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Research Article

Integrated effects of genotype, sowing date, and plant density on wheat grain yield

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Abstract

Wheat yields in production often fall below the genetic potential of varieties, creating a persistent challenge in improving productivity. This study investigated the effects of genotype, sowing date, sowing density, and fertilization model on wheat yield, as well as their interactions, to identify optimal management strategies. Field trials were conducted during two successive growing seasons in the Semberija region, Republic of Srpska, Bosnia and Herzegovina, using three wheat varieties. The experiment followed a randomized split-plot design with three replications, including three varieties, three sowing dates, five sowing densities, and three fertilization models. Data were analyzed with four-factor ANOVA, and significant differences were tested using Fisher's LSD at the 0.05 and 0.01 probability levels. The results showed that average yields exceeded 8,000 kg ha^{-1} in the first year, but decreased with delayed sowing. Yield losses due to late sowing could not be offset by increasing seed density, although 400-500 seeds m^{-2} proved optimal. Fertilization effects varied across conditions, with the second fertilization model producing the highest yields under favorable circumstances. Overall, both individual treatments and their interactions significantly affected yield, underscoring the importance of tailoring sowing and fertilization practices to specific varieties and environments.

Keywords: agronomic management; crop management; nitrogen fertilization; productivity; sowing rate; *Triticum aestivum*; variety

Abbreviations: G - genotype; E -environment (year of cultivation); M - management strategy (one of the researched factors: 1. sowing date, 2. sowing density, 3. fertilization); ANOVA-Analysis of variance; CAN-Calcium Ammonium, Nitrate; FAO - Food and Agriculture Organization; ISO-International

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Organization for Standardization; LSD-Least significant differences; NPK-Nitrogen, Phosphorus, Potassium

Introduction

Wheat is one of the world's most important cereal crops, accounting for nearly one-third of total cereal production. It is the primary staple in many regions and is cultivated on over 220 million hectares, producing more than 800 million tons in 2024/25 (FAO STAT 2025). By 2050, the global population is projected to exceed 9 billion, with food demand expected to rise by 70% (Senapati *et al.*, 2020). Meeting this challenge requires substantial increases in wheat productivity. While expanding sown areas is limited by land availability, yield improvements must come from exploiting the biological potential of wheat varieties and adopting advanced agronomic practices (Li *et al.*, 2020).

In Bosnia and Herzegovina, wheat occupies approximately 65,650 hectares, with an average yield of 4,500 kg ha^{-1}. However, modern varieties are often bred for high performance under optimal nutrient conditions, with limited adaptation to low-input environments (Matković Stojšin *et al.*, 2022a). Among the major agronomic factors influencing yield, sowing time and soil preparation are the most important, as they strongly affect germination, early development, and final grain yield (Hayman *et al.*, 2024). Delayed sowing shortens phenological phases, reduces tillering, and limits biomass accumulation, ultimately decreasing yield and grain quality (Kanapickas *et al.*, 2024). Determining the optimal sowing date under local climatic conditions is therefore essential for maximizing productivity (Belaqziz *et al.*, 2021).

Sowing density is another key determinant of yield. It regulates competition for light, water, and nutrients, affecting tiller number, spike density, thousand-grain weight, and biological yield (Lachutta and Jankowski, 2024). Low seeding densities may encourage tillering but cannot always compensate for reduced plant numbers, while unfavorable conditions at low densities increase weed pressure and soil evaporation (Lollato *et al.*, 2019). Conversely, high densities can raise spike number per unit area but reduce grain size and increase susceptibility to diseases and pests (Kondić *et al.*, 2017; Dong *et al.*, 2021). Thus, optimal seeding density should be adapted to environmental conditions and integrated with fertilization practices to enhance nutrient uptake (Ren *et al.*, 2019; Marinho *et al.*, 2022).

Nitrogen nutrition plays a decisive role in wheat yield and quality. Although phosphorus and potassium are very important, nitrogen is the primary driver of productivity. Its effectiveness depends not only on the amount applied but also on its timing and distribution during critical growth stages such as tillering, stem elongation, and grain filling (Knežević *et al.*, 2013; Yu *et al.*, 2022). Both nitrogen dose and seeding density interact to influence spike weight and yield components (Zečević *et al.*, 2014; Grahmann *et al.*, 2016). On a global scale, nitrogen application averages ~98 kg ha^{-1} in wheat (West *et al.*, 2014). Some studies indicate that the highest productivity is often achieved with rates of 110-120 kg ha^{-1}, applied in split doses across key developmental stages (Tsvey *et al.*, 2021). However, the yield response varies widely depending on genotype, soil fertility, and weather conditions (Alijošius *et al.* ,2016). Rising temperatures further complicate yield stability by accelerating phenological development and shortening crop duration, leading to reduced grain filling and yield (Agnolucci *et al.*, 2020; Wang *et al.*, 2020; IPCC, 2023).

Increases in wheat productivity over the past decades have largely resulted from breeding and higher nitrogen fertilizer use (Kaur and Ram, 2023). Grain yield, however, is not determined by a single factor but by the combined effects of genetic traits, soil properties, climatic conditions, and management practices (Ghafoor *et al.*, 2024). Future strategies must integrate varietal improvement with optimized agronomic practices to ensure resilience under changing climatic conditions (Knežević *et al.*, 2020). The development of new varieties is a complex, multidisciplinary process, and while genetic improvement has contributed significantly to yield gains-for example, 38% in China (Liu *et al.*, 2021) - optimal outcomes also require suitable cultivation practices and the absence of abiotic stress (Kedir, 2020).

To better understand these interactions, crop productivity modeling provides useful frameworks for integrating genotype, environment, and management factors (Sánchez *et al.*, 2025). By simulating the relationships among these variables, models can guide decisions on sowing date, seeding density, and fertilizer use under specific environmental conditions. Although models remain simplifications of reality, they are valuable tools for identifying optimal production strategies and improving system efficiency (Manivasagam and Rozenstein, 2020).

This study provides a comprehensive multi-factorial evaluation of wheat grain yield by simultaneously analyzing the interactions among genotype, sowing date, sowing density, and nutritional models across two consecutive growing seasons. The results show that yield varies depending on the combinations of these factors (treatments), and that yield varies on the same treatments depending on eco-climatic conditions and genotype-specific responses. By demonstrating the importance of adaptive management strategies and highlighting significant G × E × M interactions [(genotype x environment x management factors (sowing date, and density, fertilizer nutrition)], the study contributes novel insights for climate-smart wheat production and sustainable yield improvement.

The objectives of this research were to: (i) analyze the interaction between the genotypic specificity of wheat varieties and microclimatic conditions, (ii) assess the effects of sowing date, seeding density, and fertilization model on grain yield across two contrasting growing seasons, and (iii) develop a model for integrating agronomic treatments with varietal and environmental factors to optimize wheat production.

Materials and Methods

Experimental site and field treatments

The field experiment was conducted during two growing seasons (2016/17 and 2017/18) at Novo Selo in the Bijeljina region, Semberija plain (44°45′16″ N, 19°12′59″ E; 90 m a.s.l.), located between the Sava and Drina rivers. The site lies between the Sava and Drina rivers. The preceding crop was maize. In autumn, plots were fertilized with 300 kg ha^{-1} of NPK 10:20:30 (Nitrogen, Phosphorus, Potassium), followed by 200 kg ha^{-1} of NPK 15:15:15 before sowing. Standard crop protection practices were applied.

The experiment was arranged as a four-factor randomized complete block design with a split-plot arrangement and three replications. Treatments included three winter wheat varieties ('Nova Bosanka', 'Simonida', and 'Prima'), three sowing dates (the first sowing date was in October 11th; the second sowing was in October 25th; and the third was in November 16th), five sowing densities (350, 450, 550, 650, and 750 seeds m^{-2}), and three fertilization (nutrition) models.

Nitrogen fertilization differed among the nutrition models as follows:

Nutrition model 1 (N control): Nitrogen was applied exclusively as calcium ammonium nitrate (CAN; 27% N) at a total rate of 350 kg ha^{-1}, split into two applications (200 kg ha^{-1} in March and 150 kg ha^{-1} in April), corresponding to a total nitrogen input of 94.5 kg N ha^{-1}.

Nutrition model 2 (CAN + DRIN): This model included the same basal nitrogen fertilization as model 1 (94.5 kg N ha^{-1} from CAN) supplemented with one foliar application of DRIN, applied at a rate of 150 mL per 100 L water during stem elongation in April. DRIN is a liquid foliar fertilizer/biostimulant, containing nitrogen in readily available form together with growth-promoting compounds designed to enhance nitrogen uptake and utilization efficiency during active vegetative growth. DRIN contains 6.3% % nitrogen and organic compounds (19.0% organic carbon, and 39.0% amino acids), contributing a minor but physiologically effective nitrogen input through foliar uptake.

