

## Interaction between climatic conditions and sowing density on yield performance of maize genotypes

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### Abstract

Maize production is increasingly challenged by climate variability, making the optimization of genotype choice and sowing density essential for stable yields. The objective of this study was to assess the effects of sowing density (SD I, SD II, SD III), genotype (ZP 434, NS 4023, ZP 555, NS 5051, ZP 666, NS 6030), and climatic conditions on maize grain yield and its main components (number of grain rows per cob, thousand kernel weight, number of plants at harvest) over four consecutive years (2014-2017). The AMMI model was used to quantify the contribution of genotype (G), environment (E), and their interaction (G×E) to yield variability. Results showed that the highest yields were recorded in 2016 under favorable climatic conditions, with hybrids ZP 555 (15.07 t ha<sup>-1</sup>) and NS 5051 (14.68 t ha<sup>-1</sup>), while the lowest yields occurred in 2015 due to drought and high summer temperatures, particularly at higher sowing density (SD I), with NS 5051 yielding only 5.73 t ha<sup>-1</sup>. The environment accounted for 83.56% of yield variability, whereas the G×E interaction explained 12.26%. Hybrids ZP 555 and NS 5051 exhibited the greatest yield stability. Lower sowing density (SD III) proved advantageous under dry conditions, whereas higher density (SD I) was optimal in favorable years. Grain yield was strongly correlated with the number of grain rows ( $r = 0.75^{**}$ ) and thousand kernel weight ( $r = 0.73^{**}$ ). These findings provide valuable insights into hybrid performance under variable climates and offer practical recommendations for optimizing hybrid selection and sowing density to improve maize adaptation to climate change.

**Keywords:** AMMI model; maize; precipitation deficit; temperature stress; yield variability

### Introduction

Maize (*Zea mays* L.) is one of the most important agricultural crops in the world thanks to its adaptability to different agro-climatic conditions and its wide application in human nutrition, animal feed, industrial

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processing and biofuel production (Szareski *et al.*, 2018; Pareja-Sanchez *et al.*, 2019; Dustgeer *et al.*, 2021; Meng *et al.*, 2022; Mandić *et al.*, 2024). Maize production is carried out on over 197 million hectares, with a production of more than 1.13 billion tons of grain (Zhao, 2022; Queenta *et al.*, 2022). In Serbia, the average yield of maize is  $4.4 \text{ t ha}^{-1}$ , with an annual production of approximately 6.631 million tons (SORS, 2023). Despite the significant yield potential, yield fluctuations are often the result of unfavorable weather conditions, such as lack of rainfall, poor distribution of rainfall, as well as factors such as inadequate soil preparation, insufficient fertilization, inappropriate sowing density and sowing time (Assefa *et al.*, 2016; Biberdžić *et al.*, 2018; Bernhard and Belov, 2020; Mandić *et al.*, 2024). With climate change, certain agrotechnical measures can cause large changes in soil fertility, which significantly affects crop productivity and crop response to climate change, according to Wei *et al.* (2021).

In order to solve the increasingly present decrease in yields caused by climate change, Ali *et al.* (2022) conducted tests using different adaptation options. The selection of a stress-resistant maize genotype, changing the sowing date and increasing the sowing density were highlighted as the most suitable adaptation options, while in the research of Tian *et al.* (2020) the influence of sowing density on the content of oil and protein in rapeseed was not determined. Genetic characteristics of hybrids, together with production conditions and applied agrotechnical measures, play a key role in yield formation (Paraschivu *et al.*, 2019; Partali and Paraschivu, 2020). The number of rows of grains per cob, as a heritable trait, can change under the influence of agrotechnical factors (Abuzar, 2011), while the weight of a thousand grains varies between hybrids and depends on agrometeorological conditions and the level of applied nutrients (Wang *et al.*, 2023). Seeding density significantly affects yield and yield components, such as number of rows of grains per ear, weight of 1000 grains and number of plants at harvest (Assefa *et al.*, 2016; Testa *et al.*, 2016; Paraginski *et al.*, 2024). Increasing seeding density often leads to a decrease in grain weight (Shafi *et al.*, 2012), while different genotypes show variability in response to increased density (Tokatlidis, 2013; Yerlikaya *et al.*, 2020). Sowing density and its impact on yield depend on several factors, among which are the length of hybrid vegetation (Stojiljković *et al.*, 2025), morphological characteristics of the plant, moisture reserves in the soil, sowing time and fertility level (Djalović *et al.*, 2024; Partali *et al.*, 2021). Climatic factors, such as rising temperatures and lack of precipitation during July and August, significantly reduce yields, especially in dry years (Branković-Radojčić *et al.*, 2018; Hong *et al.*, 2019; Wang *et al.*, 2022; Li *et al.*, 2022). Hybrids with a shorter growing season show advantages in avoiding summer droughts, which contributes to yield stability (Wu *et al.*, 2024).

Genotype selection (G) and management (M) of maize under different environmental conditions (E) and their interactions are essential to increase maize productivity. Genotype  $\times$  environment (G $\times$ E) interactions significantly influence maize yield stability and adaptation of agrotechnical measures such as seeding density, especially under changing climatic conditions. Zhang *et al.* (2017) used the CERES-Maize model to fit G $\times$ E $\times$ M interactions across the Chinese Maize Belt. On that occasion, they found that certain genotypes and optimal densities (11.4-12.7 plants/m<sup>2</sup>) increased yields by over 10% in low-yielding environments. Kunwar *et al.* (2024) state that AMMI analysis revealed statistically significant ( $p \leq 0.05$ ) genotype, environment and genotype-environment interaction (GEI) effects, explaining yield variance with interaction effects, captured by 3 interaction principal components (IPC).

The aim of this research was to examine the influence of seeding density, genotype and climatic conditions on the yield and yield components of maize using the AMMI model, with a special focus on the identification of hybrids with the highest stability and yield under climatic extremes. The research provides a new perspective through a detailed analysis of the stability of hybrids in conditions of drought and acidic soils, with specific recommendations for adjusting the sowing density to climatic conditions, which represents a significant contribute to the improvement of corn production in southern Serbia.

Although genotype-environment interactions in maize have been studied, few studies combine seeding density with climate variability using the AMMI model in this region. This paper examines the influence of

seeding density, genotype and climatic conditions on the yield of corn grains and its components (number of rows of grains in the cob, weight of 1000 grains, number of plants at harvest) in Jablanički District during a four-year period (2014-2017). A special contribute of this research lies in the identification of optimal sowing densities (SD I, SD II, SD III) for hybrids of different vegetation lengths, in different climatic conditions, with practical recommendations for farmers in Leskovac.

## Materials and Methods

### *Experimental design*

A four-year field experiment was conducted during the growing seasons of 2014-2017 at the Leskovac location (43°01'476" N, 21°56'126" E), on alluvial soil, at an altitude of 225 m. The experiment was set up on the farm of the secondary agricultural school in Leskovac (Jablanički district) under dry farming conditions. The pre-crop in all investigated years was winter wheat, which ensured a uniform starting point for the research. The trial was set up in a randomized block system with three replications. Each plot had four rows of hybrids 7 m long.

### *Plant material*

The experiment used six perspective maize hybrids, created at the Maize Research Institute Zemun Polje, and the Institute of Field and Vegetable Crops, National Institute of the Republic of Serbia, Novi Sad. Hybrids from three different FAO ripening groups were selected, to determine the influence of different hybrids on yield and yield components. 6 maize hybrids were tested: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. Sowing was done in mid-April every year in three sowing densities: 20×70 cm (SD I), 25×70 cm (SD II) and 30×70 cm (SD III), which target plant densities of approximately 71.428, 57.143 and 47.619 plants per hectare were achieved.

