Evaluation of Yield Stability and Adaptability of Oat Genotypes (*Avena sativa* L.)

Ocjena stabilnosti prinosa i adaptibilnosti genotipova zobi (*Avena sativa* L.)

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EVALUATION OF YIELD STABILITY AND ADAPTABILITY OF OAT GENOTYPES (*Avena sativa* L.)

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SUMMARY

This study's main objectives were (i) to determine the stability of oat genotypes for the grain yield (t ha^{-1}), (ii) to investigate the relationship of stability parameters with the grain yield in the analyzed set of genotypes, and (iii) to identify the high-yielding, stable, and adaptive oat genotypes for breeding purposes. The study was conducted during the 2015-22 period and involved fourteen winter oat genotypes maintained in the Bulgarian Seed Gene Bank. The trial was laid out in a randomized block design of variants in three replications and an experimental plot size of 10 m^2. Sixteen grain yield stability parameters were determined. The AMMI stability value (ASV), the yield stability index (YSI), and the genotype selection index (GSI) were also calculated. A year and genotype x year interaction had an almost equally dominant effect on the grain yield per hectare. The Spearman's rank correlation coefficients indicated that grain yield had significant positive associations with Thennarasu's non-parametric statistics—the NP$^{(2)}$, NP$^{(3)}$, and NP$^{(4)}$, Kang's rank-sum (KR), and the YSI. The yield stability parameters estimated the G11, G12, G13, and the G1 genotypes as the most stable. The ASV identified the G14, G8, and the G12 as the most stable genotypes, while the YSI detected the G14, G12, and G11, respectively. The GSI classified the G14, G12, G8, and the G11 as genotypes with the broadest adaptability to adverse climatic conditions. Thus, they could serve as a source material in winter oat breeding programs.

Keywords: oat, yield, adaptability, stability, analysis

INTRODUCTION

Oat is a valuable forage and food grain crop whose grain has a specific forage, dietary, and medicinal qualities. It has a wide range of uses as a green, dry, and concentrated feed and as a food for human consumption. It holds the sixth place in the world's grain production (https://www.statista.com)

Scientific research and facts prove several advantages of oat over other cereal crops. It is less demanding in terms of growing conditions and requires fewer resources for its production.

In recent years, it has been an attractive crop for Bulgarian agriculture. According to the statistics, the oat–sown area in Bulgaria in 2022 amounted to 11,726 ha (Agro Statistica, 2023). Its distribution is greatest in Southwestern, Northwestern, and Southeastern Bulgaria. Oat produces higher yields in the regions of Northern Bulgaria. The yields are lower in Southern Bulgaria, mainly due to the early summer drought, which coincides with the critical phases of crop development.

An opportunity to respond to the needs of agricultural production is the development of highly productive, broadly adaptable, and yield-stable oat varieties that can prove their genetic potential in the face of the dynamic climatic changes observed in recent years.

Yield is a complex trait that depends on many genes and is affected by various factors, including the genotype, environment, and their interactions. It is influenced by the actions and interactions of yield-related traits such as a plant height, number of productive tillers, panicle length, number of grains per Panicle, grain weight per panicle, the thousand-grain mass, harvest index, and other traits (Altuner, 2022; Kebede et al., 2023a). The breeders often use yield components to enhance the grain yield, even though these components compensate for each other in practice, meaning that an increase in one component results in a decrease in another (Popović et al., 2021).

In breeding and agrobiological contexts, one of the primary ways to differentiate the plant genotypes is assessing their yield stability and adaptability (Ohunakin et al., 2021). Yield stability is a complex indicator of genotype's

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ability to utilize the available environmental factors and achieve its maximum potential fully and is closely linked to its overall adaptability. It is influenced by the genotype, its response rate, and the environmental conditions. The adaptability of a variety across diverse environments is typically evaluated, based on its interaction with different growing conditions. A variety or genotype is deemed more adaptive or stable if it exhibits a high mean yield but a low variability in yielding ability when grown in diverse environments (Boakyewaa, 2012). It is important to consider the genotype-environment interaction (GEI), especially in terms of exposure (Singh et al., 2019). The GEI occurs when different genotypes respond differently to the changes in the environment. Both environmental factors and an individual's genetic makeup usually affect the expression of a trait (Kebede et al., 2023a). The breeders encounter a challenge when evaluating the genotypes in multilocational trials due to the presence of genotype-by-environment interaction (GEI). Minimizing and quantifying the GEI is a top priority for any breeding program, as it reduces the association between the phenotypic and genotypic values, thereby impeding genetic progress in plant breeding programs (Amelework et al., 2023).