Nutrition model 3 (CAN + repeated DRIN): This model consisted of the basal CAN fertilization used in models 1 and 2 (94.5 kg N ha^{-1}) plus three foliar DRIN applications: one at stem elongation and two additional applications during early May and late May (booting to early heading stages), each applied at 150 mL per 100 L water. These repeated applications were intended to prolong nitrogen availability and support grain formation under intensified nutritional management.

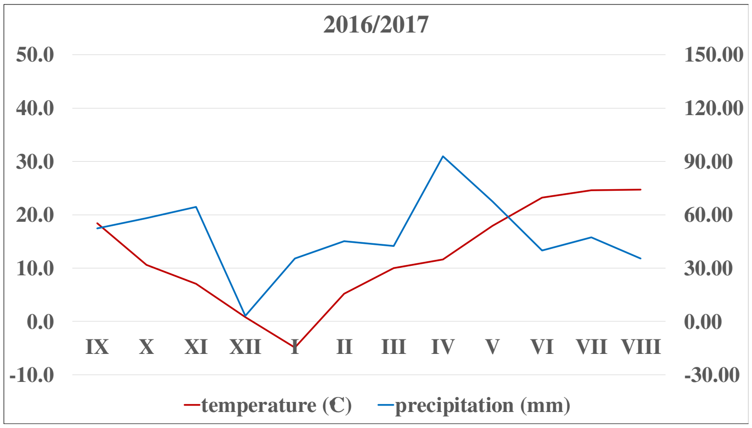
All plots measured 18 m², resulting in a total of 405 plots (7,290 m²). Wheat was harvested manually from a 1 m² area per plot at physiological maturity at the beginning of July and grain yield was standardized to 13% moisture content.

Plant material

Three medium-early winter wheat varieties (cultivars) from different breeding centers were used in this research: 'Nova Bosanka' (Agricultural Institute of the Republic of Srpska, Banja Luka, Bosnia and Herzegovina), 'Simonida' (Institute of Field and Vegetable Crops, Novi Sad, Serbia), and 'Prima' (Bc Institute, Zagreb, Croatia). The varieties differed in morpho-physiological, productive, and qualitative characteristics.

Weather conditions of the research area

Climate diagrams according to Walter (1955) were used to assess growing conditions (Figure 1 and 2).



Figures 1. Climate diagrams according to Walter for the experimental period 2016-2017 (Walter, 1955)

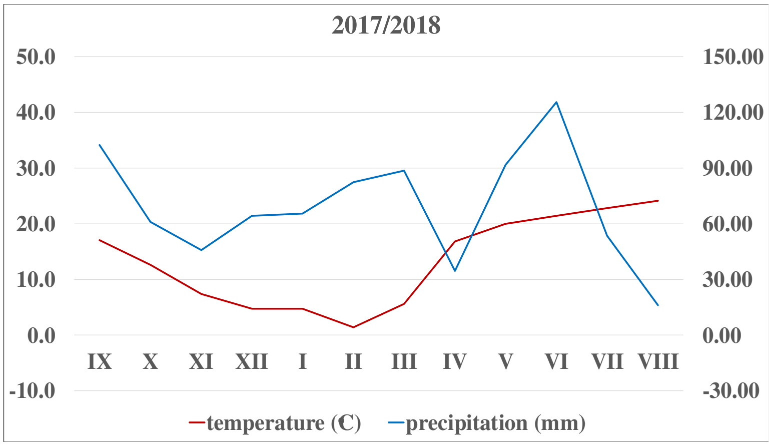


Figure 2. Climate diagrams according to Walter for the experimental period 2017-2018 (Walter, 1955)

In both growing seasons (2016/17 and 2017/18), temperature and precipitation conditions during sowing and crop emergence (October-November) were generally favourable (Figures 1-2). During the winter period, air temperature and total precipitation were lower in 2016/17 than in 2017/18. In addition, temperature and precipitation conditions from February to May were more favourable in 2016/17, supporting uninterrupted crop development. Overall, the 2016/17 growing season can be classified as favourable (good) for wheat production.

In contrast, the 2017/18 growing season can be classified as moderate, due to a less favourable rainfall distribution, including a short dry period in April that may have constrained crop development. Although conditions during the grain-filling period (May) were generally favourable in both seasons, a pronounced rainy period occurred in June 2018 during the wax maturity stage, which may have further reduced grain yield (Figures 1-2).

Soil conditions of the research area

The soil was classified as alluvial carbonate soil (Fluvisol), derived from Drina River deposits. Soil samples were collected in September 2016 and 2017 (pre-tillage) from 0-30 cm depth. Samples were air-dried, ground, and sieved (<2 mm) following ISO 11464:2006 (ISO 2006).

pH was measured in 1 M KCl and distilled water (1:2.5 v/v) using a glass electrode (Radiometer pH M240, ISO 10390:2005) (ISO 2005).

Hydrolytic acidity was determined in calcium acetate by titration (Kappen, 1929).

Humus content was analyzed colorimetrically (sulfochromic oxidation, ISO 14235:1998) (ISO, 1998).

Available P_2O_5 and K_2O were extracted using the ammonium lactate method and quantified by spectrophotometry and atomic absorption spectrophotometry (PYE UNICAM SP-9) (Egnér *et al.* 1960) (Table 1).

Table 1. Basic agrochemical properties of the soil for the examined years at the experimental location Novo Selo (Bijeljina region)

Year of examination	Sampling depth (cm)	pH		Humus	P_2O_5	K_2O
		H_2O	KCL	(%)	mg/100g	mg/100g
2016	0-30	7.4	6.0	2.8	24.6	15.9
2017	0-30	8.2	7.3	3.2	27.2	18.7

Soil pH ranged from neutral to slightly alkaline, favorable for nitrogen availability. Humus content (2.8-3.2%) classified the soil as low-moderate in organic matter. Available phosphorus was high (24.6-27.2 mg 100 g^{-1}), while potassium was moderate (15.9-18.7 mg 100 g^{-1}). Properties remained relatively stable across years.

Statistical analysis

Grain yield data were analyzed separately for each growing season using a four-factor factorial analysis of variance (ANOVA). The fixed factors included sowing density (A), sowing time (B), variety (C), and nutrition model (D). All main effects and their two-, three-, and four-way interactions were tested. Prior to analysis, data were checked for compliance with the assumptions of ANOVA. Residuals were inspected for normality and homogeneity of variances and were found to be acceptable.

The significance of effects was evaluated using F-tests, and results are presented as degrees of freedom, mean squares, F-values, and p-values. Complete ANOVA tables for the 2016/17 and 2017/18 growing seasons are provided in the Results section.

Mean separation was performed using Fisher's LSD (Least significant difference) at the 5% and 1% probability levels ($LSD_{0.05}$ for $p \leq 0.05$ and $LSD_{0.01}$ for $p \leq 0.01$), calculated using the residual mean square error from the corresponding ANOVA (df = 268) for each growing season. Mean separation was performed using Fisher's LSD test only when the F-test was significant.

Results

Wheat grain yield varied widely across treatments and years, reflecting strong interactions among sowing time, sowing density, variety, and nutrition model. Yield levels were substantially higher in 2016/17 than in 2017/18, indicating a strong seasonal effect.

Effects of experimental factors and their interactions

Four-factor ANOVA identified sowing time as the dominant main effect on grain yield in both growing seasons ($p < 0.001$; Tables 2 and 3). In the 2016/17 season, sowing density, variety, and nutrition model did not exhibit significant main effects, and only a subset of interaction terms-primarily those involving sowing time-were statistically significant. In contrast, the 2017/18 season showed a markedly more complex interaction structure, with variety and nutrition model also exerting significant main effects, and all two-, three-, and four-way interactions being statistically significant ($p < 0.001$).

