop management practices, including irrigation, tillage, application methods, timing, and frequency, have been recognized as influential factors affecting the crop's response to N inputs [26,27].

Spring-sown wheat has high N requirements during key growth stages, including tillering, stem elongation, booting, heading, and grain filling, which are essential for reproductive organ development and kernel protein accumulation [28]. N fertilization can significantly enhance the protein content of wheat grains, even when it does not result in a corresponding increase in grain yield [29].

Split application of N fertilizer across various growth stages can enhance NRE, grain quality, and wheat yield [30]. Globally, only 35% of applied N is absorbed by crops, with excessive fertilizer application serving as a primary driver of diminished NRE [31]. Consequently, minimizing surplus N inputs is critical to improving overall efficiency [32]. Applying an appropriate N fertilizer rate at the optimal growth stage not only mitigates production costs [30] but also optimizes yields while minimizing environmental repercussions [33].

Spring and facultative wheat genotypes differ in their response to N fertilization [33,34]. While increased N supply generally enhances grain yield and protein concentration, the magnitude of this response is genotype-dependent. Facultative wheat has recently been shown to outperform spring wheat at conventional N rates (100–200 kg N ha⁻¹), suggesting that genotype selection and N management should be considered jointly when developing climate adaptation strategies [34].

Walsh et al. (2018) [35] identified a robust correlation between applied N rates and spring wheat grain yield across multiple site-years; however, this relationship exhibited significant variability depending on the specific environment and growing season. These data indicate that N fertilizer recommendations should be tailored to individual locations and years.

Numerous studies have examined the independent effects of SD and N fertilization on wheat performance; however, comparatively little information is available on their combined influence on grain yield, grain protein content, grain N uptake, and NRE in spring and facultative wheat grown under the variable climatic conditions of Central and Eastern Europe. Furthermore, a scarcity of information remains regarding the specific responses of different genotypes to reduced N inputs, which is becoming increasingly significant in light of European policies that advocate sustainable fertilizer use.

We hypothesized that (i) delayed spring sowing would reduce grain yield, grain N uptake, and NRE, while increasing grain protein concentration; (ii) N fertilization would improve grain yield, protein content, grain N uptake, and NRE, although it would not fully compensate for the adverse effects of delayed sowing; and (iii) spring and facultative wheat genotypes would differ in their responses to N fertilization under contrasting SDs. Therefore, the objective of this study was to determine the combined effects of spring SD and N fertilization on grain yield, grain protein content, grain N uptake, and NRE of spring and facultative wheat genotypes under the temperate environmental conditions of northwestern and central Romania.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at the experimental field of the Wheat Breeding Laboratory at ARDS Turda. The station is situated between 345 and 493 m above sea level on the Transylvanian Plain of Romania. It is located at coordinates 46°35' N latitude and 23°47' E longitude. The experimental field was managed under a three-year crop rotation system (maize, peas, and wheat), as shown in Figure 1a.



Figure 1. (a) Location of the wheat breeding field at ARDS Turda [36]; (b) site of the experimental trials in the field (2019) [37].

The experiments were performed on a Phaeozem soil, characterized by a loamy-clay texture [38]. Chemical analysis of the soil was carried out at the Department of Technical and Soil Sciences within the Faculty of Agriculture at the University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agrochemical analyses were performed on soil samples collected from the 0–20 cm arable layer. The soil exhibits a neutral pH ranging from 6.8 to 7.2, a clay content between 51.8% and 55.5%, and a humus content of 2.20% to 3.12%. Total N content varies from 1.24 g/kg to 1.62 g/kg, while phosphorus concentrations range from 0.9 to 5 mg/kg, and potassium levels are well-supplied, measuring between 126 and 140 mg/kg [39].

2.2. Biological Materials

Field trials were conducted during the 2018, 2019, and 2020 growing seasons using six wheat genotypes registered in the Official Catalogue of the State Institute for Variety Testing and Registration (ISTIS) [40]. These included three facultative genotypes (Taisa, Ciprian, and Lennox) and three spring genotypes (Pădureni, Granny, and Triso). Although traditionally classified as a spring wheat cultivar, recent breeder documentation indicates that ‘Granny’ also exhibits facultative growth habits, making it suitable for late autumn sowing outside the typical winter wheat window [41]. A brief description of these genotypes is presented in Table 1, with further detailed morphological and agronomic characterization provided by Chețan et al. [42].

Table 1. Agronomic and morphological characteristics of the tested wheat genotypes.

Characteristics	Spring Wheat Genotypes			Facultative Wheat Genotypes		
	Pădureni	Granny	Triso	Taisa	Ciprian	Lennox
Botanical variety	<i>ferrugineum</i>	<i>erythrospermum</i>	<i>lutescens</i>	<i>erythrospermum</i>	<i>erythrospermum</i>	<i>lutescens</i>
Growing period (days)	113–130	107–129	103–128	130–270	109–265	107–271
Plant height (cm)	105–120	80–95	>100	90–100	82–85	90–100
1000-kernel weight (g)	29–38	40–41	33–38	43–47	40–45	45–50
Test weight (kg hl ⁻¹)	75–80	medium values	medium values	74–79	70–84	79–81
Lodging resistance	medium-low	medium	excellent	medium-high	medium-high	high

2.3. Research Methods in Field

A three-factorial ($A \times B \times C$) experiment was conducted over three growing seasons (2018–2020) using a split-split plot design. The experimental factors were as follows:

- Sowing date (main plot)—SD I—optimal sowing, before 15 March; SD II—delayed sowing, postponed by two weeks;
- Nitrogen fertilization rate (subplot)—N₃₆, N₁₀₈, and N₁₄₁ kg N ha⁻¹;
- Wheat genotype (sub-subplot)—Pădureni, Granny, Triso, Taisa, Ciprian, and Lennox (detailed in Section 2.2—Biological Materials).

Each year, the total number of experimental plots was 108, determined by the combination of 2 SD, 3 fertilization rates, 6 wheat genotypes, and 3 replicates. Each individual plot encompassed an area of 7.5 m² (1.25 m × 6 m) and was sown at a density of 550 germinable seeds m⁻² using a Wintersteiger Plot Seed Drill (Wintersteiger Seedmech GmbH, Wintersteigerstrasse 1, 4910 Ried im Innkreis, Austria).

The preceding crop was unfertilized peas, harvested in late June or early July depending on meteorological conditions, with residues baled and removed. Between pea harvest and the sowing of spring wheat, the following operations were performed annually: summer plowing to a depth of 15 cm, two passes with a rotary harrow, and one pass with a cultivator to incorporate the basal autumn fertilizer applied in autumn. In spring, one pass with a harrow and one pass with a cultivator were carried out prior to sowing.

Fertilization was applied in two stages, in autumn and spring. In early October, all experimental plots received a basal fertilizer uniformly broadcast using a fertilizer spreader at a rate of 200 kg ha⁻¹, supplying 36 kg N ha⁻¹ and 92 kg P ha⁻¹.

In spring, additional N was applied at two rates, resulting in three total N treatments: N₃₆: no additional spring N (control); N₁₀₈: 36 kg N ha⁻¹ basal + 72 kg N ha⁻¹ top-dressed; and N₁₄₁: 36 kg N ha⁻¹ basal + 105 kg N ha⁻¹ top-dressed. A non-volatile granular fertilizer (N₂₇Ca₁₂Mg₅), containing N, calcium, and magnesium, was applied manually. The fertilizer was pre-weighed for each plot using a high-precision electronic balance and distributed in individual bags according to the prescribed application rate. For both the N₁₀₈ and N₁₄₁ treatments, the fertilizer was applied during the booting stage (Feekes 10) [43] according to the long-term fertilization protocol adopted by ARDS Turda. This application timing was selected to coincide with the critical period of grain development and protein accumulation under the environmental conditions of the study area.