### *Soil preparation and fertilization*

The basic cultivation of the soil was carried out by autumn ploughing at a depth of 30 cm, after which the mineral fertilizer NPK 16:16:16 (supplied by Elixir Zorka, Šabac, Serbia) was applied in the amount of 500 kg ha<sup>-1</sup>. In the spring, nitrogen fertilizer calcium ammonium nitrate (CAN, 27% N) was applied in two phases: 60% of the required nitrogen was applied in the 3-4 leaf phase, while the rest was applied in the 7-8 leaf phase. Weed control was carried out at the sixth leaf stage with a tank mix of Callisto WG<sup>®</sup> (mesotrione 125 g a.i. ha<sup>-1</sup> - Syngenta, Rosentalstrasse 67, 4058 Basel, Switzerland) plus Motivell extra 6 OD<sup>®</sup> (nicosulfuron 45 g a.i. ha<sup>-1</sup> - CertisBelchim, Technologielaan 7, 1840 Londerzeel, Belgium) was applied for postemergence weed control.

### *Soil characteristics*

To determine the pH value, the content of humus, nitrogen, phosphorus and potassium, and the presence of carbonates, an agrochemical analysis of the soil was performed before the start of the experiment (Table 1).

**Table 1.** Provision of nutrients to the soil

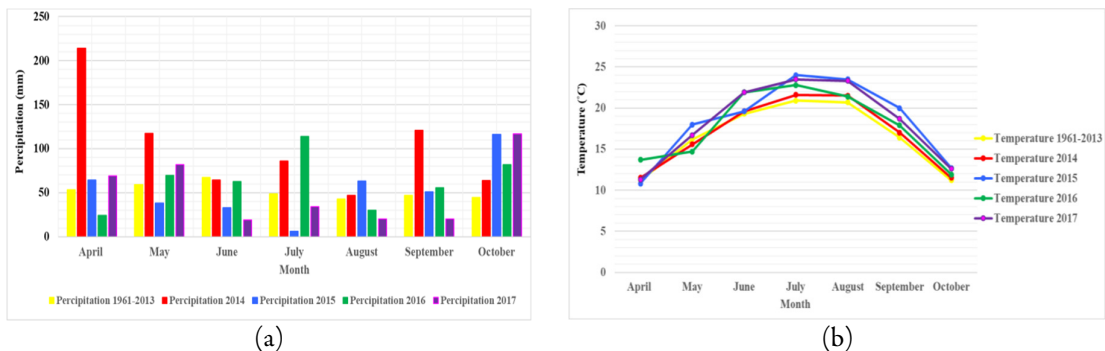
Depth (cm)	Humus (%)	N (%)	Available (mg 100 g <sup>-1</sup> soil)		pH KCl
			P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	
0-30	2.65	0.13	17.56	34.00	5.78
30-60	2.10	0.06	8.90	21.76	6.10

The soil is moderately acidic (pH in KCl 5.78). The measured humus content in the topsoil (2.65%) classifies this soil into the group of poorly supplied with humus and moderately supplied with total nitrogen (0.13%). An optimal content of phosphorus (17.56 mg P<sub>2</sub>O<sub>5</sub> 100 g<sup>-1</sup> of soil) and a high content of potassium (34.00 mg K<sub>2</sub>O 100 g<sup>-1</sup>) were found, while carbonates were not found.

#### *Meteorological conditions*

Meteorological data on average daily temperatures and precipitation were collected from the meteorological station in Leskovac, which is located near the experimental field (distance 1500 m). Figure 1 shows data on average monthly air temperatures (Figure 1a), amount and distribution of precipitation (Figure 1b) during the experiment and multi-year averages for the Leskovac location, which were obtained from the meteorological station in Leskovac.

Significant annual variations in climate conditions were observed both during the multi-year period (1961-2013) and during the study period. In 2015, during the growing season, 433.9 mm fell, which is 337.0 mm less than in 2014 (Figure 1a), while the average monthly temperature during the growing season was 17.0 °C, which is 1.2 °C higher than in 2014 that is 1.7 °C compared to the multi-year average, when the average temperature was 15.3 °C. (Figure 1b). A particularly unfavorable period was during June, July and August, with 102.8 mm of precipitation and an average monthly temperature of 22.4 °C during these three months, which classifies the year 2015 as extremely unfavorable for maize production. During the vegetation period in 2016, 569.8 mm fell, with an average monthly temperature of 16.4 °C, while in 2017 only 434 mm fell, with an average temperature of 16.9 °C. In 2014, 2015, 2016, and 2017, the average air temperature was higher for 0.5 °C, 1.7 °C, 1.1 °C, and 1.6 °C, which is higher than the multi-year average, especially in important periods of growth and development (Figure 1b).



**Figure 1.** The distribution of precipitation (a) and temperature (b) during the experimental periods of 2014-2017 and multi-year averages in the Leskovac location

\*Notes: The data for rainfall shown covers the period from 1 April to 30 October

#### *Measurement and analysis methods*

During the harvest at the technological maturity of maize, the following traits were monitored: grain yield reduced to 14% moisture, total number of plants at harvest (NPH), number of grain rows on the cob (NGR), thousand kernel weight (TKW). Samples of 12 plants from each plot were used for laboratory analyses, which were performed in the laboratory of PSSS Leskovac. The thousand kernel weight was determined by measuring on an analytical balance, while the number of rows of grains was visually counted on the cobs.

#### *Statistical analysis*

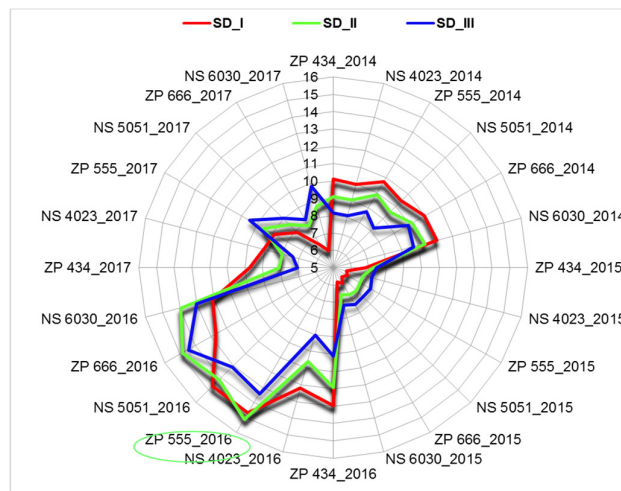
IBM SPSS v25 (2022) and GenStat 18.1 (2021) were utilized. To evaluate the impact of years, hybrids, and sowing density, an analysis of variance (ANOVA) was used, with a significance level of  $p < 0.05$ . The relationship between yield components was also verified using Pearson's correlation analysis. To evaluate the

relationship between environment and genotype, AMMI analysis (Additive Main Effects and Multiplicative Interaction) was employed. The hybrid stability and adaptability are seen through the use of AMMI 1 and AMMI 2 diagrams, which graphically present the results.

## Results

### Grain yield

Figure 2 shows the average grain yield values of six maize hybrids grown at different seeding densities over four years. The highest average grain yield values were achieved in the third year of research (2016), viewed in general, as well as by values for each grown hybrid separately. The meteorological conditions that prevailed in this growing season were the most favorable for the hybrids to realize their full genetic potential. The highest performance is observed in ZP 555 (15.07 t ha<sup>-1</sup>) and NS 5051 (14.68 t ha<sup>-1</sup>) with SD I and SD II, and ZP 666 (14.85 t ha<sup>-1</sup>), with SD II and SD III (Figure 2). Observing average values that were obtained in the first year of research (2014), the highest yield was achieved with all hybrids in the higher sowing density SD I, and the obtained values ranged from 9.96 t ha<sup>-1</sup> (NS 4023) to 11.06 t ha<sup>-1</sup> (NS 6030).