Table 2. Factorial analysis of the variance of the average yield (kg×ha^{-1}) of wheat in the experiment with 5 sowing densities × 3 sowing times × 3 varieties × 3 nutritive models at the locality Novo Selo in 2016/2017

Sources of variation	df	MS	F	p value
Factor A (seeds m^{-2})	4	2,640,481.728	1.519^{ns}	0.197
Factor B (sowing time)	2	522,102,375.6	300.3209**	<0.001
Factor C (variety)	2	2,847,371.852	1.638 ^{ns}	0.196
Factor D (nutritive model)	2	408,348.8889	0.235 ^{ns}	0.791
Interaction A×B	8	25,761,838.7	14.818**	<0.001
Interaction A×C	8	3,287,722.963	1.891 ^{ns}	0.062
Interaction A×D	8	3,276,548.889	1.885 ^{ns}	0.062
Interaction B×C	4	59,132,118.89	34.013**	<0.001
Interaction B×D	4	48,983,238.89	28.176**	<0.001
Interaction C×D	4	2,832,965.556	1.629 ^{ns}	0.167
Interaction A×B×C	16	18,901,967.5	10.873**	<0.001
Interaction A×B×D	16	11,251,867.5	6.472**	<0.001
Interaction A×C×D	16	4,540,098.056	2.611**	<0.001
Interaction B×C×D	8	23,173,828.89	13.330**	<0.001
Interaction A×B×C×D	32	13,533,958.06	7.785**	<0.001
Error	268	1,738,485.323	-	
In total	404	2,225,249.318		

df: degrees of freedom; MS: mean square; F: F-value; p: probability level

Table 3. Factorial analysis of the variance of the average yield ($kg\times ha^{-1}$) of wheat in the experiment with 5 sowing densities × 3 sowing times × 3 varieties × 3 nutritive models at the locality Novo Selo in 2017/2018

Sources of variation	df	MS	F	p values
Factor A (seeds m^{-2})	4	1,342,003.333	1.7655^{ns}	0.136
Factor B (sowing time)	2	238,779,370.6	314.13^{**}	<0.001
Factor C (variety)	2	9,248,327.654	12.167^{**}	<0.001
Factor D (nutritive model)	2	25,205,784.69	33.159^{**}	<0.001
Interaction A×B	8	19,378,007.84	25.493^{**}	<0.001
Interaction A×C	8	4,087,154.136	5.377^{**}	<0.001
Interaction A×D	8	7,941,966.173	10.448^{**}	<0.001
Interaction B×C	4	40,794,845.68	53.668^{**}	<0.001
Interaction B×D	4	66,662,334.57	87.699^{**}	<0.001
Interaction C×D	4	21,467,779.57	28.242^{**}	<0.001
Interaction A×B×C	16	12,322,046.98	16.210^{**}	<0.001
Interaction A×B×D	16	11,211,016.42	14.749^{**}	<0.001
Interaction A×C×D	16	6,506,162.253	8.559^{**}	<0.001
Interaction B×C×D	8	40,364,225.9	53.102^{**}	<0.001
Interaction A×B×C×D	32	11,877,753.35	15.626^{**}	<0.001
Error	268	760,126.3682	-	
In total	404	1,445,054.391		

df: degrees of freedom; MS: mean square; F: F-value; p: probability level

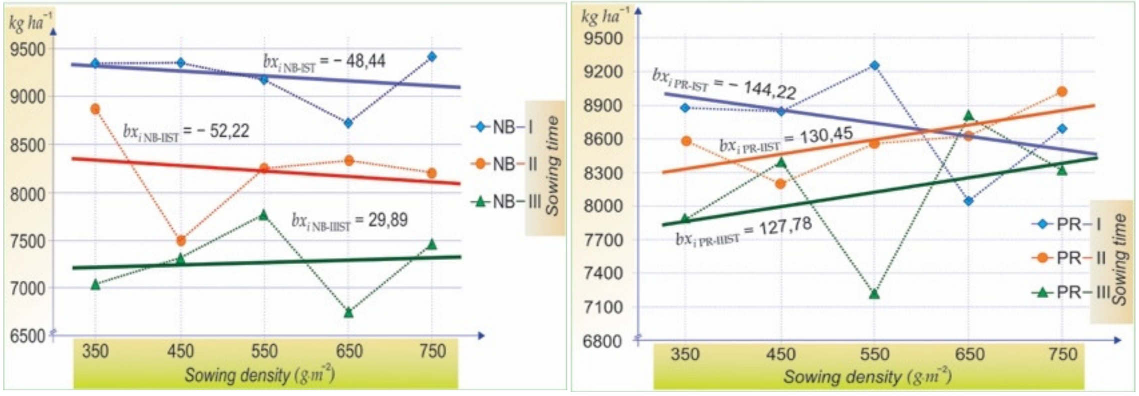
Comparison of the two seasons indicates that sowing time consistently exerted the strongest influence on grain yield. However, interaction complexity increased substantially in 2017/18, when variety and nutrition model became significant main effects, and all interaction terms were significant, in contrast to the more limited interaction structure observed in 2016/17. Overall, these results demonstrate that while sowing time consistently governed yield variation, the magnitude and structure of interactions among agronomic and genetic factors were strongly year dependent.

Interaction among variety, sowing date, and sowing density

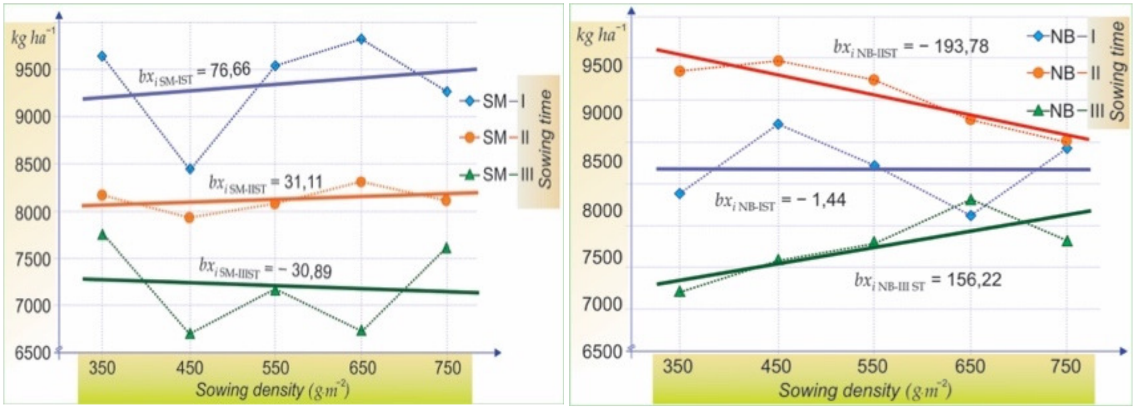
Grain yield of each wheat variety was strongly influenced by the interaction between sowing date and sowing density in both growing seasons (Table 4, Figure 3). Across varieties, the highest yields were generally obtained at the earliest sowing date, declined at the second sowing date, and reached their lowest levels at the third sowing date, highlighting the overriding importance of sowing time.

Table 4. Average wheat yields (kg ha^{-1}) for variety × sowing time × sowing density interaction [regardless of the nutritive model (F_{exp}^{**})] in two vegetation seasons

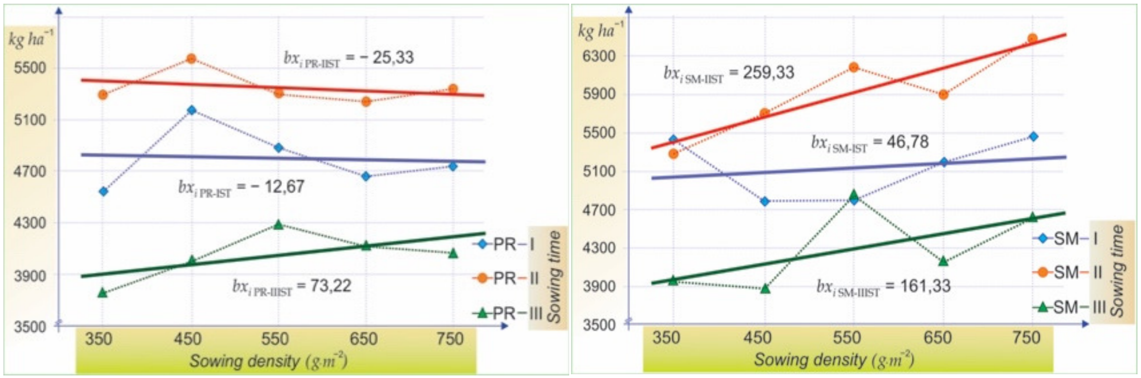
Vegetation season		**2016/2017**						**2017/2018**					
Variety (C)	**Sowing time (B)**	**Sowing density (seeds m^{-2}) (A)**						**Sowing density (seeds m^{-2}) (A)**					
		350	**450**	**550**	**650**	**750**	**Average**	**350**	**450**	**550**	**650**	**750**	**Average**
'Nova Bosanka'	I	9344	9344	9191	8718	9415	9202	5010	5672	5281	4800	5439	5240
	II	8860	7484	8238	8296	8193	8214	6177	6275	6091	5711	5490	5949
	III	7033	7307	7764	6739	7467	7262	4064	4364	4524	4948	4553	4491
	Average	8412	8045	8398	7917	8358	8226	5084	5437	5299	5153	5161	5227
'Prima'	I	8868	8847	9256	8046	8698	8743	4547	5170	4883	4663	4737	4800
	II	8577	8196	8553	8627	9014	8594	5296	5572	5306	5234	5338	5349
	III	7884	8396	7220	8797	8322	8124	3756	4006	4286	4120	4066	4047
	Average	8443	8479	8343	8491	8678	8487	4533	4916	4825	4672	4714	4732
'Simonida'	I	10067	8707	9953	10282	9662	9734	5423	4792	4800	5189	5458	5133
	II	8380	8127	8293	8551	8323	8335	5287	5706	6183	5899	6487	5924
	III	7924	6729	7242	6749	7760	7281	3954	3876	4846	4153	4622	4290
	Average	8790	7854	8496	8527	8582	8449	4888	4791	5277	5080	5523	5112
Total average		8548	8126	8412	8312	8539	8387	4835	5048	5134	4969	5132	5023
A x B x C		$Lsd_{0.05}$= 1218.24; $Lsd_{0.01}$= 1601.11						$Lsd_{0.05}$= 805.54; $Lsd_{0.01}$= 1058.70					
A x B		$Lsd_{0.05}$= 703.35; $Lsd_{0.01}$= 924.40						$Lsd_{0.05}$= 465.08; $Lsd_{0.01}$= 611.25					
A x C		$Lsd_{0.05}$= 703.35; $Lsd_{0.01}$= 924.39						$Lsd_{0.05}$= 465.08; $Lsd_{0.01}$= 611.25					
B x C		$Lsd_{0.05}$= 544.8; $Lsd_{0.01}$= 716.02						$Lsd_{0.05}$= 360.25; $Lsd_{0.01}$= 473.47					