N application rates were established in compliance with European Union policies aimed at reducing the environmental impact of chemical fertilizers, notably the “Farm to Fork” Strategy and the Nitrates Directive (Council Directive 91/676/EEC). As the experiment was conducted in a wheat breeding field, reduced N rates were used to facilitate the identification of genotypes capable of maintaining high productivity under low-input conditions.

The specific SD for each experimental year was categorized into two distinct levels (optimal and delayed) and is presented in Table 2, along with the corresponding heading and harvest dates.

Table 2. Calendar dates corresponding to the sowing, heading, and harvesting of spring and facultative wheat genotypes.

Year	2018		2019		2020	
Sowing date (SD)	SD I	SD II	SD I	SD II	SD I	SD II
	15 March	4 April	4 March	18 March	4 March	18 March
Genotype	Heading date					
Pădureni	1 June	4 June	5 June	10 June	6 June	6 June
Granny	29 May	31 May	4 June	8 June	4 June	8 June
Triso	30 May	3 June	7 June	9 June	5 June	11 June
Taisa	6 June	20 June	13 June	18 June	12 June	17 June
Ciprian	25 May	2 June	2 June	6 June	4 June	9 June
Lennox	30 May	2 June	4 June	9 June	6 June	11 June
Harvest date	23 July	7 August	24 July	24 July	4 August	7 August

Note: SD I = optimal sowing date (before 15th March); SD II = delayed sowing date (postponed by two weeks).

For the duration of the three-year study period, which spanned from March to August each year, meteorological data—including air temperatures and precipitation levels—were recorded by the Turda Meteorological Station (coordinates: 46°35′ N, 23°47′ E; altitude: 427 m), as summarized in Table 3.

Table 3. Environmental conditions of the research area during the growing seasons (2018–2020).

Month	Rainfall [mm]				Temperature (°C)			
	2018	2019	2020	LTA	2018	2019	2020	LTA
March	40.9	12.3	34.0	23.6	3.3	7.3	6.1	4.7
April	26.2	62.6	17.8	45.9	15.3	11.3	10.3	9.9
May	56.8	152.4	44.4	68.7	18.7	13.6	13.7	15.0
June	98.3	68.8	166.6	84.8	19.4	21.8	19.1	17.9

July	85.7	35.0	86.8	77.1	20.4	20.4	20.2	19.7
August	38.2	63.8	58	56.5	22.3	22.1	21.5	19.3

Note: LTA = long-term average (65 years).

In 2018, heavy rainfall during February and the second half of March delayed spring sowing by 15–20 days relative to the optimal sowing period for the region. Consequently, April and May exhibited reduced precipitation and abnormally elevated temperatures, which accelerated wheat growth and development. These climatic conditions had a particularly pronounced effect on the later-maturing genotypes, including Taisa and Pădureni.

Both April and May 2019 were marked by high precipitation levels, with positive deviations of 16.7 and 83.7 mm, respectively, compared with the long-term average. In addition, the mean temperature recorded in May was 1.4 °C below the long-term average. These climatic conditions contributed to a prolongation of the wheat-growing season. However, owing to late spring sowing, the heading, flowering, grain formation, and grain-filling stages of the cultivar Taisa coincided with the dry period recorded during June and July, which adversely affected its yield performance.

In June 2020, the meteorological conditions were characterized by substantial rainfall and elevated temperatures, which promoted the emergence and proliferation of fungal pathogens (*Septoria* spp., *Puccinia* spp., and *Fusarium* spp.). This disease pressure led to premature leaf desiccation and severely affected the plant stems (*Puccinia recondita*). Consequently, these climatic factors contributed to the lowest wheat yields recorded across the three experimental years, as detailed further in Section 3.1.

Each year, a uniform phytosanitary treatment was administered based on the recommendations of ARDS Turda. The crop protection strategy involved a single tank-mix application of the following commercial formulations: two herbicides (0.12 L ha⁻¹ Sekator OD—Bayer, Leverkusen, Germany and 0.6 L ha⁻¹ Amino 600—Mifalchim Group SRL, Onești, Romania), one fungicide (0.6 L ha⁻¹ Falcon Pro—Bayer, Leverkusen, Germany), and one insecticide (0.2 L ha⁻¹ Apis 200 SE—Innvigo Agro SRL, Cluj-Napoca, Romania). According to the standard BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) growth scale, this treatment was applied when the wheat plants reached the late tillering stage (BBCH 24–25) and the broadleaf (dicotyledonous) weeds were at the 2–4 leaf stage (BBCH 12–14). The same products and application rates were used in each experimental year, with timing determined by crop growth stage rather than calendar date.

2.4. Harvesting and Yield Determination

Harvesting was conducted mechanically using a Wintersteiger Plot Combine (Wintersteiger AG, Ried im Innkreis, Austria). The total grain yield collected from each individual plot was recorded and expressed in kg ha⁻¹, with all values adjusted to a standard grain moisture content of 14%.

Grain protein content was determined by near-infrared (NIR) spectroscopy using a Perten Inframatic 9500 analyzer (Perten Instruments, PerkinElmer Inc., Waltham, MA, USA).

Grain N content was calculated by dividing the protein content by the standard N-to-protein conversion factor of 5.7, which is widely accepted for common wheat [44]. Wheat grain N uptake was subsequently calculated by multiplying total grain yield by the grain N concentration. NRE was assessed by calculating the difference in N uptake between a fertilized treatment and a control receiving no additional spring N. This difference was then divided by the amount of N applied. NRE was calculated using the following equation [33,34,45,46]:

$$NRE (\%) = \left(\frac{N \text{ uptake fertilized} - N \text{ uptake control}}{N \text{ fertilizer applied}} \right) \times 100$$

2.5. Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) for a split-split plot design using the PolyFact statistical software package (Version 2020). The ANOVA model included four factors: year (2018, 2019, and 2020), SD (SD I and SD II), N fertilization rate (N₃₆, N₁₀₈, and N₁₄₁), and genotype (six graduations), together with all possible interactions.

The ANOVA followed the hierarchical structure of the experimental design. Year represented the environmental factor, whereas SD was assigned to the main plots, N fertilization rate to the subplots, and genotype to the sub-subplots. The significance of the main effects and interactions was tested using the corresponding error terms associated with each level of the split-split plot design (Error Y, Error SD, Error F, and Error G).

When the ANOVA indicated significant treatment effects, treatment means were compared using Fisher's protected least significant difference (LSD) test. Statistical significance was evaluated at three probability levels ($p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$), whereas effects with $p > 0.05$ were considered non-significant. ANOVA results are presented as degrees of freedom (df), mean squares (MS), F-values, and corresponding p -values. All figures and graphical representations were generated using Microsoft Excel and PAST software (version 4.03).