**Figure 2.** Effects of different seeding densities, genotypes and years on the yield

\*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

The lowest average values for all hybrids at different sowing densities were achieved in the second year of the study (2015). This year, in terms of climatic conditions (values of mean monthly air temperatures and the distribution and amount of precipitation) during the growing season, was significantly different compared to other years, which adversely affected the qualitative characteristic of grain yield, which is why maize is grown (Figure 2). The lowest average grain yield was achieved in the first sowing density SD I with NS 5051 (5.73 t ha<sup>-1</sup>), NS 4023 (5.79 t ha<sup>-1</sup>) and NS 6030 (5.87 t ha<sup>-1</sup>). The highest yields in conditions of high temperatures and poor distribution of precipitation are achieved with the lowest sowing density (SD III). These obtained values are significantly lower compared to the values (2016), which produced the best results are shown in Figure 2. The 2015 growing season was characterized by a rainfall deficit, with only 255.9 mm recorded compared to 569.8 mm in 2016. There was a noticeable increase in temperature in July 2015 (24 °C vs. 22.8 °C in 2016), which had a bad effect on pollination and grain formation, which are key phenological phases for

yield formation. In 2016, when precipitation was abundant and evenly distributed (114 mm in July), competition between plants was less pronounced.

All maize hybrids and their genetic characteristics showed variations at different sowing densities, indicating that the examined factors had a statistically significant impact, both individually and in mutual interaction.

Analysis of the variance of the AMMI model revealed a statistically very significant influence of genotype (G), the external environment (E) and their interaction G×E on grain yield (Table 2). At the same time, the external environment had the greatest influence on the total variation of the sample and explained 83.56% of the variability of this complex trait. The share of genotype was significantly lower and amounted to 3.53%, while the share of interaction was 12.26%.

**Table 2.** Variance analysis of the AMMI model for grain yield maize genotypes

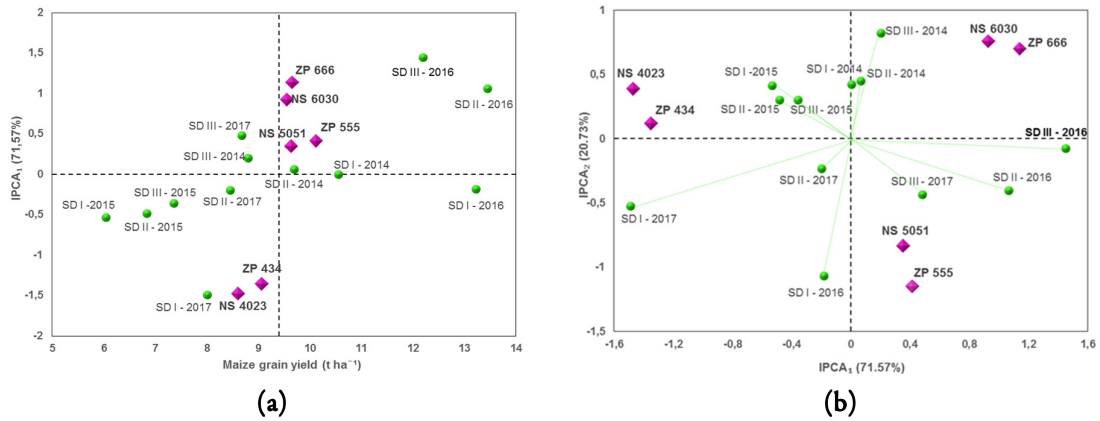
Source of variation	df	SS	MS	F	p-level	SS (%)
Total	215	1419.4	6.60	-	-	-
Treatments	71	1410.1	19.86	294.92**	0.00000	99.34
Genotypes	5	50.0	10.00	148.48**	0.00000	3.53
Environments	11	1186.1	107.82	2150.50**	0.00000	83.56
Block	24	1.2	0.05	0.74 <sup>ns</sup>	0.79612	0.08
Interactions	55	174.1	3.17	47.00**	0.00000	12.26
IPCA1	15	124.6	8.31	123.36**	0.00000	71.57
IPCA2	13	31.6	2.43	36.08**	0.00000	20.73
IPCA3	11	14.8	1.35	20.01**	0.00000	8.5
Residuals	16	3.1	0.19	2.85	0.00059	0.22
Error	120	8.1	0.07	-	-	-

\*Notes:\*\*-Highly significant at  $p < 0.01$  probability level; <sup>ns</sup>-Not significant at  $p > 0.05$  level; df-Degree of freedom; SS-Sum of squares; MS-Mean Squares; F-F value calculated; p-level-p value calculated; IPCA1-The first-interaction principal components axes; IPCA2-The second-interaction principal components axes; IPCA3-The third-interaction principal components axes

The high share of the external environment in the total variation reflects the existence of significant differences between sowing densities and years, which caused most of the variation in the formation of maize grain yield. Analysis of the interaction revealed three main components, with all three components exhibiting statistical significance ( $p < 0.01$ ), which are shown in Table 2. The first principal component explained 71.57% (IPCA1) of the interaction, the second 20.73% (IPCA2) and the third 8.5% (IPCA3) of the interaction (Table 2).

In all observed environments (years-sowing densities), the highest stability of grain yield in relation to the first main component (IPCA1) was shown by hybrids ZP 555 and NS 5051, which achieved a higher average value of grain yield than the general average of the trial. The least stability and the lowest average grain yield were recorded in hybrids NS 4023 and ZP 434 (Figure 3a, Table 3).

The highest grain yield was achieved in 2016 in SD I, SD II and SD III sowing density. At the same time, the tested corn hybrids achieved the highest yield in SD I sowing density, while in the SD II and SD III densities they had high interaction values (Figure 2). This is explained by the fact that the yield of these densities in 2016 was very variable. Grain yields in 2014 were the highest in SD I and SD II, while the lowest yields were achieved in SD III, significantly lower than the general average of the trial. At the same time, the most stable yields were achieved in SD I and SD II.



**Figure 3.** AMMI 1 (a) and AMMI 2 (b) biplot analysis of yield stability in six maize hybrids in four years and three seeding densities

\*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

**Table 3.** Mean value, AMMI model stability coefficient (AVS) and stability ranks of genotypes for grain yield

Genotypes	Grain yield		IPCA1	IPCA2	AVS	
	Average	Rank			Value	Rank
ZP 434	9.06	5	-1.353	0.120	5.33	5
NS 4023	8.60	6	-1.474	0.392	5.82	6
ZP 555	10.11	1	0.413	-1.146	1.99	2
NS 5051	9.62	3	0.351	-0.830	1.61	1
ZP 666	9.65	2	1.137	0.703	4.54	4
NS 6030	9.54	4	0.925	0.761	3.73	3

During 2015 and 2017, there were very unfavorable conditions for the growth and development of maize. In the period of grain formation and pouring, in both studied years, high air temperatures and low amounts of precipitation were recorded, as a result of which the studied maize hybrids, in all three sowing densities, achieved below-average yields (Figure 3a, Table 3). However, the most stable yields in 2014 were achieved in SD II, and in 2015 in SD III sowing density. In 2017, the low rainfall in July (34 mm) and high temperature (23.5 °C) during grain filling further explain the below-average yields, emphasizing the critical role of moisture availability at this stage.

A more precise explanation of the interaction, i.e. the behaviour of maize hybrids in different environmental conditions, is shown by the AMMI 2 biplot, where the first and second components (IPCA1 and IPCA2) explain 92.3% of the impact of the interaction on grain yield. According to this model, ZP 555 and NS 5051 stood out as the most stable hybrids. The greatest interaction effect, and thus the lowest stability in all studied environments, was achieved by hybrids of FAO ripening group 400 (ZP 434 and NS 4023) in Table 3 and Figure 3b.

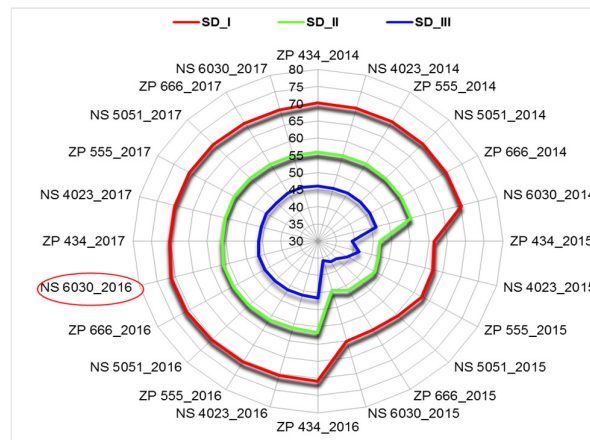
The examined conditions of the external environment (year-density of sowing), which are located closer to the centre, are characterized by greater stability. In this regard, 2014 stood out in SD I and SD II, as well as 2017 in SD II. The highest interaction value, and thus instability, was observed in 2016 in the SD III (Table 4, Figure 3b).