(A) Cv. 'Nova Bosanka' (B) Cv. 'Prima'



(C) Cv. 'Simonida' (D) Cv. 'Nova Bosanka'



(E) Cv. ‘Prima’ (F) Cv. ‘Simonida’

Figure 3. Graphical analysis of the interaction among cultivar, sowing time, and sowing density for the variety's grain yield (kg ha^{-1}) in 2016/2017 (A, B, C) and 2017/2018 (D, E, F)

In the 2016/17 season, ‘Simonida’ generally produced the highest yields under early sowing across most densities, particularly at medium to high sowing rates, whereas ‘Prima’ consistently yielded less across density levels. ‘Nova Bosanka’ showed intermediate performance, with optimal yields at moderate densities and a tendency toward reduced performance at both lower and higher sowing rates. Under the second sowing date, yields decreased for all varieties, with ‘Prima’ displaying relatively better performance at several densities, while ‘Nova Bosanka’ showed pronounced reductions at intermediate densities. At the third sowing date, yields were lowest overall, and varietal differences became more pronounced, with ‘Prima’ maintaining comparatively higher yields at high sowing density, while ‘Simonida’ and ‘Nova Bosanka’ showed reduced performance.

In the 2017/18 season, overall yield levels were substantially lower, but density-dependent varietal responses became more distinct. Under early sowing, ‘Simonida’ generally achieved the highest yields across densities, while ‘Prima’ tended to produce the lowest yields at both low and high sowing rates. ‘Nova Bosanka’ performed best at intermediate densities. At the second sowing date, ‘Nova Bosanka’ showed superior performance at low to moderate densities, whereas ‘Simonida’ responded more positively to increasing density, achieving its highest yields at higher sowing rates. At the third sowing date, ‘Nova Bosanka’ consistently outperformed the other varieties across most densities, while ‘Prima’ exhibited the lowest and most stable yields.

Analysis of density response patterns revealed clear genotype-specific trends. ‘Nova Bosanka’ generally exhibited declining yields with increasing density under early and intermediate sowing dates, whereas yield responses under late sowing were less consistent. ‘Prima’ displayed non-linear density responses in both seasons, with occasional yield compensation at higher densities under late sowing in 2016/17, but consistently low yields under delayed sowing in 2017/18. ‘Simonida’ showed the greatest responsiveness to sowing density, particularly in 2017/18, when yield increased steadily with increasing density under the second sowing date (Figure 3).

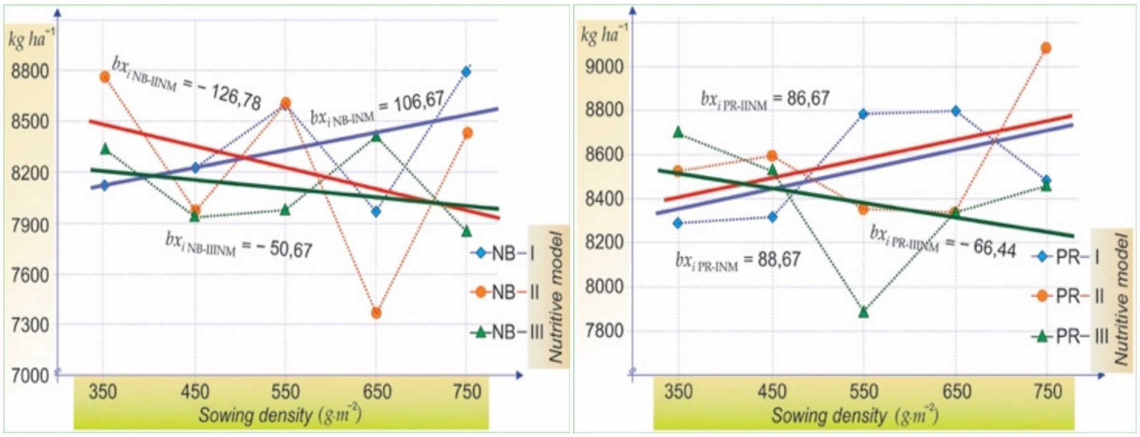
Overall, these results demonstrate that yield responses to sowing density were highly dependent on sowing date and variety, with early sowing enhancing yield potential across all genotypes, while varietal differences in density tolerance became more pronounced under delayed sowing and less favorable seasonal conditions.

Interaction among variety, nutrition model, and sowing density

Grain yield was significantly influenced by the interaction among variety, nutrition model, and sowing density in both growing seasons (Table 5, Figure 4). Overall, yield responses differed markedly among varieties depending on nutrient management and plant density, indicating strong genotype-specific nutrient use patterns.

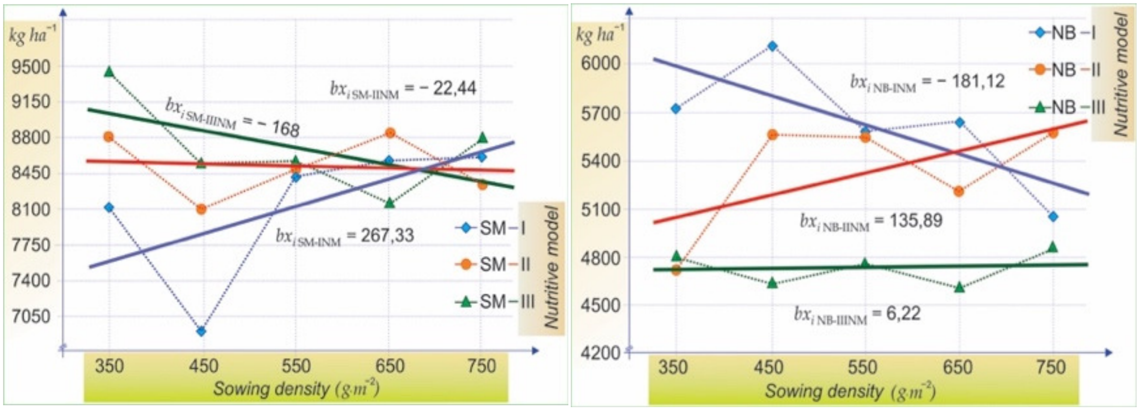
Table 5. Average wheat yields (kg ha^{-1}) for variety × nutritive model × sowing density interaction [regardless of sowing time (F_{exp}^{**})] in two vegetation seasons