3. Results

3.1. Grain Yield

ANOVA revealed that grain yield was primarily influenced by sowing date (SD), followed by genotype (G) and year (Y), while the significant Y × SD interaction indicated that the effect of sowing time depended strongly on environmental conditions (Table 4). Fertilization (F) also significantly increased grain yield but explained a smaller proportion of the total variance. In addition, the Y × F interaction was significant, indicating that the yield response to N fertilization varied among experimental years. The significant F × G interaction further indicates that wheat genotypes differed in their response to increasing N supply, confirming genotype-dependent variation in N use and yield formation. In contrast, the SD × F, Y × F × G, SD × F × G, and Y × SD × F × G interactions had no significant effect on yield.

Table 4. Analysis of variance and the effect of experimental factors on grain yield.

Analysis of Variance					Effect of Factors	
Source of Variance	df	MS	F	p -Value	Variable	Yield (kg ha ⁻¹)
Year (Y)	2	5183.86800	250.362	0.0001	2018	5680 ^A
Sowing date (SD)	1	4305.76500	1213.928	0.0001	2019	4747 ^B
Fertilization (F)	2	1126.822	46.688	0.01	2020	4318 ^C
Genotype (G)	5	2487.939	370.393	0.0001	SD I	5283 ^A
Y × SD	2	1049.351	295.844	0.0001	SD II	4554 ^B
Y × F	4	95.21252	3.945	0.05	N ₃₆	4563 ^C
Y × G	10	94.45496	14.062	0.01	N ₁₀₈	4997 ^B
SD × F	2	42.33186	1.754	ns	N ₁₄₁	5195 ^A
SD × G	5	128.24190	19.092	0.01	Pădureni	4224 ^C
F × G	10	15.97867	2.379	0.01	Granny	5059 ^B
Y × SD × F	4	129.38110	5.361	0.01	Triso	5595 ^A
Y × SD × G	10	140.42180	20.905	0.01	Taisa	3965 ^D

Y × F × G	20	10.10271	1.504	ns	Ciprian	5119 ^B
SD × F × G	10	9.47205	1.410	ns	Lennox	5547 ^A
Y × SD × F × G	20	9.84497	1.466	ns		
Error Y	4	20.70553				
Error SD	6	3.54697				
Error F	24	24.13517				
Error G	180	6.71703				

Note: ns = not significant at the $p \leq 5\%$ level. Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant.

Mean grain yield was highest in 2018 (5680 kg ha⁻¹) and declined to 4747 and 4318 kg ha⁻¹ in 2019 and 2020, respectively (Figure 2). Among the genotypes, Triso and Lennox achieved the highest mean grain yields over the three-year period, whereas Taisa and Pădureni recorded the lowest values. The highest individual grain yields (>6350 kg ha⁻¹) were obtained by Triso and Lennox in 2018, while the lowest yield was recorded for Taisa in 2020 (3458 kg ha⁻¹).

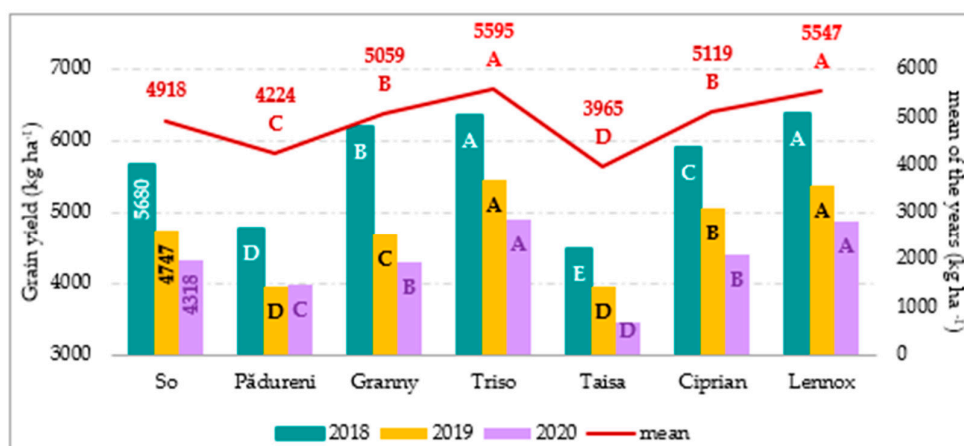


Figure 2. Mean grain yield of spring and facultative wheat over the three experimental years. Note: So—mean of the genotypes for each year. The left scale is for the bar chart; the right scale is for the line chart. Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant.

The results presented in Table 5 show significant effects of N fertilization and SD on grain yield, with responses varying among genotypes and years. Compared with the control receiving no additional spring N (N₃₆), yield increased by 268–600 kg ha⁻¹ under N₁₀₈ and by 392–815 kg ha⁻¹ under N₁₄₁, with the largest response observed in Triso. SD II generally reduced yield, with losses ranging from 400 kg ha⁻¹ in Ciprian to 1312 kg ha⁻¹ in Taisa.

Table 5. The effect of N rate and sowing date on grain yield (kg ha⁻¹) of spring and facultative wheat.

Genotype (G)	Fertilization (F)	2018			2019			2020			F × G Interaction	SD × G Interaction	
		SD I	SD II	Diff.	SD I	SD II	Diff.	SD I	SD II	Diff.		SD I—Ct.	SD II
Pădureni	N ₃₆ —Control	4555	4031	−524	3348	4022	674	4482	2855	−1627	3882		
		M	N	°	R	OPQ	*	FGHIJ	Q	°°°	J		
	N ₁₀₈	5302	4591	−711	3700	4157	457	4751	3324	−1427	4304	4550	3898
		L	M	°	QR	NOP	ns	EFGHI	NOPQ	°°°	H	E	F
	N ₁₄₁	5373	4702	−671	4458	3949	−509	4983	3452	−1531	4486		
		KL	M	°	LMN	OPQ	°	CDEF	MNOP	°°°	G		

Granny	N ₃₆ —Control	5760 HIJK	5329 KL	−431 ns	4258 MNO	4605 JKLMN	347 ns	5202 BCDE	2954 PQ	−2248 ooo	4685 F		
	N ₁₀₈	6453 CDE	6208 DEFGH	−245 ns	4723 IJKLM	4721 IJKLM	−2 ns	5243 BCDE	3268 OPQ	−1975 ooo	5103 D	5437 B	4681 E
	N ₁₄₁	6902 AB	6498 BCD	−404 ns	5184 EFGH	4674 JKLM	−510 o	5212 BCDE	3876 KLMN	−1336 ooo	5391 C		
Triso	N ₃₆ —Control	6027 EFGHI	5551 JKL	−476 ns	4642 JKLM	5320 DEFG	678 *	5436 ABCD	3764 LMNO	−1672 ooo	5123 D		
	N ₁₀₈	6684 ABC	6333 CDEF	−351 ns	5836 ABC	5553 BCDE	−283 ns	5549 ABC	4383 GHIJK	−1166 oo	5723 B	5910 A	5280 C
	N ₁₄₁	7026 A	6524 BCD	−502 ns	6006 A	5388 CDEFG	−618 o	5984 A	4369 HIJK	−1615 ooo	5938 A		
Taisa	N ₃₆ —Control	4888 M	3062 O	−1826 ooo	3689 QR	3406 R	−283 ns	4039 JKLM	3037 PQ	−1002 oo	3687 K		
	N ₁₀₈	5835 GHIJ	3409 O	−2426 ooo	4524 KLMN	3696 QR	−828 ooo	3844 KLMNO	3079 PQ	−765 o	4065 I	4621 E	3309 G
	N ₁₄₁	6324 CDEF	3373 O	−2951 ooo	4683 JKLM	3727 PQR	−956 oo	3761 LMNO	2992 PQ	−769 o	4143 HI		
Ciprian	N ₃₆ —Control	5484 JKL	5360 KL	−124 ns	4738 HIJKL	4998 GHIJ	260 ns	4951 DEFG	3864 KLMN	−1087 oo	4899 E		
	N ₁₀₈	6235 CDEFG	6155 DEFGH	−80 ns	5030 FGHIJ	5158 EFGHI	128 ns	5014 CDEF	3410 NOPQ	−1604 ooo	5167 D	5319 BC	4919 D
	N ₁₄₁	6146 DEFGH	6106 DEFGH	−40 ns	5419 CDEFG	4972 GHIJK	−447 ns	4856 DEFGH	4245 IJKL	−610 o	5291 CD		
Lennox	N ₃₆ —Control	5987 FGHI	5604 IJKL	−383 ns	4510 KLMN	5320 DEFG	810 **	5440 ABCD	3752 LMNO	−1688 ooo	5102 D		
	N ₁₀₈	6906 AB	6191 DEFGH	−715 o	5663 ABCD	5483 BCDEF	−180 ns	5561 ABC	3915 JKLMN	−1646 ooo	5620 B	5858 A	5235 C
	N ₁₄₁	7071 A	6511 BCD	−560 o	5916 AB	5423 CDEFG	−493 ns	5672 AB	4914 DEFGH	−758 o	5918 A		
LSD 5%		539		506	544	498		577	563	208	136		