**Table 4.** Mean value, AMMI model stability coefficient (AVS) and environmental stability rankings for grain yield

Environment	Grain yield		IPCA1	IPCA2	AVS	
	Average	Rank			Value	Rank
SD I 2014	10.54	4	0.000	0.426	0.42	1
SD II 2014	9.69	5	0.062	0.453	0.50	2
SD III 2014	8.79	6	0.201	0.825	1.08	4
SD I 2015	6.04	12	-0.534	0.417	1.91	9
SD II 2015	6.82	11	-0.484	0.305	1.72	7
SD III 2015	7.35	10	-0.359	0.302	1.29	6
SD I 2016	13.21	2	-0.185	-1.068	1.25	5
SD II 2016	13.43	1	1.064	-0.400	3.74	10
SD III 2016	12.19	3	1.447	-0.075	5.05	11
SD I 2017	8.00	9	-1.491	-0.524	5.23	12
SD II 2017	8.45	8	-0.201	-0.230	0.74	3
SD III 2017	8.66	7	0.480	-0.431	1.73	8

*Number of plants in harvest*

The obtained results clearly show that all the tested maize hybrids achieved the highest values of the number of plants in harvest (NPH) when they were grown in the group of plants that was formed at the first sowing density (SD I) and this trend was observed throughout all growing seasons (Figure 4, Table 4). In the third year of research (2016), the highest achieved average values of the NPH were recorded at the sowing density SD I, in the hybrid NS 6030, NPH was 71.074, in ZP 666, 70.926 were found and in ZP 434, 70.637 plants were measured. These values are very different compared to the values achieved by the same hybrids in this growing season, only in other sowing densities (SD II and SD III). The first year (2014) of the research is also characterized by higher average values for the NPH, which were close to those achieved in the most favourable year (2016). In 2014, the highest achieved average values of the NPH were recorded at the sowing density SD I, in the hybrid ZP 434 (70.423), NS 5051 (70.221), and ZP 4023 (70.215), shown in Figure 4.



**Figure 4.** Effects of different seeding densities, genotypes and years on the number of plants at harvest  
 \*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

A significantly lower NPH in all six hybrids were formed at the SD III sowing density in all growing seasons. The lowest values for all maize hybrids were achieved in the second year of research (2015) at different sowing densities. The lowest NPH was measured in SD III and was 35.763 (NS 6030), 36.931 (ZP 666) and 37.118 (NS 5051). These values show that the sowing density factor had a statistically very significant influence on the NPH and, in interaction with the year, showed significant differences in the obtained values by vegetation seasons in the monitored genotypes (Figure 4, Table 4). The lower NPH in 2015, especially at SD III, is a consequence of extremely low rainfall in July (6 mm) and elevated temperatures (24 °C). In contrast, the higher NPH in 2016 at SD I is a consequence of the field layout and the amount of precipitation in July (114 mm).

AMMI analysis of variance for NPH showed a very significant influence of genotype, external environment and G×E interaction ( $p < 0.01$ ), where the external environment accounts for the largest part of the sum of squares of the samples (99.37%), and significantly less for the genotype and interaction (0.07%, 0.38%). This indicates that between the studied external environments, both year and sowing density, there was a significant difference that caused most of the variations in the formation of these features. The analysis of the multivariate part revealed three main components, of which only the first showed statistical significance and explained 86.67% of the interaction, while IPCA2 participated in the GEI variation with 1.60%, and IPCA3 with 1.02%, both with non-significant effects on the GEI variation (Table 5).

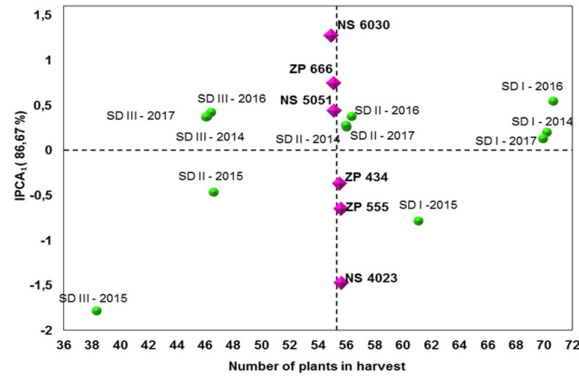
**Table 5.** Variance analysis of the AMMI model for number of plants at harvest maize genotypes

Source of variation	df	SS	MS	F	p-level	SS (%)
Total	215	23884	111.1	-	-	-
Treatments	71	23841	335.8	1000.36**	0.00000	99.82
Genotypes	5	17	3.5	10.34**	0.00000	0.07
Environments	11	23734	2157.7	24351.33**	0.00000	99.37
Block	24	2	0.1	0.26 <sup>ns</sup>	0.99980	0.01
Interactions	55	90	1.6	4.85**	0.00000	0.38
IPCA1	15	78	5.2	15.54**	0.00000	86.67
IPCA2	13	7	0.5	1.60 <sup>ns</sup>	0.09511	7.78
IPCA3	11	4	0.3	1.02 <sup>ns</sup>	0.43423	4.44
Residuals	16	1	0.0	0.13	0.99999	0.004
Error	120	40	0.3	-	-	-

\*Notes:\*\*- Highly significant at  $p < 0.01$  probability level; <sup>ns</sup>-Not significant at  $p > 0.05$  level; df-Degree of freedom; SS-Sum of squares; MS-Mean Squares; F-F value calculated; p-level-p value calculated; IPCA1-The first-interaction principal components axes; IPCA2-The second-interaction principal components axes; IPCA3-The third-interaction principal components axes

The AMMI 1 biplot analysis shows that in relation to the first main component, ZP 434 and NS 5051 stood out as the most stable hybrids for NPH (Figure 5). All studied hybrids achieved average NPH values at the level of the general average of the trial (Figure 5, Table 6).

According to the biplot (Figure 5) and the average values (Table 6) based on the points of the seeding densities (SD I, SD II, and SD III), it can be noticed that the tested maize genotypes had higher average values of the number of plants at harvest in SD I and SD II in the first 2014 growing season, I sowing density in the third 2016 growing season and SD II sowing density in the fourth 2017 growing season. In all three seeding densities in the 2015 season, it can be noticed that the tested maize genotypes had below-average values of the number of plants at harvest (Figure 5).



**Figure 5.** AMMI 1 biplot analysis of number of plants at harvest stability in six maize hybrids in four years and three seeding densities

\*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

**Table 6.** Mean value, AMMI model stability coefficient (AVS) and genotype stability ranks for the number of plants at harvest

Genotypes	Number of plants in harvest		IPCA1	IPCA2	AVS	
	Average	Rank			Value	Rank
ZP 434	55.510	3	-0.365	0.091	0.36	1
NS 4023	55.632	1	-1.468	0.611	0.87	4
ZP 555	55.615	2	-0.644	-0.705	0.8	2
NS 5051	55.122	4	0.446	-0.433	0.8	2
ZP 666	55.089	5	0.750	-0.207	0.86	3
NS 6030	54.908	6	1.281	0.644	1.08	5

As expected, the highest number of plants at harvest in all four analyzed years was achieved in SD I, slightly lower in SD II, and the lowest in SD III (Table 7).