Vegetation season		2016/2017						2017/2018					
Variety (C)	Nutritive model (D)	Sowing density (seeds m^{-2}) (A)						Sowing density (seeds m^{-2}) (A)					
		350	450	550	650	750	Average	350	450	550	650	750	Average
'Nova Bosanka'	I	8127	8229	8598	7962	8793	8342	5723	6108	5582	5643	5050	5621
	II	8767	7971	8613	7370	8433	8231	4719	5561	5551	5204	5577	5322
	III	8344	7936	7982	8420	7849	8106	4808	4643	4763	4612	4856	4736
	Average	8412	8045	8398	7917	8358	8226	5083	5437	5299	5153	5160	5227
'Prima'	I	8284	8313	8784	8796	8487	8533	4718	5427	5114	5145	4894	5060
	II	8524	8591	8356	8340	9083	8579	4549	4797	4762	4960	4640	4742
	III	8698	8533	7889	8336	8464	8384	4258	4523	4599	3912	4606	4380
	Average	8502	8479	8342	8490	8678	8499	4508	4916	4825	4673	4713	4727
'Simonida'	I	8113	6902	8422	8580	8611	8126	5627	5634	5752	5687	6028	5746
	II	8816	8109	8489	8844	8336	8519	4553	4453	5337	4752	5202	4859
	III	9442	8551	8578	8158	8799	8706	4484	4286	4741	4802	5336	4730
	Average	8790	7854	8496	8527	8522	8450	4888	4791	5277	5080	5523	5112
Total average		8568	8126	8412	8311	8539	8391	4827	5048	5133	4969	5132	5022
A x C x D		$Lsd_{0.05}$=1218.24;$Lsd_{0.01}$= 1601.11						$Lsd_{0.05}$= 805.54; $Lsd_{0.01}$= 1058.70					
A x C		$Lsd_{0.05}$= 703.35; $Lsd_{0.01}$= 924.40						$Lsd_{0.05}$= 465.08; $Lsd_{0.01}$= 611.25					
A x D		$Lsd_{0.05}$= 703.35; $Lsd_{0.01}$= 924.40						$Lsd_{0.05}$= 465.08; $Lsd_{0.01}$= 611.25					
C x D		$Lsd_{0.05}$= 544.8; $Lsd_{0.01}$= 716.02						$Lsd_{0.05}$= 360.25; $Lsd_{0.01}$= 473.47					



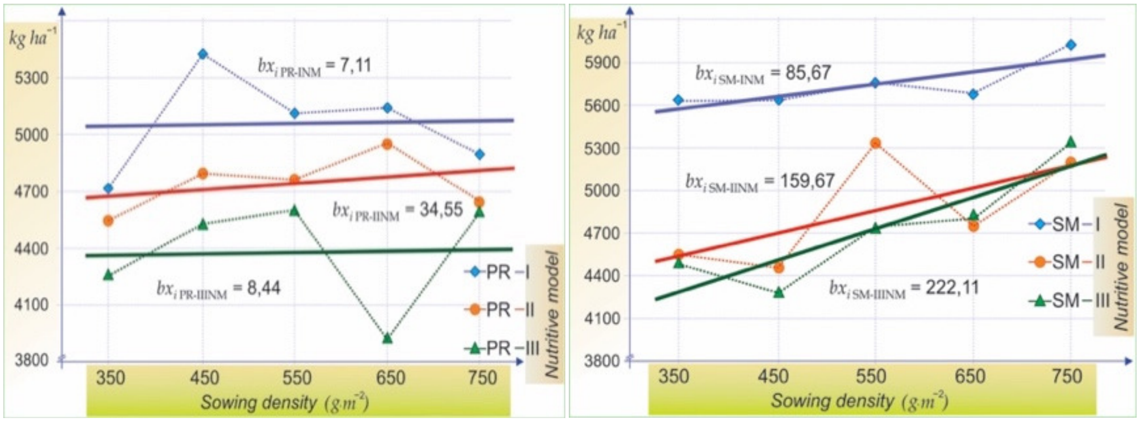
(A) Cv. 'Nova Bosanka'

(B) Cv. 'Prima'



(C) Cv. 'Simonida'

(D) Cv. 'Nova Bosanka'



(E) Cv. ‘Prima’ (F) Cv. ‘Simonida’

Figure 4. Graphical analysis of the interaction between cultivar, nutritive model, and sowing density for the variety's grain yield (kg ha^{-1}) in 2016/2017 (A, B, C) and 2017/2018 (D, E, F)

In the 2016/17 season, ‘Nova Bosanka’ and ‘Prima’ generally achieved their highest yields under the first and second nutrition models, whereas yield performance declined under the third model, particularly at higher sowing densities. In contrast, ‘Simonida’ consistently performed best under the third nutrition model across a wide range of densities, frequently outperforming the first and second models. These contrasting responses highlight substantial varietal differences in nutrient-use efficiency and density tolerance.

Across varieties, the first nutrition model tended to produce the highest yields, followed by the second, while the third model was associated with reduced yield levels for ‘Nova Bosanka’ and ‘Prima’. ‘Simonida’, however, showed a distinct advantage under the third model, particularly at medium to high sowing densities, where its yield potential exceeded that observed under the other nutrition regimes.

Density-response patterns further differed among varieties. In 2016/17, yields of ‘Nova Bosanka’ and ‘Prima’ generally increased with sowing density under the first and second nutrition models but declined under the third, whereas ‘Simonida’ exhibited a strong positive density response under the first model and a pronounced yield reduction under the third. In the 2017/18 season, ‘Nova Bosanka’ again achieved its highest yields under the first nutrition model but showed decreasing performance with increasing density. By contrast, ‘Simonida’ displayed consistent yield increases with higher sowing density under all three nutrition models, although absolute yield levels remained highest under the first model (Figure 4).

Taken together, these results demonstrate that the effect of the nutrition model on grain yield was strongly variety- and density-dependent, with ‘Simonida’ showing greater adaptability to reduced or alternative nutrient regimes, while ‘Nova Bosanka’ and ‘Prima’ responded more favorably to conventional nutrition under moderate plant densities.

Interaction among sowing date, nutrition model, and sowing density

Grain yield was significantly affected by the combined effects of sowing date, nutrition model, and sowing density in both growing seasons (Table 6, Figure 5). Across treatments, sowing date exerted the strongest influence on yield, consistently overriding the effects of the nutrition model and plant density.

Table 6. Average wheat yields (kg ha^{-1}) for sowing time × nutritive model × sowing density interaction [regardless of the variety (F_{exp}^{**})] in two vegetation seasons

Vegetation season		2016/2017						2017/2018					
Sowing time (B)	**Nutritive model (D)**	**Sowing density (seeds m^{-2}) (A)**						**Sowing density (seeds m^{-2}) (A)**					
		350	**450**	**550**	**650**	**750**	**Average**	**350**	**450**	**550**	**650**	**750**	**Average**
I – sowing time	I	9296	8200	9404	9193	9242	9067	5056	5722	5048	5481	5168	5295
	II	9307	9260	9695	8518	9500	9256	4844	5222	4901	5059	5111	5027
	III	9678	9437	9300	9336	9033	9357	5080	4690	5014	4112	5355	4850
	Average	9427	8966	9467	9016	9258	9227	4993	5211	4987	4884	5211	5057
II – sowing time	I	7788	7976	8242	8393	8580	8196	5732	5963	5897	5753	5888	5847
	II	8916	8131	8456	8789	8372	8533	5293	5431	5852	5184	5374	5427
	III	9288	7700	8387	8291	8579	8449	5659	6159	5830	5907	6052	5921
	Average	8664	7936	8362	8491	8510	8393	5561	5851	5860	5615	5771	5732
III sowing time	I	7440	7269	8157	7751	8069	7737	5280	5484	5502	5241	4918	5285
	II	7884	7280	7307	7248	7980	7540	3683	4158	4897	4673	4933	4469
	III	7518	7882	6762	7287	7500	7390	2812	2603	3259	3308	3390	3074
	Average	7614	7477	7409	7429	7849	7556	3925	4082	4553	4407	4414	4276
Total average		8568	8126	8412	8312	8539	8391	4826	5048	5134	4969	5132	5022
AxBxD		$Lsd_{0.05}$= 1218.24; $Lsd_{0.01}$= 1601.11						$Lsd_{0.05}$= 805.54; $Lsd_{0.01}$= 1200.50					
A x B		$Lsd_{0.05}$= 703.35; $Lsd_{0.01}$= 924.40						$Lsd_{0.05}$= 465.08; $Lsd_{0.01}$= 611.25					
A x D		$Lsd_{0.05}$= 703.35; $Lsd_{0.01}$= 924.40						$Lsd_{0.05}$= 465.08; $Lsd_{0.01}$= 611.25					
B x D		$Lsd_{0.05}$= 544.8; $Lsd_{0.01}$= 716.02						$Lsd_{0.05}$= 360.25; $Lsd_{0.01}$= 473.47					

In the 2016/17 season, the first sowing date produced the highest yields across all nutrition models and sowing densities, whereas yields declined markedly at the second sowing date and reached their lowest values at the third. Under early sowing, the second and third nutrition models generally enhanced yield performance at intermediate sowing densities, while under delayed sowing their ability to compensate for yield loss was limited. At the second sowing date, yield differences among nutrition models were reduced, and only specific model–density combinations showed significant advantages. At the third sowing date, yields were uniformly low, with the first nutrition model consistently outperforming the second and third across most densities.