Note: Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant. ns = not significant. *, ° = $p \leq 0.05$; **, oo = $p \leq 0.01$; and, ooo = $p \leq 0.001$. SD I = optimal sowing date; SD II = delayed sowing date; diff. = SD II – SD I.

In 2018, N₁₄₁ produced the highest yields under SD I, with significant increases over N₃₆ for all cultivars. The largest responses were recorded for Taisa (+1436 kg ha^{−1}), Granny (+1142 kg ha^{−1}), and Lennox (+1084 kg ha^{−1}). SD II significantly reduced yield only in the later-maturing cultivars Pădureni, Taisa, and Lennox, with Taisa showing the greatest reduction (37.4–46.7%, depending on N rate).

In 2019, N significantly increased grain yield only under SD I, with the greatest responses observed in Triso and Lennox. Under SD II, yield increased in the N₃₆ treatment in Pădureni, Triso, and Lennox but declined under N fertilization in Taisa and, to a lesser extent, Pădureni, Granny, and Triso.

In 2020, SD II significantly reduced grain yield across all N treatments because of unfavorable weather conditions, with losses ranging from 610 to 2248 kg ha^{−1} depending on genotype and fertilization level.

Overall, N fertilization increased grain yield under favorable conditions, whereas SD II substantially reduced yield. The magnitude of both responses depended on genotype and growing season.

3.2. Protein Content

Grain protein content was significantly affected by genotype (G), N fertilization (F), and year (Y), with genotype and fertilization showing the largest F-values among the main effects (Table 6). Environmental factors (Y) significantly impacted the physiological mechanisms regulating grain protein accumulation. The sowing date (SD) did not significantly affect protein content. Among the two-way interactions, $Y \times SD$, $Y \times F$, $Y \times G$, $SD \times G$, and $F \times G$ were all highly significant ($p \leq 0.01$), whereas $SD \times F$ showed no significant effect. All three-way interactions reached significance ($p \leq 0.01$), with the exception of $SD \times F \times G$. The four-way interaction $Y \times SD \times F \times G$ was also non-significant.

Table 6. Analysis of variance and the effect of experimental factors on protein content.

Analysis of Variance					Effect of Factors	
Source of Variance	df	MS	F	p-Value	Variable	Protein (%)
Year (Y)	2	51.79873	46.583	0.01	2018	13.48 ^C
Sowing date (SD)	1	0.73198	3.312	ns	2019	13.08 ^B
Fertilization (F)	2	127.02190	231.111	0.01	2020	14.42 ^A
Genotype (G)	5	35.98434	356.651	0.01	SD I	13.62 ^A
$Y \times SD$	2	11.36077	51.409	0.01	SD II	13.71 ^A
$Y \times F$	4	4.01253	7.301	0.01	N ₃₆	12.47 ^C
$Y \times G$	10	3.99422	39.588	0.01	N ₁₀₈	13.92 ^B
$SD \times F$	2	0.00836	0.015	ns	N ₁₄₁	14.6 ^A
$SD \times G$	5	0.61753	6.121	0.01	Pădureni	14.46 ^A
$F \times G$	10	0.85181	8.443	0.01	Granny	12.6 ^D
$Y \times SD \times F$	4	3.10744	5.654	0.01	Triso	13.18 ^C
$Y \times SD \times G$	10	0.57922	5.741	0.01	Taisa	14.18 ^B
$Y \times F \times G$	20	0.23001	2.280	0.01	Ciprian	14.5 ^A
$SD \times F \times G$	10	0.01636	0.162	ns	Lennox	13.06 ^C
$Y \times SD \times F \times G$	20	0.08499	0.842	ns		
Error Y	4	1.11198				
Error SD	6	0.22099				
Error F	24	0.54961				
Error G	180	0.10090				

Note: ns = not significant at the $p \leq 5\%$ level. Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant.

Mean protein content ranged from 13.08% in 2019 to 14.42% in 2020. There was a significant increase in protein content with N fertilization, rising from 12.47% under N₃₆ to 13.92% under N₁₀₈ and further to 14.60% under N₁₄₁. Among the different genotypes, Ciprian (14.50%) and Pădureni (14.46%) exhibited the highest mean protein content, while Granny recorded the lowest at 12.60% (see Figure 3).

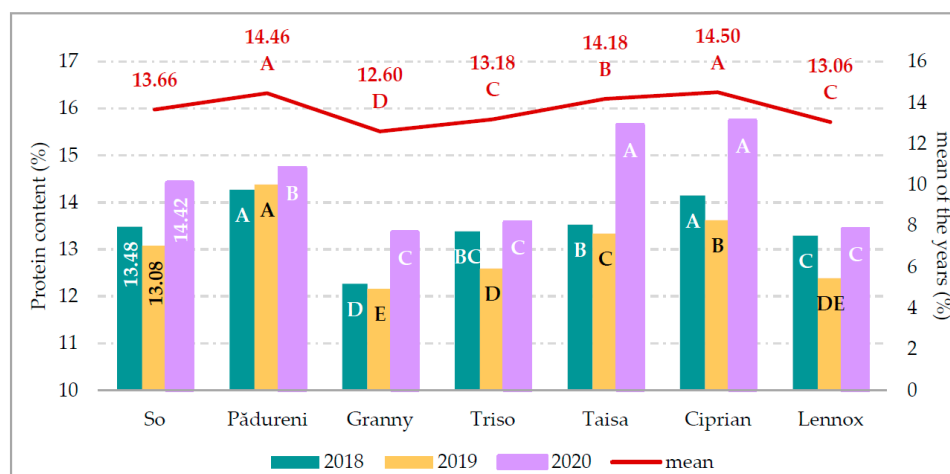


Figure 3. Mean protein content of spring and facultative wheat over the three experimental years. Note: So—mean of the genotypes for each year. The left scale is for the bar chart; the right scale is for the line chart. Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant.