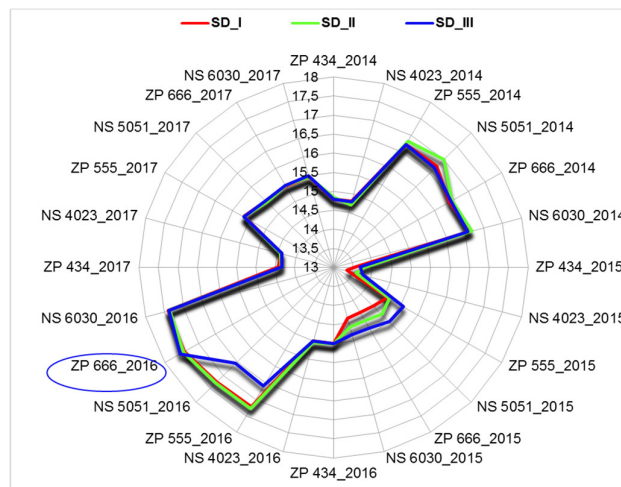
**Table 7.** Mean value, AMMI model stability coefficient (AVS) and environmental stability rankings for the number of plants at harvest

Environment	Number of plants in harvest		IPCA1	IPCA2	AVS	
	Average	Rank			Value	Rank
SD I 2014	70.202	2	0.208	0.015	0.015	1
SD II 2014	55.997	6	0.265	0.008	0.69	2
SD III 2014	46.159	10	0.382	0.012	2.24	4
SD I 2015	61.112	4	-0.775	-0.129	5.95	8
SD II 2015	46.625	8	-0.458	-1.067	5.5	7
SD III 2015	38.306	12	-1.779	0.502	4.03	5
SD I 2016	70.647	1	0.550	0.240	2.08	3
SD II 2016	56.374	5	0.384	0.118	11.86	9
SD III 2016	46.409	9	0.427	0.128	16.12	10
SD I 2017	69.899	3	0.135	0.009	16.61	11
SD II 2017	55.961	7	0.286	-0.009	2.24	4
SD III 2017	46.062	11	0.375	0.171	5.35	6

In the SD III in 2015, the greatest effect of inerrancy was manifested (Table 7). The analyzed hybrids achieved the highest number of plants at harvest stability in SD I and SD II in 2014, SD I in 2016 and SD II in 2017 (Figure 5).

#### *Number of rows of grains in a maize cob*

Analyzing the maize yield component, the number of rows of grains in the maize cob (NGR), we can see, based on the data shown in Figure 6, that the highest average values were achieved in 2016. Maize hybrids ZP 666, NS 6030 and NS 5051 showed a statistically very significant difference in the obtained values for this trait compared to the rest of the tested hybrids. The highest average value was measured with ZP 666, NS 6030 and NS 5051, but in different sowing densities. The highest value of the NGR in the maize cob in the hybrid ZP 666 of 17.56 was found at the sowing density SD III, then in NS 6030 in the sowing density SD I (17.41) and in the hybrid NS 5051 in the density SD II (17.30).



**Figure 6.** Effects of different seeding densities, genotypes and years on the number of rows of grains  
 \*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

It can be clearly seen from Figure 6 that the lowest average values of the number of rows of grains in the ear of maize were achieved in the second year of the research and this is the case with all examined hybrids of maize. The increased NGR in 2016, especially in ZP 666 at SD III, corresponds to optimal temperatures (21.9 °C in June, 22.8 °C in July) and precipitation (63 mm and 114 mm, respectively) during silking, which had a positive effect on pollination. In contrast, the lower number of NGR at NS 4023 at SD I in 2015 is a consequence of insufficient rainfall in June (33 mm) and high temperature in July (24 °C). The unfavorable conditions that prevailed during 2015 affected the functionality of pollen and grain formation.

The year factor had a statistically significant influence on NGR, both individually and in interaction with the sowing density factor shown in Figure 6. The lowest average values were at the sowing density of SD I with the hybrid NS 4023 (13.35), and then at the same sowing density with the hybrids ZP 434 (13.57) and NS 6030 (14.40). The fourth year of research (2017) is characterized by the fact that hybrids ZP 434 and NS 4023 achieved similar results in all planting densities. Average values for ZP 434 ranged from 14.32 (SD III) to 14.42 (SD I). In NS 4023, average values of 14.37 (SD III) to 14.41 (SD II) were measured. The remaining monitored hybrids (ZP 555, NS 5051, ZP 666, and NS 6030) also had approximate values of the NGR of grains in a maize cob that ranged from 15.43 to 15.66 at different sowing densities (Figure 6). Sowing density showed a statistically significant effect in interaction with year, as well as in interaction with different hybrids.

The analysis of the variance of the AMMI model showed that in NGR expression, all sources of variation, both additive (genotype, sowing density and year) and non-additive (G×E) showed high significance (Table 8). Within the main effects of the analysis of variance, the largest share of the sum of squares belongs to the external environment (50.37%) and genotype (39.24%), while the share of interaction is significantly smaller (5.34%), Figure 6. Within the multivariate part, three main components were singled out, the first two of which showed high statistical significance ( $p < 0.01$ ). The first principal component explained 78.30% of the variation, the second 17.33%, and the third component only 1.67% of the variation (Table 8).

**Table 8.** Variance analysis of the AMMI model for the number of rows of grains in the maize cob

Source of variation	df	SS	MS	F	p-level	SS (%)
Total	215	302.62	1.408	-	-	-
Treatments	71	287.33	4.047	39.27**	0.00000	94.95
Genotypes	5	118.76	23.752	230.49**	0.00000	39.24
Environments	11	152.43	13.857	113.93**	0.00000	50.37
Block	24	2.92	0.122	1.18 <sup>ns</sup>	0.27367	0.96
Interactions	55	16.15	0.294	2.85**	0.00000	5.34
IPCA1	15	12.92	0.861	8.36**	0.00000	78.30
IPCA2	13	2.86	0.220	2.13*	0.01671	17.33
IPCA3	11	0.27	0.024	0.24 <sup>ns</sup>	0.99451	1.67
Residuals	16	0.11	0.007	0.06	100.000	0.03
Error	120	12.37	0.103	-	-	-

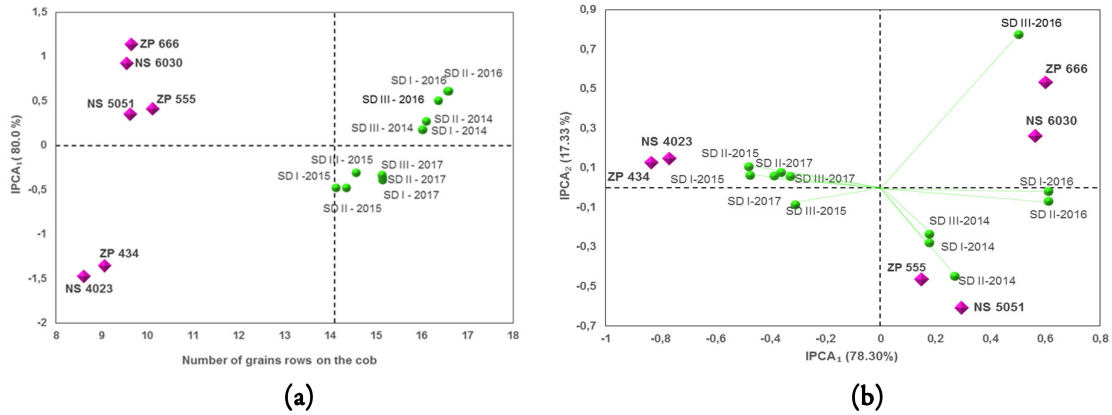
\*Notes:\*\*-Highly significant at  $p < 0.01$  probability level; \*-Significant at  $p < 0.05$  probability level; <sup>ns</sup>-Not significant at  $p > 0.05$  level; df-Degree of freedom; SS-Sum of squares; MS-Mean Squares; F-F value calculated; p-level-p value calculated; IPCA1-The first-interaction principal components axes; IPCA2-The second-interaction principal components axes; IPCA3-The third-interaction principal components axes

The AMMI 1 biplot shows the relationship between the first principal component (IPCA1) and the average value of NGR in three sowing densities over four years shown in Table 9 and Figure 7a. In all observed environments, hybrids ZP 555 and NS 5051 exhibited the highest stability in relation to IPCA1, while the lowest stability was observed in hybrids ZP 434 and NS 4023 (Figure 7a). However, all studied hybrids achieved lower average NGR values than the general average of the trial.