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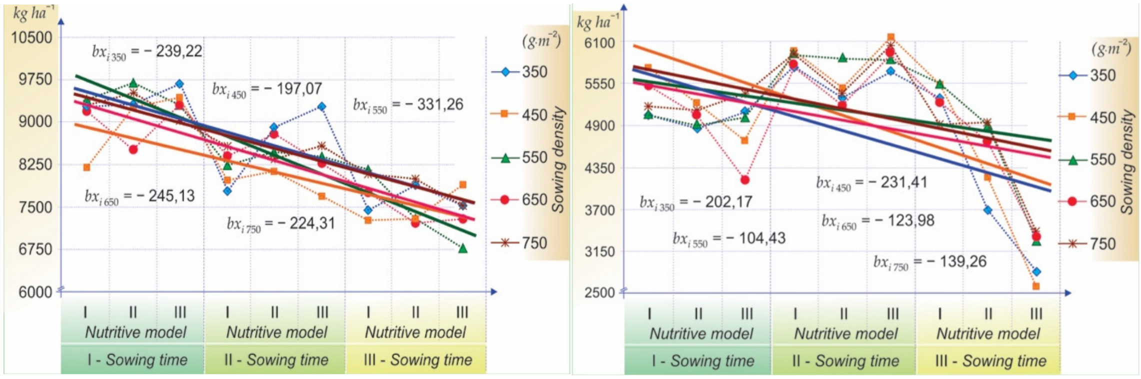
Across both seasons, nutrition model effects were strongly density- and sowing-date dependent. The first and third nutrition models tended to perform best under early sowing conditions, particularly at intermediate plant densities, while the second nutrition model often enhanced yield under mid- to late-sowing scenarios. These patterns underscore the importance of synchronizing sowing time, plant density, and nutrient management to optimize grain yield under contrasting seasonal conditions (Figure 5).



2016/2017 2017/2018

Figure 5. Graphical analysis of the interaction among sowing time, nutritive model, and sowing density for grain yield (kg ha^{-1}) in two vegetation seasons 2016/2017 and 2017/2018

Interaction among variety, sowing time, and nutrition model

Grain yield of the three wheat varieties showed strong dependence on sowing time and nutrition model in both growing seasons (Table 7). In the 2016/17 season, early sowing consistently resulted in the highest yields across all varieties and nutrition models, whereas delayed sowing led to substantial yield reductions. 'Simonida' generally achieved the highest yields under early sowing, particularly under the first and second nutrition models, while 'Nova Bosanka' performed best under the third model. Under later sowing dates, 'Prima' tended to outperform the other varieties, indicating greater stability under less favourable conditions.

Table 7. Average wheat yields (kg ha^{-1}) for variety × sowing time × nutritive model interaction [regardless of sowing density (F_{exp}^{**})] in two vegetation seasons

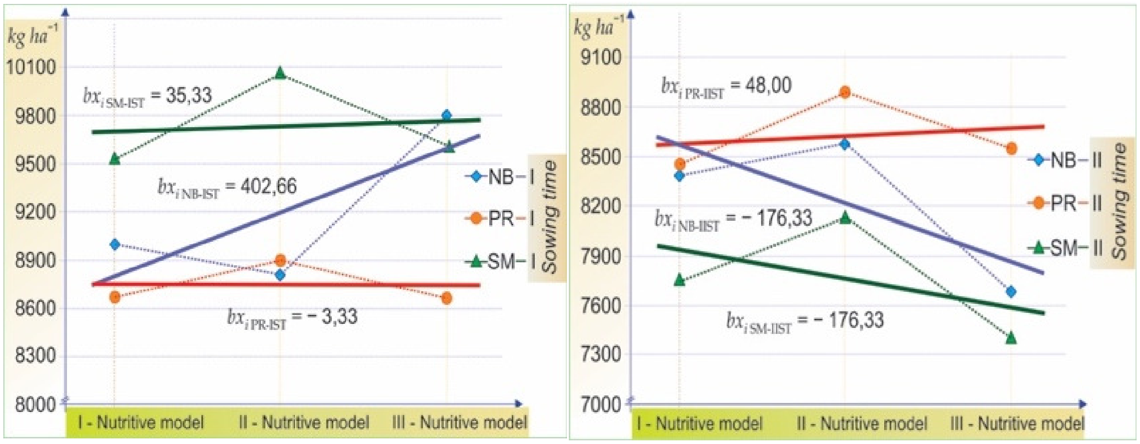
Vegetation season		2016/2017				2017/2018			
Variety (C)	Nutritive model (D)	Sowing time (B)				Sowing time (B)			
		I	II	III	Average	I	II	III	Average
'Nova Bosanka'	I	8996	8388	7641	8342	5270	6019	5574	5621
	II	8811	8576	7306	8231	5664	5616	4687	5323
	III	9801	7679	6838	8106	4786	6211	3213	4737
	Average	9203	8214	7262	8226	5241	5949	4491	5227
'Prima'	I	8669	8450	8479	8533	4846	5496	4837	5060
	II	8897	8889	7950	8579	4970	5022	4233	4742
	III	8663	8546	7943	8384	4584	5484	3071	4380
	Average	8743	8629	8124	8499	4800	5334	4047	4727
'Simonida'	I	9536.	7749	7092	8126	5769	6025	5444	5746
	II	10 060	8133	7362	7748	4448	5643	4487	4859
	III	9607	7397	7388	8131	5181	4881	2940	4334
	Average	9571	7759	7281	8001	5132	5516	4290	4980
Total average		9122	8201	7556	8293	5058	5599	4276	4978
B x C x D		$Lsd_{0.05}$= 943.64; $Lsd_{0.01}$= 1240.21				$Lsd_{0,05}$= 623,97; $Lsd_{0,01}$= 820,08			
B x C		$Lsd_{0.05}$= 544.8; $Lsd_{0.01}$= 716.02				$Lsd_{0.05}$= 360.25; $Lsd_{0.01}$= 473.47			
B x D		$Lsd_{0.05}$= 544.8; $Lsd_{0.01}$= 716.02				$Lsd_{0.05}$= 360.25; $Lsd_{0.01}$= 473.47			
C x D		$Lsd_{0.05}$= 544.8; $Lsd_{0.01}$= 716.02				$Lsd_{0.05}$= 360.25; $Lsd_{0.01}$= 473.47			

Comparisons among sowing times confirmed that yields were significantly higher under early than late sowing for 'Nova Bosanka' and 'Simonida' across most nutrition models, whereas 'Prima' exhibited a more stable response, with significant differences observed only under specific nutritional conditions (Table 7).

In the 2017/18 season, overall yield levels were lower, and the response pattern shifted, with the second sowing time producing the highest yields across most variety × nutrition combinations. 'Nova Bosanka' showed the best performance under these conditions, while 'Simonida' exhibited the strongest yield reductions under late sowing, particularly under the third nutrition model. 'Prima' again displayed intermediate but relatively stable yields across treatments.

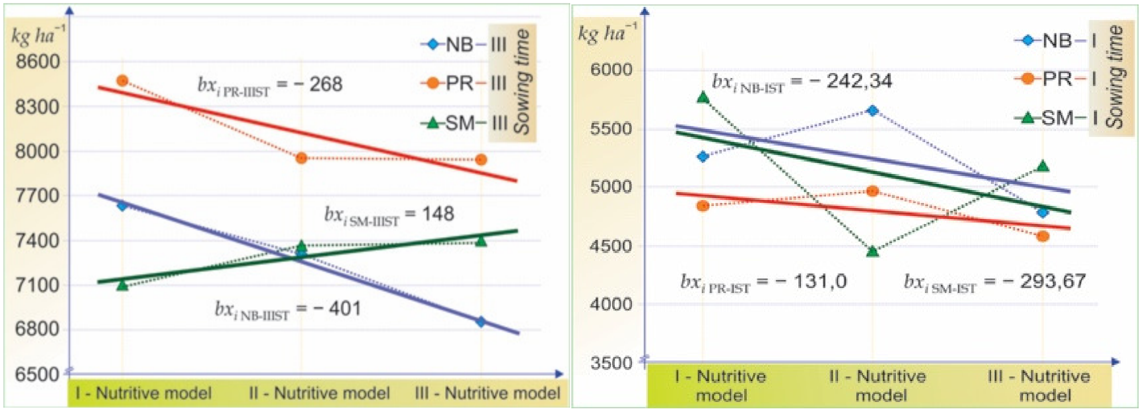
The significant effect of sowing time was further confirmed in 2017/18, as yields at the second sowing time were consistently higher than those at the third sowing time for all varieties, although the magnitude of this effect varied depending on the nutrition model (Table 7).

Graphical analyses (Figures 6 and 7) highlighted clear genotype-specific response patterns. In 2016/17, 'Nova Bosanka' showed the steepest yield decline with delayed sowing, especially under the third nutrition model, whereas 'Prima' maintained more stable yields across sowing times. 'Simonida' displayed a mixed response, with high yield potential under early sowing but increased sensitivity to unfavorable combinations. In 2017/18, the second sowing time was optimal for all varieties, but 'Simonida' remained the most sensitive to adverse sowing and nutritional conditions.