N fertilization significantly increased grain protein content in all cultivars (Table 7). Compared with the control receiving no additional spring N (N_{36}), protein content increased by 1.10–1.87% under N_{108} and by 1.60–2.76% under N_{141} , with the largest responses recorded in Ciprian. Protein content in Pădureni and Ciprian consistently exceeded 14% under N_{108} and 15% under N_{141} , indicating a strong genetic component.

Table 7. The effect of N fertilization rate and sowing date on the grain protein content (%) of spring and facultative wheat.

Genotype (G)	Fertilization (F)	2018			2019			2020			F × G Interaction	SD × G Interaction	
		SD I	SD II	diff.	SD I	SD II	diff.	SD I	SD II	diff.		SD I—Ct.	SD II
Pădureni	N_{36} —Control	12.97 KL	12.83 LM	−0.13 ns	12.17 KLM	13.47 FGHI	1.3 **	14.13 J	13.33 KLM	−0.8 °	13.15 HI		
	N_{108}	14.57 CDEF	14.83 CDE	0.27 ns	14.23 CDE	14.80 BC	0.57 ns	15.07 HI	14.83 I	−0.24 ns	14.72 D	14.38 AB	14.54 A
	N_{141}	14.90 CD	15.50 A	0.6 ns	15.67 A	15.93 A	0.26 ns	15.70 EFG	15.33 GHI	−0.37 ns	15.51 B		
Granny	N_{36} —Control	11.40 QR	11.10 R	−0.3 ns	9.93 Q	11.80 MN	1.87 **	12.90 MN	12.90 MN	0.0 ns	11.67 L		
	N_{108}	12.67 LMN	12.70 LMN	0.03 ns	12.10 LM	12.67 JKL	0.57 ns	13.27 KLM	13.70 JKL	0.43 ns	12.85 J	12.39 F	12.80 E
	N_{141}	12.83 LM	12.93 KL	0.1 ns	12.70 JKL	13.73 DEF	1.03 *	13.70 JKL	13.70 JKL	0.0 ns	13.27 GH		
Triso	N_{36} —Control	12.43 MN	11.97 OP	−0.47 ns	10.43 PQ	11.67 MN	1.23 **	13.13 LM	12.37 N	−0.77 °	12.00 K		
	N_{108}	13.77 HIJ	13.70 IJ	−0.07 ns	12.60 JKL	12.93 HIJ	0.33 ns	13.87 JK	13.67 JKL	−0.2 ns	13.42 G	13.17 CD	13.20 C
	N_{141}	14.13 FGHI	14.30 FG	0.17 ns	13.90 DEF	14.00 DEF	0.10 ns	14.23 J	14.20 J	−0.03 ns	14.13 EF		
Taisa	N_{36} —Control	12.87 LM	11.93 OP	−0.93 °	11.40 NO	13.67 DEFG	2.27 **	15.73 DEFG	13.73 JKL	−2 °°°	13.22 GH	14.30 B	14.05 B
	N_{108}	14.10	13.33	−0.77	13.03	13.70	0.67	16.30	15.43	−0.87	14.32		

		FGHI	JK	ns	GHIJ	DEFG	ns	BCD	FGH	°	E		
Ciprian	N ₁₄₁	14.40	14.57	0.17	13.90	14.37	0.47	16.97	15.73	−1.23	14.99	14.46	14.55
		EFG	CDEF	ns	DEF	CD	ns	A	DEFG	°°	C		
	N ₃₆ —Control	12.70	12.33	−0.37	10.83	12.47	1.63	15.13	14.27	−0.87	12.96		
		LMN	NO	ns	OP	JKL	**	HI	J	°	IJ		
	N ₁₀₈	14.93	14.53	−0.4	13.43	14.10	0.67	16.03	15.97	−0.07	14.83		
		BCD	DEF	ns	FGHI	DEF	ns	CDE	CDEF	ns	CD		
Lennox	N ₁₄₁	15.03	15.37	0.33	15.33	15.53	0.20	16.67	16.40	−0.27	15.72	13.01	13.12
		BC	AB	ns	AB	A	ns	AB	BC	ns	A		
	N ₃₆ —Control	12.27	11.80	−0.47	10.20	11.40	1.20	12.87	12.50	−0.37	11.84		
		NO	PQ	ns	PQ	NO	*	MN	N	ns	KL		
	N ₁₀₈	13.77	13.70	−0.07	12.57	12.83	0.26	13.17	13.87	0.7	13.39		
		HIJ	IJ	ns	JKL	IJK	ns	LM	JK	*	G		
	N ₁₄₁	13.97	14.23	0.27	13.60	13.77	0.17	14.23	13.97	−0.26	13.96	0.20	
		GHI	FGH	ns	EFGH	DEF	ns	J	J	ns	F		
LSD 5%		0.94		0.80	0.62		0.75	0.64		0.67	0.28		

Note: Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant. ns = not significant. *, ° = $p \leq 0.05$; **, °° = $p \leq 0.01$; and °°° = $p \leq 0.001$. SD I = optimal sowing date; SD II = delayed sowing date; diff. = SD II – SD I.

SD II had a minimal overall impact on grain protein content; however, significant responses varied by genotype and year. In 2019, SD II resulted in an increase in protein content under N₃₆ across all cultivars, while under N₁₀₈ and N₁₄₁, it influenced only the Granny genotype. Conversely, during the challenging conditions of 2020, SD II led to a significant reduction in protein content for Pădureni, Triso, Taisa, and Ciprian, with the most notable decrease observed in Taisa (2.00%).

3.3. Grain N Uptake and Nitrogen Recovery Efficiency

Grain N uptake was significantly influenced by all four main experimental factors: sowing date (SD), genotype (G), fertilization (F), and year (Y) (Table 8). Among the two-way interactions, Y × SD exerted the strongest effect, followed by SD × G, Y × G, Y × F, and F × G, while SD × F was non-significant. The three-way interactions Y × SD × G and Y × SD × F were also significant, whereas Y × F × G, SD × F × G, and Y × SD × F × G had no significant effect on grain N uptake.

Table 8. Analysis of variance and the effect of experimental factors on grain N uptake and NRE.

Analysis of Variance					Effect of Factors		
Source of Variance	Grain N Uptake		NRE		Variable	Grain N Uptake (kg ha ⁻¹)	NRE (%)
	F	<i>p</i> -Value	F	<i>p</i> -Value			
Year (Y)	108.662	0.01	8.759	0.05	2018	134.63 ^A	42.44 ^A
Sowing date (SD)	631.909	0.0001	17.175	0.01	2019	108.90 ^B	32.98 ^{AB}
Fertilization (F)	139.136	0.01	0.035	ns	2020	108.92 ^B	16.43 ^B
Genotype (G)	212.168	0.01	12.445	0.01	SD I	126.12 ^A	33.94 ^A
Y × SD	287.542	0.01	40.531	0.01	SD II	108.85 ^B	27.30 ^B
Y × F	6.795	0.01	1.331	ns	N ₃₆	99.3 ^C	-
Y × G	8.985	0.01	3.204	0.01	N ₁₀₈	121.37 ^B	30.32 ^A
SD × F	1.771	ns	0.016	ns	N ₁₄₁	131.78 ^A	30.91 ^A
SD × G	19.896	0.01	2.099	ns	Pădureni	107.64 ^C	30.16 ^{BC}
F × G	3.836	0.01	0.064	ns	Granny	111.66 ^B	27.24 ^C
Y × SD × F	5.365	0.01	0.215	ns	Triso	129.58 ^A	36.47 ^A

Y × SD × G	14.950	0.01	2.720	ns	Taisa	98.49 ^D	21.65 ^D
Y × F × G	1.411	ns	1.120	ns	Ciprian	130.03 ^A	32.27 ^{AB}
SD × F × G	1.470	ns	1.084	ns	Lennox	127.49 ^A	35.92 ^A
Y × SD × F × G	1.302	ns	1.061	ns			

Note: ns = not significant at the $p \leq 5\%$ level. Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant.