**Table 9.** Mean value, AMMI model stability coefficient (AVS) and hybrid stability ranks for the number of rows of grains in the maize cob

Genotypes	Number of grain rows		IPCA1	IPCA2	AVS	
	Average	Rank			Value	Rank
ZP 434	9.06	5	-0.835	0.128	3.77	6
NS 4023	8.60	6	-0.770	0.148	3.48	5
ZP 555	10.11	1	0.148	-0.464	0.81	1
NS 5051	9.62	3	0.294	-0.607	1.46	2
ZP 666	9.65	2	0.601	0.533	2.77	4
NS 6030	9.54	4	0.562	0.262	2.48	3

In order to interpret the G×E interaction in more detail, on the manifestation of NGR, the AMMI 2 biplot is shown. According to this model, the hybrids from FAO group 500 (ZP 555 and NS 5051) in Table 9 and Figure 7a, showed the highest stability, with a mean value of the NGR within the general average, while genotypes ZP 434 and NS 4023 showed the highest instability.



**Figure 7.** AMMI 1 (a) and AMMI 2 (b) biplot analysis of the number of rows of grains in the maize cob stability in six maize hybrids in four years and three seeding densities

\*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

Observing the studied environments, it can be seen that the highest average values of NGR were achieved in 2016 at all three sowing densities. At the same time, the highest interaction effects and thus the lowest stability were observed in these environments. The highest stability of NGR was achieved in 2014 and then in 2017, with all three sowing densities as shown in Figure 7a. At the same time, the average values of NGR were significantly higher in 2014 compared to 2017 (Table 10).

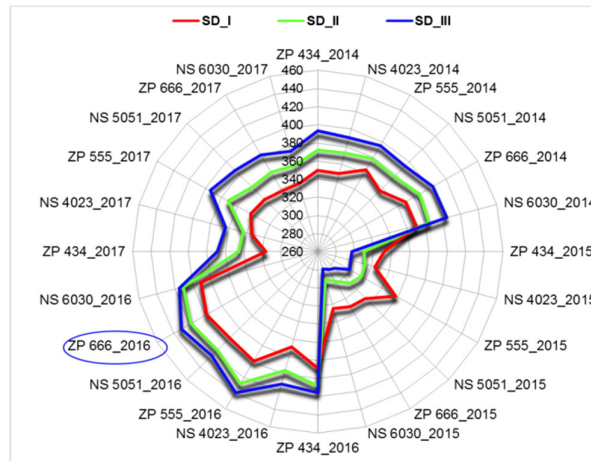
The lowest interaction effect and thus the highest stability of NGR was achieved in 2014 at all sowing densities, while the highest interaction effect was achieved in 2016 (SD I, SD II and SD III sowing density), Figure 7b and Table 10. The lowest stability in all of the studied environments (year-plant density) hybrids of FAO ripening group 400 (ZP 434 and NS 4023) showed.

**Table 10.** Mean value, AMMI model stability coefficient (AVS) and stability rankings of external environments for the number of rows of grains in the maize cob

Environment	Number of grain rows		IPCA1	IPCA2	AVS	
	Average	Rank			Value	Rank
SD I 2014	16.02	5	0.177	-0.280	0.85	2
SD II 2014	16.09	4	0.269	-0.449	1.29	3
SD III 2014	16.00	6	0.176	-0.236	0.83	1
SD I 2015	14.12	12	-0.475	0.063	2.15	8
SD II 2015	14.34	11	-0.480	0.106	2.17	9
SD III 2015	14.55	10	-0.310	-0.085	1.4	4
SD I 2016	16.56	2	0.609	-0.020	2.75	11
SD II 2016	16.58	1	0.611	-0.067	2.77	12
SD III 2016	16.36	3	0.503	0.775	2.4	10
SD I 2017	15.14	7	-0.387	0.061	1.75	7
SD II 2017	15.13	8	-0.362	0.076	1.64	6
SD III 2017	15.12	9	-0.330	0.057	1.49	5

*Thousand kernel weight*

The average values of the thousand kernel weight (TKW) are shown in Figure 8, where we can see that the highest values were achieved in the most favorable year of the research, 2016. All maize hybrids achieved the highest values of TKW when grown in SD III.



**Figure 8.** Effects of different seeding densities, genotypes and years on the thousand kernel weight  
 \*Notes: SD I, SD II and SD III represent maize seeding densities of 20×70 cm (71.428 plants ha<sup>-1</sup>), 25×70 cm (57.143 plants ha<sup>-1</sup>) and 30×70 cm (47.619 plants ha<sup>-1</sup>), respectively. Six maize genotypes of study: ZP 434 and NS 4023 from FAO group 400, ZP 555 and NS 5051 from FAO group 500, and ZP 666 and NS 6030 from FAO group 600. 2014, 2015, 2016 and 2017 represent four years of research

The highest average TKW value of 438.20 g was measured in hybrid ZP 555, followed by hybrid ZP 666 of 430.78 g and NS 5051 of 422.79 g shown in Figure 8. It is noted that in the first growing season (2014) the average values of TKW at the sowing density SD II were the smallest differences in values between the hybrids and ranged from 372.37 g to 387.15 g. The lowest average values for all maize hybrids were recorded in the second year of the research (2015) and when growing with a sowing density of SD III. Thousand kernel weight values were 280.16 g for NS 6030, 282.90 g for ZP 666 and 286.32 g for ZP 5051 are shown in Figure 8.

**Table 11.** Variance analysis of the AMMI model for thousand kernel weight of maize hybrids

Source of variation	df	SS	MS	F	p-level	SS (%)
<b>Total</b>	215	368946	1716	-	-	-
<b>Treatments</b>	71	350635	4939	37.58**	0.00000	95.037
<b>Genotypes</b>	5	7857	1571	11.96**	0.00000	2.13
<b>Environments</b>	11	333077	30280	285.83**	0.00000	90.28
<b>Block</b>	24	2542	106	0.81 <sup>ns</sup>	0.72291	0.69
<b>Interactions</b>	55	9701	176	1.34 <sup>ns</sup>	0.09272	2.63
<b>IPCA1</b>	15	5002	333	2.54**	0.00264	51.56
<b>IPCA2</b>	13	2932	226	1.72 <sup>ns</sup>	0.06574	30.22
<b>IPCA3</b>	11	1174	107	0.81 <sup>ns</sup>	0.62787	12.1
<b>Residuals</b>	16	593	37	0.28	0.99711	0.16
<b>Error</b>	120	15769	131	-	-	-

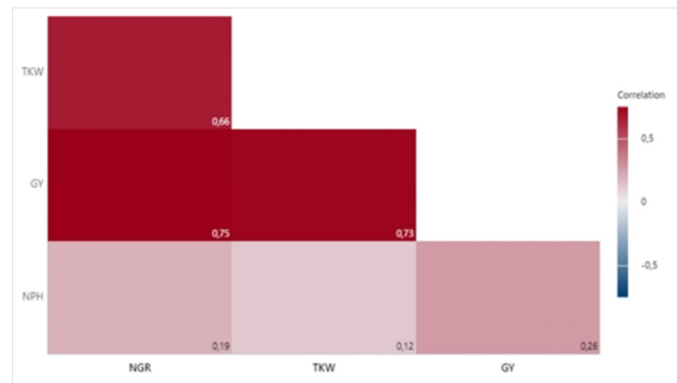
\*Notes: \*\*-Highly significant at p < 0.01 probability level; <sup>ns</sup>-Not significant at p > 0.05 level; df-Degree of freedom; SS-Sum of squares; MS-Mean Squares; F-F value calculated; p-level-p value calculated; IPCA1-The first-interaction principal components axes; IPCA2-The second-interaction principal components axes; IPCA3-The third-interaction principal components axes

A significant increase in TKW in 2016 at SD III, especially for ZP 555, is closely related to higher precipitation in July and August (114 mm and 30 mm) and moderate temperatures (22.8 °C and 21.4 °C), which had a positive impact on the phenological phase of grain filling. In 2015, a drastic decrease in TKW for NS 6030 at SD III was due to drought in July (6 mm) and high temperature (24 °C).