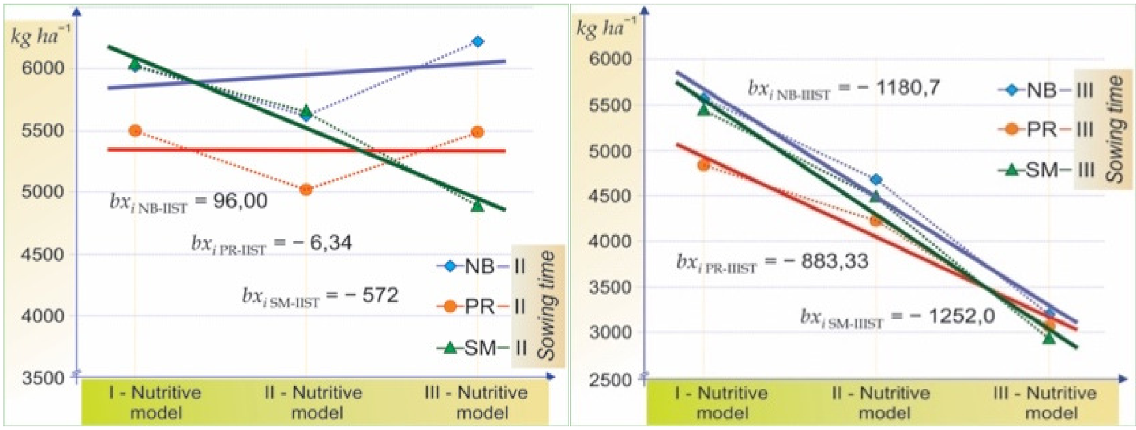
(A) Cv. 'Nova Bosanka'

(B) Cv. 'Prima'



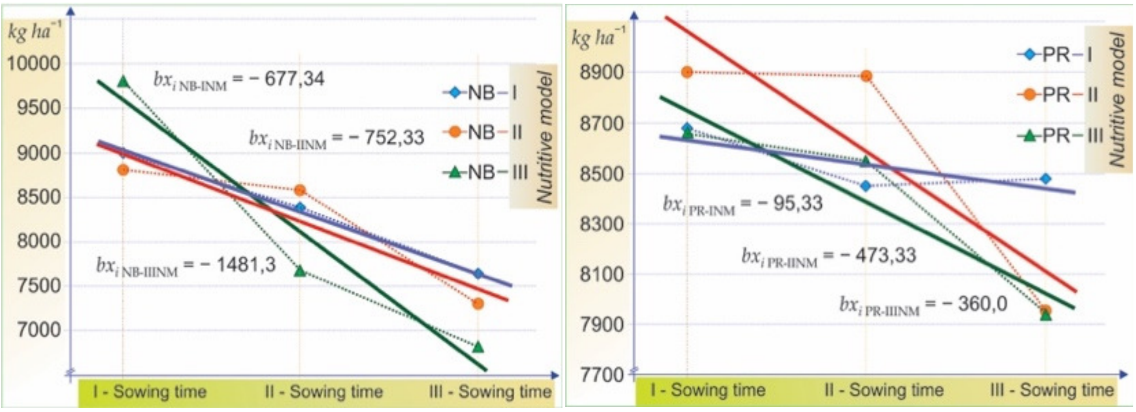
(G) Cv. 'Simonida'

(H) Cv. 'Nova Bosanka'

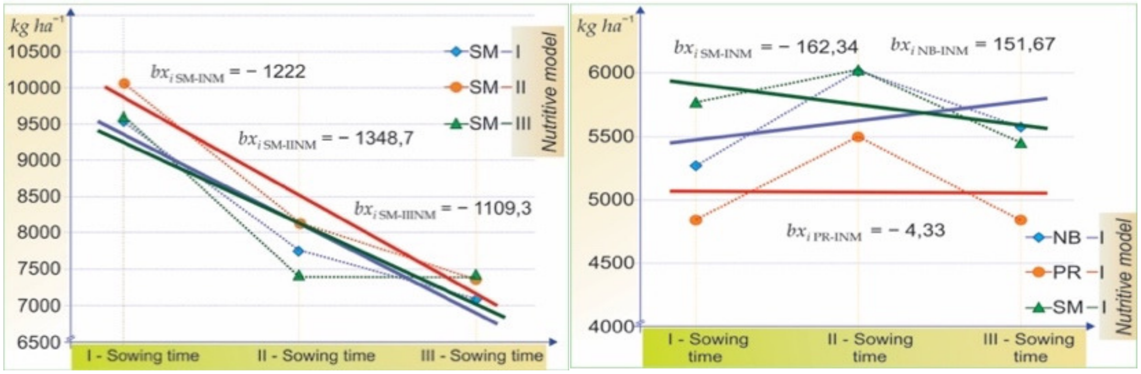


(I) Cv. 'Prima' (J) Cv. 'Simonida'

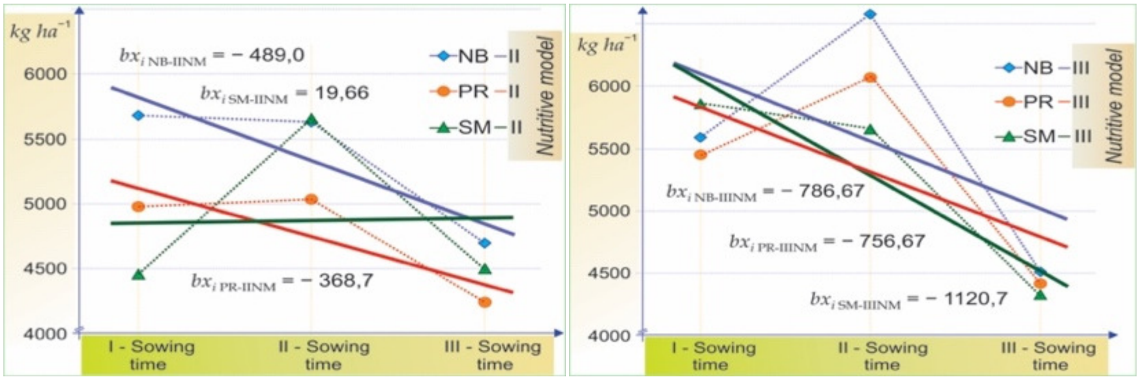
Figure 6. Graphical analysis of the interaction between variety, sowing time, and nutritive model for the variety's grain yield (kg ha^{-1}) in vegetation season in 2016/17 (A, B, C) and 2017/18 (D, E, F)



(A) Cv. 'Nova Bosanka' (B) Cv. 'Prima'



(C) Cv. 'Simonida' (D) Cv. 'Nova Bosanka'



(E) Cv. 'Prima' (F) Cv. 'Simonida'

Figure 7. Graphical analysis of the interaction between cultivar, sowing time, and nutritive model for the variety's grain yield (kg ha^{-1}) in the vegetation season in 2016/17 (A, B, C) and 2017/18 (D, E, F)

In summary, grain yield varied significantly among the three varieties and was strongly influenced by sowing time and nutritional model across both growing seasons. In the 2016/2017 season, grain yield peaked at the first sowing time for all varieties. 'Simonida' achieved the highest yield (10,060 kg ha^{-1}) under the second nutritional model, whereas 'Nova Bosanka' recorded the lowest yield (6,838 kg ha^{-1}) under the third model. At the first sowing time, 'Simonida' produced the highest yields under both the first and second nutritional models, while 'Nova Bosanka' performed best under the third model. At later sowing times, 'Prima' generally exhibited higher yields, particularly at the second sowing time. Comparisons indicated significantly higher yields under early sowing for both 'Nova Bosanka' and 'Simonida'.

In the 2017/2018 season, overall yields were reduced, with the second sowing time resulting in higher yields compared with the first and third sowing times. 'Nova Bosanka' achieved the highest yield at the second sowing time (6,211 kg ha^{-1}), whereas 'Simonida' recorded the lowest yield at the third sowing time (2,940 kg ha^{-1}). Sowing time had a significant effect on grain yield in both seasons, confirming higher yields at the second sowing time compared with the third.

Discussion

Studying the interactions among genotype, sowing date, seeding density, and nutritional models is essential for optimizing wheat yield under increasingly variable climatic conditions (Ortiz-Bobea *et al*., 2019). Our two-year field experiment clearly demonstrated that the contribution of each factor to yield was season-dependent, with significant differences between the 2016/2017 and 2017/2018 growing seasons.