NRE was significantly affected by SD, G, Y, Y × SD, and Y × G, whereas F and all remaining interactions had no significant effect.

Mean grain N uptake was highest in 2018 (134.63 kg ha⁻¹) and did not differ between 2019 and 2020 (108.9 kg ha⁻¹). NRE declined from 42.44% in 2018 to 16.43% in 2020. Among genotypes, Ciprian, Triso, and Lennox recorded the highest grain N uptake, while Triso and Lennox also exhibited the highest NRE. Taisa consistently showed the lowest values for both traits (Figure 4).

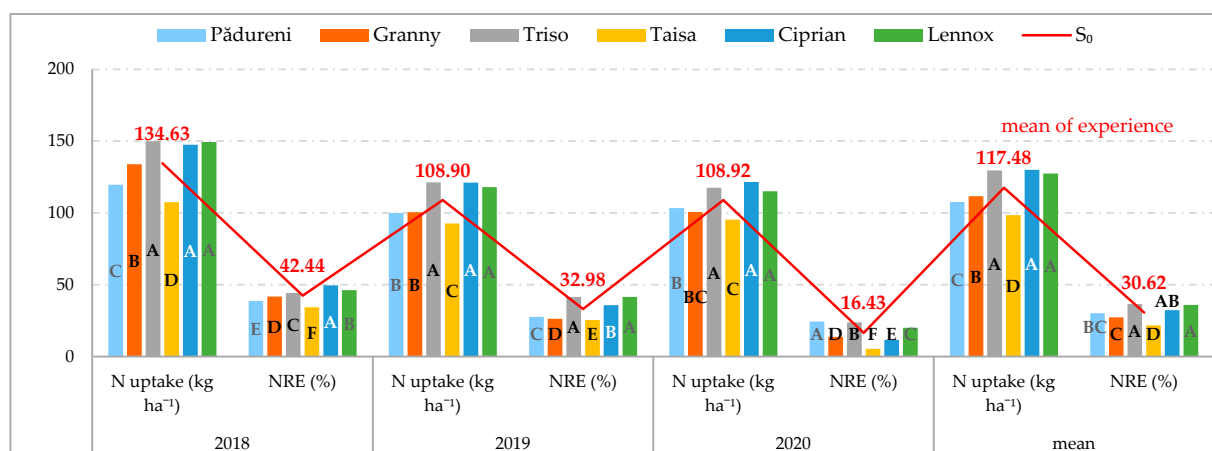


Figure 4. Grain N uptake and NRE of spring and facultative wheat over the three experimental years. Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant. So—mean of the genotypes for each year.

Additional N fertilization significantly increased grain N uptake in all cultivars (Table 9), with increases ranging from 15.83 to 26.67 kg ha⁻¹ under N₁₀₈ and from 22.36 to 38.82 kg ha⁻¹ under N₁₄₁ compared with the control receiving no additional spring N (N₃₆). Triso and Lennox showed the greatest response, whereas Taisa consistently exhibited the lowest grain N uptake under both fertilization rates.

Table 9. Grain N uptake (kg ha⁻¹) according to fertilization and sowing date under the conditions of experimental years.

Genotype	Fertilization (G)	2018			2019			2020			F × G Interaction	SD × G Interaction	
		SD I	SD II	diff.	SD I	SD II	diff.	SD I	SD II	diff.		SD I—Ct.	SD II
Pădureni	N ₃₆ —Control	103.65	90.73	−12.91	71.48	95.05	23.56	111.11	66.77	−44.34	89.80		
		Q	R	ns	R	MNOP	**	FGH	N	ooo	I		
	N ₁₀₈	135.53	119.45	−16.08	92.37	107.94	15.57	125.61	86.48	−39.13	111.23	115.56	99.72
		JHL	NOP	ns	OP	IJKL	*	CDEF	LMN	ooo	DE	E	G
	N ₁₄₁	140.45	127.86	−12.59	122.56	110.36	−12.19	137.25	92.84	−44.41	121.89		
		IJK	LMN	ns	DEFGH	IJKL	o	ABC	KLM	ooo	C		
Granny	N ₃₆ —Control	115.20	103.78	−11.42	74.18	95.33	21.15	117.73	66.85	−50.88	95.51	118.78	104.55
		OP	Q	ns	R	MNOP	**	EFG	N	ooo	H	DE	F

Triso	N ₁₀₈	143.44 HIJ	138.32 IJKL	−5.12 ns	100.26 LMNO	104.94 JKLM	4.68 ns	122.06 CDEF	78.55 MNO	−43.51 °°°	114.59 D		
	N ₁₄₁	155.36 CDEFG	147.40 FGHI	−7.96 ns	115.50 FGHIJ	112.59 HIJK	−2.92 ns	125.27 CDEF	93.16 KLM	−32.11 °°	124.88 C		
	N ₃₆ —Control	131.43 KLM	116.57 OP	−14.86 ns	84.94 PQ	108.92 IJKL	23.98 **	125.22 CDEF	81.69 LMNO	−43.53 °°°	108.13 EF		
	N ₁₀₈	161.47 CD	152.21 DEFGH	−9.26 ns	129.01 CDE	125.97 CDEF	−3.04 ns	135.03 ABCD	105.12 GHIJ	−29.91 °°	134.80 B	137.46 A	121.70 BC
	N ₁₄₁	174.17 A	163.67 ABCD	−10.50 ns	146.46 A	132.34 BCD	−14.12 °	149.39 A	108.84 EFG	−40.55 °°°	145.81 A		
	N ₃₆ —Control	110.37 PQ	64.09 T	−46.82 °°°	73.78 R	81.68 QR	7.9 ns	111.46 FGH	73.15 NO	−38.31 °°°	85.76 I		
Taisa	N ₁₀₈	144.34 GHIJ	79.72 S	−64.62 ns	103.42 KLMN	88.83 PQ	−14.58 °	109.92 FGHI	83.35 LMN	−26.57 °°	101.59 G	115.47 E	81.51 H
	N ₁₄₁	159.76 CDE	86.22 RS	−73.54 °°°	114.20 GHIJK	93.96 NOP	−20.24 °°	111.97 FG	82.57 LMN	−29.40 °°	108.12 EF		
	N ₃₆ —Control	122.19 MNO	115.95 OP	−6.24 ns	90.02 OPQ	109.34 IJKL	19.32 **	131.42 BCDE	96.74 HIJK	−34.68 °°°	110.94 DEF		
Ciprian	N ₁₀₈	163.31 ABCD	156.90 CDEF	−6.41 ns	118.51 EFGHI	127.59 CDE	9.08 ns	141.01 AB	95.54 IJK	−45.47 °°°	133.81 B	135.14 A	124.92 B
	N ₁₄₁	162.06 BCD	164.65 ABC	2.59 ns	145.74 A	135.47 BC	−10.28 ns	142.02 AB	122.14 CDEF	−19.88 °	145.34 A		
	N ₃₆ —Control	128.88 LMN	116.01 OP	−12.87 ns	80.71 QR	106.40 IJKL	25.69 **	122.83 CDEF	82.28 LMN	−40.55 °°°	106.19 F		
Lennox	N ₁₀₈	166.83 ABC	148.80 EFGHI	−18.03 °	124.88 CDEF	123.42 DEFG	−1.47 ns	132.68 BCDE	95.11 IJK	−37.57 °°°	131.28 B	134.30 A	120.68 CD
	N ₁₄₁	173.30 AB	162.55 BCD	−10.75 ns	141.15 AB	131.01 BCD	−10.14 ns	141.60 AB	120.44 DEFG	−21.16 °	145.01 A		
	LSD 5%	18.32	16.27		12.53	11.90		14.23	14.80		4.49	3.67	

Note: Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant. ns = not significant. *, ° = $p \leq 0.05$; **, °° = $p \leq 0.01$; and, °°° = $p \leq 0.001$. SD I = optimal sowing date; SD II = delayed sowing date; diff. = SD II – SD I.