Using the analysis of variance of the AMMI model, a very significant influence of genotype and external environment ( $p < 0.01$ ) on thousand kernel weight was determined, while the influence of the G×E interaction was not statistically significant (Table 11). In the sum of squares of the total variance, as much as 90.28% is attributed to the external environment, 2.13% to the genotype and 2.63% to the interaction.

### *Correlation coefficients*

The research examined whether there is a significant correlation between the characteristics of maize in relation to the year and the sowing density (Figure 9).



**Figure 9.** Correlation coefficients between the studied productive traits of maize hybrids

\*Notes: GY-grain yield, NGR-number of rows of grains in the maize cob, NPH-number of plants at harvest, TKW-thousand kernel weight. Correlation is significant at the 0.01 level\*\*

Between the studied productive traits of maize hybrids, the correlation coefficients showed different values and statistical significance (Figure 9). The correlation dependence is positive and very strong between grain yield with the number of grain rows ( $r=0.75^{**}$ ) and thousand kernel weight ( $r=0.73^{**}$ ), and between the number of grain rows and thousand kernel weight ( $r=0.66^{**}$ ). A positive and weak correlation dependence was established between the number of plants at harvest with the number of grain rows ( $r=0.19$ ), thousand kernel weight ( $r=0.12$ ), and grain yield ( $r=0.26$ ).

## **Discussion**

The results of the study indicate that the seeding density, climatic conditions and their interaction significantly influence both the individual components of maize grain yield and the total yield. During the research, there were significant variations in the production of maize during the growing seasons. Hybrids reacted differently to climatic conditions, high air temperatures and uneven distribution of precipitation during the growing season. This suggests that genotype, seeding density and external environment have a significant influence on yield formation. Along with climate change, certain agrotechnical measures can also cause large changes in soil fertility, which significantly affects crop productivity and crop responses to climate change, according to Wei *et al.* (2021).

*Influence of sowing density and genotype on grain yield*

Research indicates that sowing density, genotype and their interaction with environmental conditions significantly affect the yield of corn grains ( $p < 0.01$ ). This statement is proven by the AMMI analysis of variance. The highest yields were recorded in 2016, where ZP 555 and ZP 666 achieved  $15.07 \text{ t ha}^{-1}$  and  $14.85 \text{ t ha}^{-1}$  at SD II ( $57.143 \text{ plants ha}^{-1}$ ), while NS 5051 reached  $14.68 \text{ t ha}^{-1}$  at SD I ( $71.428 \text{ plants ha}^{-1}$ ). These results are consistent with the research results of (Raza *et al.*, 2019; Tuong *et al.*, 2019; Zhang *et al.*, 2021; Yang *et al.*, 2024), who proved that optimal plant densities increase corn grain yield. In contrast, in 2015, the lowest yields were achieved,  $5.73 \text{ t ha}^{-1}$  was achieved in SD I by hybrid NS 5051, which indicates the sensitivity of corn hybrids to stress at different densities in unfavourable production conditions (high temperature, poor distribution, and low rainfall). That climatic conditions, especially during the growing season, have a significant impact on crop yield, especially when the interaction of multiple parameters is manifested, has been established in research (Božović *et al.*, 2022; Petrović *et al.*, 2023; Simon *et al.*, 2023; Mazibuko *et al.*, 2024; Popović *et al.*, 2024).

The effects of sowing density were specific for hybrids: hybrids from FAO group 500 (ZP 555 and NS 5051) stood out at higher densities (SD I and SD II), while hybrids from FAO group 400 (ZP 434 and NS 4023) showed weaker results at all densities under stress conditions, especially in 2015. This indicates that adjusting seeding density based on genotype is key to achieving maximum yields, which confirms the conclusions of Chen *et al.* (2017), Liu *et al.* (2017) and Solomon *et al.* (2017). The optimal plant density for maximum grain yield must be adapted to the conditions of the area (Djamana *et al.*, 2022). In their research Ni and Wellend (2024), point out that the density of sowing and the optimal number of plants differ significantly because the localities of cultivation are characterized by specific climatic conditions, primarily air temperatures and the amount and distribution of precipitation.

*Climatic conditions and their influence on yield components*

The beginning, duration, and end of the growing season and the phenological phase of maize depend on weather conditions (Wang *et al.*, 2021; Rajičić *et al.*, 2025), including average air temperature and monthly precipitation. These two climatic indicators differed between the years studied, as well as from the multi-year average. Climatic conditions, especially temperature and precipitation during key phenological stages, had a dominant influence on grain yield and its components, explaining 83.56% of the total yield variability. In 2016, favorable conditions of evenly distributed rainfall ( $569.8 \text{ mm}$ ) and an average growing season temperature of  $15.67 \text{ °C}$  enabled the hybrids to realize their genetic potential ( $12.95 \text{ t ha}^{-1}$ , average for all hybrids and densities). In 2016, the highest average values of the yield in the four-year study were recorded at the sowing density SD II, in the hybrid ZP 555 ( $15.07 \text{ t ha}^{-1}$ ). In contrast, 2015 was marked by a deficit of precipitation ( $255.9 \text{ mm}$ ) and elevated temperatures ( $17.06 \text{ °C}$ ,  $1.27 \text{ °C}$  above 2014), especially during June-August ( $102.2 \text{ mm}$ ,  $22.36 \text{ °C}$ ) when the average yield achieved for all hybrids and densities was  $6.74 \text{ t ha}^{-1}$ .

The yield increase in all hybrids was the least pronounced in 2015, the year with the least rainfall in the growing season. In the first and third years of the experiment, the average increase in the yield of all hybrids was higher, but the increasing tendency was also explained by the proper distribution of rainfall, especially in April, May and June. In a three-year study, Dugalić *et al.* (2025) also found that the lowest yield increase was in the year with the lowest precipitation, which is in agreement with the results of our research.

Temperature largely controls crop phenological stages, especially flowering and maturity, which determine the growth duration length and thus grain yield (Yang *et al.*, 2021; Dugalić *et al.*, 2024). During the silking and grain-filling phenological stages in July, an average temperature of  $24 \text{ °C}$  was recorded, which exceeded the optimal  $20\text{-}22 \text{ °C}$  for pollination (Maitah *et al.*, 2021). This was reflected in a 61% yield reduction compared to 2016 (e.g.,  $5.73 \text{ t ha}^{-1}$  in 2015 and  $14.68 \text{ t ha}^{-1}$  in 2016 by hybrid NS 5051). Yang *et al.* (2021) point out that as ambient temperature increased, and the lengths of maize growing seasons were markedly shortened (3-14 days earlier reaching flowering and maturity) compared to the baseline data. Altogether,

enhancing water use efficiency through breeding efforts, for example, by using maize hybrids resistant to drought and early ripening and managerial improvement by applying earlier sowing of maize and cover crops are warranted for moderating risk and even increasing productivity of maize in the future.

Maize yield is significantly influenced by the number of plants in the harvest, i.e. formed cobs and grain weight, while these parameters are significantly affected by weather conditions during the growing season (Yang *et al.*, 2022). The highest number of plants at harvest values, 71.074 by hybrid NS 6030 in the first sowing density in 2016, was achieved in the year with optimal amounts of precipitation (114 mm in July 2016). In 2015, the lowest number of plants at harvest values, 35.763 was achieved in the SD III by hybrid NS 6030, due to drought stress (6 mm in July).