Environmental factors significantly influence the phenological development of wheat. High temperatures accelerate, whereas low temperatures delay crop maturity. Photoperiod interacts with temperature by requiring a minimum day length for flowering and ear formation. Soil moisture affects water availability, and the duration of phenophases, and stress conditions such as drought or excessive water supply can alter phenophase length, thereby increasing phenotypic variability (Ikram *et al*., 2025).

Genotype played a significant role in shaping yield outcomes. In our study, 'Prima' achieved higher yields under favorable conditions in 2016/2017, likely due to its greater capacity to exploit extended vegetative growth and grain-filling periods, whereas 'Nova Bosanka' showed relatively better adaptation under the less favorable conditions of 2017/2018, suggesting a more conservative growth strategy and improved tolerance to shortened phenophases and climatic stress during key developmental stages. These results underscore the importance of variety-specific responses to sowing practices and environmental conditions. This observation is consistent with previous studies demonstrating that genotypic differences in tillering capacity, canopy structure, and assimilate partitioning can strongly influence yield performance under different management regimes (Rivera-Amado *et al*., 2019). From a breeding perspective, these findings highlight the need to select and develop varieties with high phenotypic plasticity - capable of responding flexibly to management inputs while maintaining yield stability under stress conditions (Liu *et al*., 2021; Matković Stojšin *et al*., 2022b).

Sowing date is a critical agronomic factor governing wheat phenological development and its interaction with seasonal weather conditions. Variations in sowing time modify the thermal and photoperiodic environment experienced during key developmental stages, thereby influencing the duration of tillering, heading, and grain filling. Earlier sowing generally extends the vegetative phase and prolongs grain filling, enhancing assimilate accumulation and supporting higher grain number and grain weight. In contrast, delayed sowing shortens phenophases due to increased temperatures and reduced day length, which can limit photosynthate production and translocation, ultimately reducing yield potential (Kaur *et al*., 2025). In the present study, sowing date exerted the strongest influence on grain yield, although the optimal timing varied between growing seasons in response to prevailing weather conditions. During the more favourable 2016/2017 season, early sowing promoted extended vegetative growth and enhanced yield formation. In contrast, the 2017/2018 season was characterized by less favourable climatic conditions, which altered crop responses to sowing time. In 2017/2018, reduced rainfall during the tillering phase likely limited tiller survival, particularly in 'Simonida', thereby reducing spike density and overall yield. These findings indicate that the advantages of early sowing can be diminished when moisture stress coincides with early developmental stages, emphasizing that sowing-date effects are strongly season dependent and that flexible adjustment of sowing time and plant density is essential to align sensitive phenophases with favourable temperature and moisture conditions. Similar responses have been reported in Central and Eastern Europe, where delayed sowing generally reduces yield potential but may occasionally mitigate early-season stress under unfavourable climatic conditions (Lopes, 2022). Overall, optimizing sowing time in combination with plant density and mineral fertilization according to specific agroecological conditions is increasingly important for maintaining yield stability under climate variability (Noor *et al*., 2023; Sun *et al*., 2023a).

Although sowing density as a main factor did not consistently exert a significant effect on grain yield, its importance became evident through interactions with sowing date and genotype. Increasing plant density generally improved soil cover, resource capture, and weed suppression; however, excessively high densities increased intra-specific competition and reduced individual plant productivity (Fazily, 2021). Our results indicate that intermediate to high sowing densities (≈550-650 seeds m^{-2}) are more suitable under stressful conditions, whereas intermediate densities are sufficient under favorable environments. These findings are consistent with those of Kondić *et al*. (2016, 2017), who reported that lower densities enhance tillering per plant, while higher densities increase grain number and total yield per unit area. Overall, appropriate adjustment of sowing density remains an important agronomic practice for balancing resource-use efficiency with yield potential, particularly under variable environmental conditions (Bożek *et al*., 2022; Chen *et al*., 2022).

Nutritional models also had varying effects across seasons. In 2016/2017, the second model resulted in the highest yields, while in 2017/2018, the first model was more effective. This variability indicates that nutrient availability interacts closely with climatic conditions. Nitrogen in particular is a key driver of wheat yield formation, affecting both tiller survival and grain filling (Sun *et al*., 2023b). However, global estimates of nitrogen use efficiency remain low, often below 35% (Omara *et al*., 2019). Our study supports the notion that optimizing nitrogen application timing and form is as critical as the applied dose, especially under conditions of increasing climatic variability. Sustainable nitrogen management not only enhances yield but also mitigates risks of leaching, greenhouse gas emissions, and soil degradation (Aula *et al*., 2021).

The observed seasonal differences can be largely attributed to eco-climatic conditions. Temperature and precipitation strongly influence the length of phenological phases, tiller survival, and assimilate accumulation (Wang *et al*. 2017). In 2016/2017, favorable conditions promoted greater assimilate translocation to reproductive organs, while in 2017/2018, environmental stressors, particularly variable rainfall distribution and higher temperatures, shortened grain filling and reduced yield. These findings are consistent with global observations that wheat yield stagnation in recent decades is partly driven by climate change and its impact on reproductive physiology (Lopes, 2022).

At the physiological level, yield components such as spike number, grain number per spike, and thousand-grain weight are influenced by both genetic potential and environmental stressors (Knežević *et al.*, 2020; Urošević *et al.*, 2024). Our data confirm that high yields result not from one factor alone, but from the integration of multiple traits and management decisions. Breeding semi-dwarf varieties during the Green Revolution improved responsiveness to nitrogen and sowing density (Knežević *et al.*, 2020), and our findings suggest that similar integrated approaches are required to overcome current yield plateaus.

Grain yield in wheat is determined by the interaction between genotype (G), environment (E), and their interaction (G × E). These interactions reflect genotype performance across diverse environmental conditions and contribute to the identification of the most suitable genotypes for cultivation. In addition to genetic and environmental influences, crop management practices such as sowing time, plant density, and fertilization play an increasingly important role in optimizing wheat yield and ensuring stable production under changing climatic conditions (Ghafoor *et al.*, 2024).

Taken together, these results support the concept that wheat yield is governed by G × E × M (genotype × environment × management) interactions (Xin and Tao, 2019). Identifying optimal combinations of variety, sowing date, density, and nutritional model allows farmers to exploit genetic potential while adapting to seasonal variability. Importantly, our results emphasize that management decisions should not be made in isolation: for example, the benefits of a given sowing density depend strongly on the chosen variety and on prevailing weather conditions.

For breeding, the findings highlight the value of incorporating adaptive traits such as efficient resource use, tolerance to heat and drought stress, and flexible tillering ability (Bhutta *et al.*, 2019). Future wheat improvement should prioritize varieties that can thrive under moderate-to-high sowing densities, efficiently use applied nitrogen, and maintain grain filling under fluctuating climatic conditions. For agronomy, tailoring seed rate and nitrogen management to local soil fertility and predicted seasonal climate is essential to ensure economic viability and sustainability (Soofizada *et al.*, 2022).

Wheat yield stagnation remains a global challenge, with annual increases slowing to <1% in many regions (Liu *et al.*, 2021). Addressing this requires a systems-based approach, integrating breeding, precision agriculture, and adaptive management. Our study demonstrates that even within two consecutive years at the same site, optimal management strategies differed substantially, highlighting the unpredictability introduced by climate variability. These results reinforce the need for dynamic decision-support tools that integrate weather forecasts, soil fertility data, and variety-specific recommendations to guide farmers in real time. Research contributes to determining the optimal combination of sowing density and nutrition models at different sowing dates to achieve high yields and economic efficiency in wheat production.

Conclusions

This study confirms that wheat grain yield is governed by complex interactions among genotype, sowing time, plant density, and nutritional management, with seasonal weather conditions strongly modulating these relationships. Among the evaluated factors, sowing time played a dominant role by influencing the duration of key phenological stages, while the effects of plant density and fertilization depended on genotype and environmental conditions. The contrasting responses of the tested varieties across seasons highlight the importance of genotype-specific adaptability and phenotypic plasticity under variable climatic conditions. Overall, the findings emphasize that yield optimization cannot rely on single management practices but requires an integrated approach that aligns sowing time, stand density, and nutrient supply with cultivar characteristics and seasonal weather patterns. Such flexible, site- and season-specific strategies are essential for improving yield stability and supporting climate-resilient wheat production systems.

Authors' Contributions

Conceptualization: DK and DK; Data curation: ST, DU and DK; Formal analysis: ST, ZJ, DU and BT; Funding acquisition: DK, BT; Investigation: ST, DK; Methodology: DK, ST; Project administration: D.; Resources: DK, BT and ZJ; Software: DK; Supervision: DK; Validation: BT, DK and DK; Visualization: ZJ, ST, DU and BT; Writing-original draft preparation: DK, DK; Writing-review and editing, DK, BT and DK.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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