SD II significantly reduced grain N uptake and NRE (Table 9 and Figure 5b). Grain N uptake declined by 10.22–55.95 kg ha^{−1} depending on genotype, while NRE decreased by up to 14.24%, with the largest reduction observed in Taisa. Despite increasing grain N uptake, supplementary N application did not significantly affect NRE (Figure 5a).

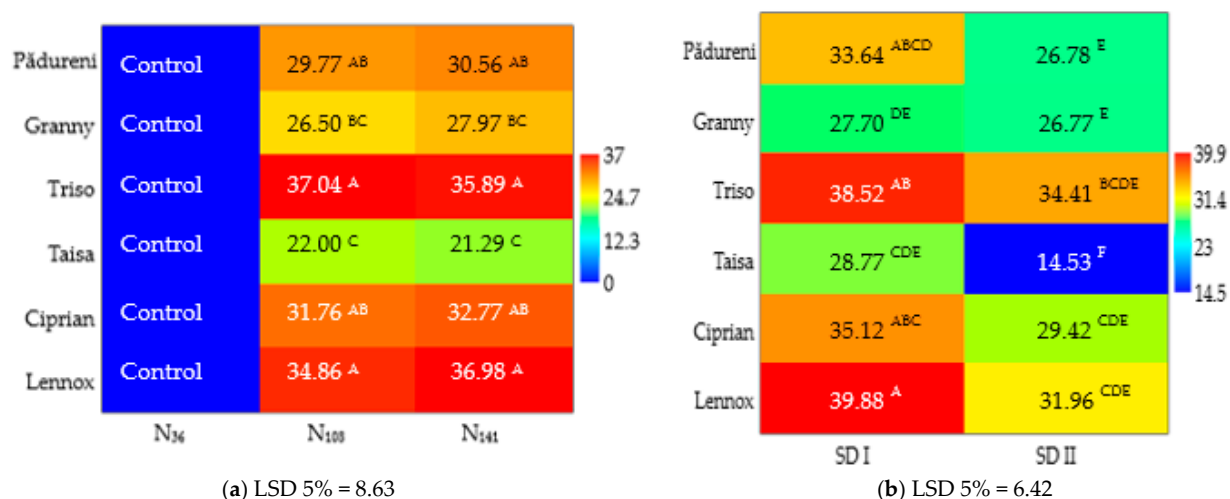


Figure 5. NRE (%) according to fertilization (a) and sowing date (b). Note: Means with different letters are statistically significant at $p \leq 0.05$ using the LSD test. Different means with similar letters are statistically non-significant. SD I = optimal sowing date; SD II = delayed sowing date.

4. Discussion

Climate change projections indicate increasing temperatures and greater interannual climatic variability, making the optimization of SD and cultivar selection increasingly important for wheat production [47]. In Romania, these trends are reflected by above-average temperatures and increasingly irregular precipitation patterns, highlighting the need to adjust spring sowing strategies and develop cultivars better adapted to abiotic and biotic stresses [48].

This study aimed to evaluate six wheat genotypes (three typical spring cultivars and three facultative cultivars) from both yield and quality perspectives. Over a three-year experimental period, these genotypes were evaluated under two spring SDs (the optimal for the region and a delayed date postponed by two weeks) and three total N application rates of 36, 108, and 141 kg N ha⁻¹, corresponding to a common basal autumn application of 36 kg N ha⁻¹ and two additional spring top-dressing rates. The spring N fertilizer was applied at the booting stage, following the long-term fertilization protocol adopted at the research station and in accordance with approaches reported in previous studies [22,28]. This timing is considered optimal to simultaneously promote the development of yield components and enhance grain quality parameters.

4.1. Grain Yield

The present study indicated that grain yield was primarily influenced by SD, followed by genotype, climatic conditions, and N fertilization (Table 4, Figure 2). Except for the predominant effect of SD, these findings are consistent with previous studies reporting that wheat productivity is largely determined by genotype, N supply, weather conditions, and their interactions [23,28,49,50]. Interannual yield variation reflected differences in temperature and rainfall patterns, which strongly affected crop phenology. Because wheat is highly temperature-dependent, delayed sowing accelerates crop development, shortens the duration of key phenological stages, and often results in earlier maturity [11,22,33,51,52].

The highly significant $Y \times SD$ interaction demonstrates that the impact of sowing time was strongly dependent on seasonal weather conditions. SD II caused relatively small yield reductions under favorable conditions in 2018 but much greater losses during the wet and warm conditions of 2020, indicating that environmental stress amplified the negative effects of shortened wheat development.

SD II was one of the principal causes of yield reduction in the present study. Grain yield losses ranged from 7.5% to 28.4% across treatments and reached 46.7% in the late-maturing cultivar Taisa under the 2018 conditions. Although these reductions were generally smaller than the 34–62% losses reported under later sowing in other environments [20,23], they confirm the importance of timely sowing for maximizing spring-sown wheat productivity. Similar reductions associated with delayed sowing have been reported by Gupta et al. [19] and Jarecki [11]. The magnitude of the response depended strongly on genotype, with the late-maturing cultivars Taisa and Pădureni exhibiting the greatest sensitivity. These findings agree with Al-Zubaidi et al. [18] and Gulino and Lopes [7], who showed that late-flowering genotypes experience greater heat and evapotranspiration during grain filling, resulting in reduced grain yield and quality. Triso and Lennox consistently produced the highest grain yields across environments, suggesting greater adaptation to variable SDs and seasonal conditions than the later-maturing cultivars.

The significant $Y \times F$ interaction (Table 4) indicates that the response of wheat grain yield to N fertilization varied among growing seasons, reflecting differences in rainfall, temperature, and disease pressure. Consequently, the effectiveness of additional N depended on the prevailing environmental conditions which further modified genotype performance. The unusually wet and warm conditions during June 2020 were highly conducive to wheat diseases characteristic of the cultivation area (*Puccinia* spp., *Septoria* spp., *Blumeria* spp., and *Fusarium* spp.), which likely contributed to premature leaf senescence, impaired grain filling, and the lowest grain yields recorded during the study. Similar relationships between disease resistance and grain productivity have been reported by Akin et al. [53].