The number of grain rows showed a highly significant interaction between genotype, seeding density and year. The highest number of grains was measured in 2016 (17.56 for ZP 666, SD III) with balanced moisture and moderate temperature (21.9-22.8 °C, June-July). In 2015, heat stress (average temperature 24 °C in July) and low rainfall (33 mm in June) negatively affected pollination, which negatively affected the number of grain rows. These results are in agreement with the results obtained by Dong *et al.* (2021). In the research of NiK *et al.* (2011) plant density had a significant effect ( $p < 0.05$ ) on the number of grain rows. The authors state that by increasing the number of plants from 65.000 plants ha<sup>-1</sup> to 95.000 plants ha<sup>-1</sup>, the number of grain rows decreases and the highest number of rows was obtained at 65.000 plants ha<sup>-1</sup> with an average of 17.95 grain rows, which is in agreement with the results of our research.

The thousand kernel weight has a significant role in determining the grain yield of maize, and the clarification of its basic genetic mechanisms is a challenge to improve its performance (Nowosad *et al.*, 2023). The highest values of thousand kernel weight were measured in 2016 (438.20 g for ZP 555, SD III) with an optimal amount of precipitation (569.8 mm), which had a favourable effect on grain filling. In 2015, the lowest thousand kernel weight values of 280.16 g (NS 6030, SD III) were measured due to a 20-day dry period in July (6 mm), which negatively affected grain formation. The negative impact of high temperatures, especially in the critical stages of corn development, has a pronounced impact on the reduction of the thousand kernel weight (Khan *et al.*, 2017; Liu *et al.*, 2021), which is in line with the results of our research. Our research findings indicate that drought and heat stress during silking (June-July) and grain filling (July-August) are the primary causes of yield reduction, which is consistent with Qi *et al.* (2022).

#### *Genotype-environment interaction (G×E) and yield stability*

AMMI analysis showed that genotype-environment (G×E) interaction accounted for 12.26% of yield variability, with IPCA1 explaining 71.57% of this effect. This gradient reflects the variability of precipitation and temperature, as 2015 and 2017 (255.9 mm and 434 mm, respectively) had below-average yields, while significantly higher yields were achieved in 2014 and 2016 (770.91 mm and 569.8 mm). Hybrids ZP 555 and NS 5051 showed the greatest stability, maintaining yields above the trial average (e.g., 15.07 t ha<sup>-1</sup> and 14.68 t ha<sup>-1</sup> in 2016) despite changing conditions. Their resistance to temperatures up to 23.3 °C (2017) and rainfall of only 434 mm emphasize their suitability for the agroecological conditions of southern Serbia.

In contrast, hybrid NS 4023 from FAO group 400 showed the least stability and lowest yields (5.79 t ha<sup>-1</sup> in 2015), indicating poor adaptation to high temperatures (24 °C in July 2015) and drought (6 mm in July 2015). The results of the research are in agreement with Rajičić *et al.* (2025), who observed the superior performance of the hybrids from FAO group 500 in changing climatic conditions. Stability was highest at SD I and SD II in 2014 (770.91 mm, 15.79 °C), while SD III in 2016 showed a high level of interaction between density and optimal rainfall (569.8 mm).

The dominant influence of the external environment on variability (83.56% for yield, 99.37% for number of plants at harvest, 90.28% for thousand kernel weight) emphasizes its influence in relation to genotypic effects (3.53% for yield, 2.13% for thousand kernel weight). This research is in agreement with the research of Wang *et al.* (2023), where the authors state that thousand kernel weight varies between hybrids and depends on agro-

meteorological conditions. For thousand kernel weight, our results deviate from Nowosad *et al.* (2023), who emphasized a genotypic influence. In this research, external factors are dominant (e.g. 90.28% of variability) due to extreme conditions during the investigated period, which indicates that the selection of hybrids alone cannot alleviate severe stress. Ljubičić *et al.* (2023) reported a lower proportion of the environment (58.97%), probably due to milder climate fluctuations in their study.

The distribution of precipitation showed a greater influence on the examined parameters than the total amount of precipitation. In 2017, the total precipitation during the period June-August was 73 mm, with an average temperature of 22.9 °C, which resulted in a higher grain yield compared to 2016 when 207 mm of precipitation fell during the period June-August. This confirms the importance of precipitation during the phenological stages of silking-grain filling, which coincides with the period June-August. This confirms the need to align seeding density and hybrid selection with seasonal forecasts, as suggested by Djamana *et al.* (2022).

By observing the average monthly air temperatures along with the amount and distribution of precipitation by month, during the four-year study, it can be concluded that the thermal conditions were the most favorable during the production year 2016. In this year, the period from June to August stands out as particularly favorable and is very important for the formation of yields. On the other hand, 2015 had much less precipitation and was the worst for corn production.

Practical recommendations: For farmers in the south of Serbia, it is recommended to use the sowing density SD III (lower density) in years prone to droughts, because it reduces the competition for water and enables more stable yields, especially for hybrids ZP 555 and NS 5051, while in wet years, higher yields can be achieved with the density SD I (higher density), which is especially suitable for these hybrids in conditions like those of 2016. These adjusted seeding densities make it possible to achieve satisfactory yields while reducing the risk of losses due to climatic stress.

Adaptation to climate change: The results of this research provide guidance for hybrid selection and seeding density in future scenarios with warmer and drier conditions. Hybrids ZP 555 and NS 5051, which showed high stability in drought conditions, on acidic soil, are recommended for areas with variable climatic conditions, such as Leskovac. Adjusting seeding density to specific hybrid requirements (SD II for ZP 555 and SD I for NS 5051 in favourable years) can significantly increase yields and mitigate losses during stressful years, such as 2015. These strategies are essential for sustainable maize production in the context of climate change, where more frequent extreme weather conditions are expected. Further research should focus on the long-term effects of climate change and testing a wider range of hybrids to develop adaptation strategies.

## Conclusions

The results of a four-year study indicate that climatic conditions and sowing density significantly affect grain yield and productive characteristics of maize. The external environment affects grain yield variation by 83.56%. Hybrids ZP 555 and NS 5051 had the highest yield stability and yielded up to 15.07 t ha<sup>-1</sup> in optimal agroclimatic conditions in 2016. The lowest yields (5.73-5.87 t ha<sup>-1</sup>) were achieved in 2015 as a result of drought and high temperatures. A lower sowing density (SD III) was optimal in dry years, reducing competition for water. To achieve stable yields, based on the results of the research, it can be recommended to sow hybrids ZP 555 and NS 5051 with adjustment of the sowing density (SD III in dry conditions, SD I in favourable years). Future research should be focused on examining the long-term effects of climate change and a wider range of hybrids to develop appropriate strategies in maize production.

Adjusting seeding density to specific hybrid requirements (sowing density SD II in the hybrid ZP 555 and the sowing density SD I in the hybrid NS 5051) can increase yield in favourable conditions (years like 2016) and mitigate losses during stress (years like 2015). Hybrids with stable yields (ZP 555 and NS 5051) are recommended for the variable climate of Leskovac, characterized by acidic soils (pH 5.78) and variable distribution and amount of precipitation (255.9-770.91 mm).

This research brings new insight into the interaction of seeding density, genotype and climate conditions on grain yield and its components in maize, using multi-year data and i adjusted statistical analysis (AMMI model). A special novelty stands out in the detailed identification of the stability of hybrids ZP 555 and NS 5051 in conditions of changing climatic factors, especially under drought stress, which has not been comprehensively investigated in previous studies for this area and hybrids. Also, the paper provides specific recommendations for optimal sowing density under favourable climatic conditions, which is rarely processed.

### Authors' Contributions

Conceptualization: JS, VR, MB and NĐ; Methodology: JS, VR, MB and NĐ; Software: DT, BŠ, KL and IT; Validation: DT, BŠ and IT; Formal analysis: JS, VR, KL, BŠ and IT; Writing-review and editing: VR, DT, BŠ and IT; Visualization: JS, VR, KL and NĐ; Supervision: JS, VR and DT; Funding acquisition: JS, VR and NĐ; Data curation: BŠ; Investigation: IT; Resources: JS; Project administration: NĐ.

All authors have 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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