N availability remains a major determinant of wheat productivity because it supports crop development, sustains photosynthetic activity, prolongs green leaf area duration, and contributes to grain protein content [28,30,33]. Across the experiment, increasing the total N rate from basal application (N_{36}) to N_{108} and N_{141} kg N ha⁻¹ through supplementary top-dressed N generally increased grain yield and grain quality, with N_{141} producing the greatest responses. These results agree with previous studies identifying an optimum N supply of approximately 100–120 kg N ha⁻¹ under similar production systems [28,43,49,54]. Likewise, Jahan et al. [55] and Koppensteiner et al. [51] reported that grain yield increased only up to an optimum N rate, after which additional fertilizer produced little or no further yield benefit.

Recent evidence also suggests that facultative wheat represents a promising adaptation strategy under changing climatic conditions. Yousefi et al. [34] reported that facultative wheat produced higher grain yields than spring wheat under conventional N rates (100–200 kg N ha⁻¹), while increased N application enhanced grain protein concentration and nutrient accumulation.

Although increasing the total N supply substantially increased grain yield, it could not fully compensate for the yield losses associated with delayed sowing. The supplementary N applied in addition to the basal fertilizer (N_{36}), particularly the later application at the booting stage, likely enhanced grain N accumulation and prolonged crop photosynthetic activity during grain filling but could not reverse the earlier reduction in yield potential caused by shortened vegetative development and diminished spike establishment. Once sink capacity has been restricted by delayed sowing, additional N primarily supports grain filling and protein accumulation rather than increasing grain number or restoring final yield. This interpretation is consistent with our finding that late N application improved grain quality more markedly than grain yield and contrasts with Jarecki [11], who reported that substantially higher N rates (200 kg ha⁻¹ N) partially compensated for delayed sowing under different environmental conditions.

4.2. Protein Content

Wheat sown in spring is characterized by a higher content of total protein [22]. Proteins, which are essential for both nutritional value and baking properties, differ in concentration within the wheat grain. This variation is influenced by factors such as species, cultivar, climatic conditions, soil fertility, and the application of N fertilizer [56]. Previous studies have shown that protein concentration varies significantly with experimental year, genotype, and N supply [23,28,49,55,57], which is consistent with our results (Table 6, Figure 3).

Although genotype and N fertilization exhibited the strongest statistical effects on grain protein content (Table 6), environmental conditions remain physiologically important [58]. Grain protein accumulation depends strongly on temperature and moisture during grain filling [59–61]. Excessive rainfall before harvest may induce pre-harvest sprouting, increasing enzymatic activity and reducing technological quality [62]. This statement likely explains the quality degradation observed in the Taisa cultivar under SD II in 2020, irrespective of N rate (Table 7).

The overall main effect of SD on grain protein content was not significant (Table 6), but the highly significant $Y \times SD$ interaction indicates that its influence depended on the prevailing environmental conditions. Under seasons characterized by accelerated grain filling, delayed sowing tended to increase grain protein concentration despite reducing grain yield, consistent with previous reports in spring wheat [16,21,22,61]. Shortened grain filling under higher temperatures limits starch deposition, reducing the dilution effect associated with carbohydrate accumulation and thereby increasing grain protein concentration [63,64]. Elevated temperatures may also promote the accumulation of nitrogenous compounds through enhanced metabolic activity and protein synthesis [65,66], which may explain the average 0.82% increase in grain protein observed under SD II in 2019 despite only a slight reduction in grain yield (Tables 5 and 7).

Increasing the total N supply through supplementary top-dressed N application in addition to the basal fertilizer further increased grain protein concentration (Table 7), confirming previous reports that grain protein content responds positively to increasing N supply [16,29,33,43,67]. However, environmental stress frequently exerts a stronger influence than N rate, as heat and moisture stress can increase grain protein content regardless of fertilizer application [16,33]. This mechanism likely contributed to the high protein concentrations recorded in both spring and facultative wheat during the unfavorable 2020 season (Table 7, Figure 3).

4.3. Grain N Uptake and Nitrogen Recovery Efficiency

Grain N uptake integrates grain yield with grain N concentration and therefore provides a comprehensive indicator of both productivity and grain quality [33]. NRE reflects the efficiency with which applied fertilizer N is recovered in harvested grain and is widely used to evaluate fertilizer N utilization [68]. Grain N originates from continued soil uptake during grain filling together with remobilization of N previously stored in vegetative tissues [69].

The timing of N application is critical for synchronizing N availability with crop demand [31]. SD II shortened crop development and reduced the duration available for N uptake and assimilation, contributing to lower grain N uptake and NRE (Table 9, Figure 5b). Because approximately 50–60% of total N uptake occurs by the end of tillering, early top-dressing generally has the greatest influence on yield formation [70]. N supplied at booting, by contrast, primarily supports grain filling rather than increasing sink capacity.

Our results support this physiological distinction. The higher total N rates, achieved by supplementing the basal fertilizer with additional top-dressed N, improved grain protein concentration and grain N uptake but did not compensate for the yield losses caused by SD II. Once spike number and potential grain number had already been limited by shortened vegetative growth, additional N could enhance N remobilization, maintain

chlorophyll and photosynthetic activity, delay functional leaf senescence, and promote assimilate transport to developing grains [71–73]. These processes improved grain N accumulation and quality, but they could not restore the yield potential that had been determined earlier in crop development.

Although all cultivars responded positively to the higher total N rates through increased grain N uptake (Table 9), substantial genotypic differences were observed in NRE (Figure 5), consistent with previous reports highlighting significant genetic variation in NRE [74,75]. Such variation emphasizes the importance of cultivar selection for optimizing N management under variable environmental conditions.

Previous studies have also shown that the N rate maximizing grain yield while maintaining high NRE differs among environments [23]. Higher N inputs generally increase grain protein while reducing NRE because of greater N losses through leaching and denitrification. Although increasing the total N rate had no significant overall effect on NRE in the present study (Table 8), this mechanism may have contributed to the low NRE observed during the exceptionally wet 2020 season. Excess rainfall likely enhanced N losses through leaching while simultaneously favoring disease development, thereby reducing the plants' capacity to utilize available N during grain filling. Consequently, the 2020 season produced the lowest grain yields despite relatively high grain protein concentrations.

5. Conclusions

Our findings indicate that in the specific pedoclimatic conditions of the Transylvanian Plain, the interaction between SDs and genetic factors underscores the absolute importance of sowing as early as possible in spring—ideally in early March—provided that weather conditions are favorable.

N fertilization substantially improved grain yield and quality in spring and facultative wheat. Increasing the total N rate from N_{36} to N_{108} and N_{141} kg N ha⁻¹, through supplementary N applied at the booting stage, increased mean grain yield by 434 and 632 kg ha⁻¹, respectively. In contrast, SD I produced a mean grain yield 729 kg ha⁻¹ higher than SD II. These results demonstrate that although increasing total N supply enhanced wheat productivity, the additional N applied at the booting stage could not fully compensate for the yield losses associated with delayed sowing.

The effect of increasing the total N rate on grain protein content was more pronounced than on grain yield, with increases reaching up to 1.87% at N_{108} and 2.76% at N_{141} , compared with the N_{36} treatment.

The present findings, which show that increasing the total N rate through supplementary N applied at the booting stage significantly increased grain N uptake but had no significant effect on NRE, suggest that optimizing N application timing, rather than increasing N rate alone, may be more effective for improving NRE under variable sowing conditions.

Furthermore, the results highlighted notable varietal differences in N management. The highest-yielding varieties, Triso and Lennox, also exhibited the highest NRE values (36.46% and 35.91%, respectively), with mean grain yields of 5595 and 5547 kg ha⁻¹, indicating that genotype selection is a key factor in optimizing both productivity and NRE.

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