When there is a high level of GEI, the genotypes may perform inconsistently across different environments, making it difficult to select and recommend the genotypes for a specific environment. To address this issue, it is important to conduct stability analysis using different statistical methods when the GEI effect is significant and the crossover type of interaction is present (Parimala et al., 2019; Kose, 2022).

The analysis and interpretation of the interaction between a genotype and the environment are commonly performed using two major groups of stability statistics: a parametric and nonparametric one. The parametric stability statistics employ univariate and multivariate approaches that are based on statistical assumptions about the distribution of genotypic, environmental, and GEI effects. The nonparametric approaches, on the other hand, are estimated based on the mean values of the response trait and the ranking of genotypes (Ohunakin et al., 2021; Pour-Aboughadareh et al., 2022; Wodebo et al., 2023). The genotypes that have consistent rankings across different environments are considered stable. A correlation between the yield and various stability parameters is used to select one or more stability statistics for predicting the responses in different environments reliably (Kebede et al., 2023a). However, there is a limited and poorly documented information on the yield stability of oat genotypes in Bulgaria using univariate and non-parametric methods.

Consequently, the main objectives of this study were (i) to determine the stability of oat genotypes for the grain yield (t ha^{-1}), (ii) to investigate the relationship of stability parameters with the grain yield in the analyzed set of genotypes, and (iii) to identify the high-yielding, stable, and adaptive oat genotypes for breeding purposes.

MATERIAL AND METHODS

The study was conducted from 2015 to 2022 on the experimental field of the IPGR 'K. Malkov' in Sadovo, Bulgaria (42°07 N and 24°56' E). The soil type was meadow cinnamon loam. The surface horizon demonstrates a relatively low permeability and a high moisture content. The final moisture content of the field amounted to approximately 75%. The reaction of the soil was close to neutral with pH=6.5. The soil was poorly stocked with nitrogen, medium to well stocked with phosphorus, and richly stocked with potassium. It had a favorable air and heat regime and was suitable for growing all field crops with rich organic-mineral fertilization (Table 1).

Table 1. Analysis of soil availability of essential nutrients (mg/kg) in the land of IPGR-Sadovo

Tablica 1. Analiza pristupačnih esencijalnih hranjiva (mg/kg) na površinama IPGR-Sadovo

N	P	K
0.15	9.540	39.61

N – nitrogen (mg/g), P – phosphorus (mg/g), K – potassium (mg/g)

The climate of the area is transitional continental, with a weak Mediterranean influence. The area is characterized by the warm and long autumns and mild and frequently snowy winters. Spring is short, with an almost abrupt transition to summer temperatures. For the conditions of the area, the low temperatures in December and January in snowless winters and the high temperatures in June, combined with the dry spells, are essential for the overwintering of autumnal crops. The average monthly temperatures and precipitation during the experimental periods are shown in Figure 1 and Figure 2. The meteorological conditions of the years during which the experiment was conducted demonstrate that they are very different and covered much of a usual variation of climatic conditions for this region.

The experiment involved fourteen accessions maintained in the National Seed Gene Bank (2 varieties, 1 landrace, and 11 breeding lines; Table 2). Sowing was performed between 20 and 30 October, at a time optimal for the region. Spring peas were used as a preceding crop. The trial was conducted using a block design with a randomized allocation of variants in three replications and an experimental plot sized 10 m^2, at a row spacing amounting to 10 cm, a depth amounting to 5 cm, and a sowing rate of 500 germinating seeds per square meter. Soil preparation involved double cultivation to a depth of 12 cm. Immediately prior to the sowing, cultivation was carried out at a depth of 8 cm, with an application of 0.25 t/ha triple superphosphate. In the tilling phase, 0.15 t/ha ammonium nitrate was applied. Throughout the growing season, necessary agronomic measures were implemented to ensure uniform plant development.

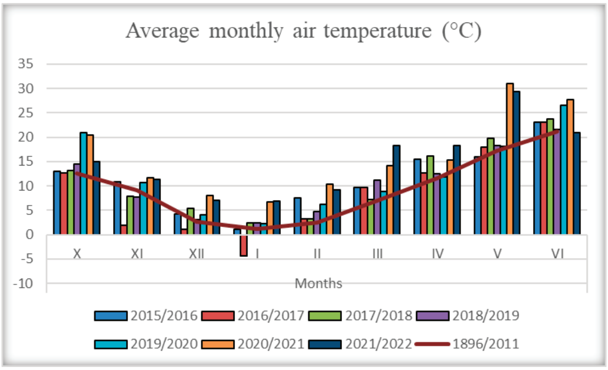

Figure 1. Average monthly air temperatures (^{0}C) for the IPGR-Sadovo area

Grafikon 1. Prosječna mjesečna temperatura zraka na području IPGR-Sadovo

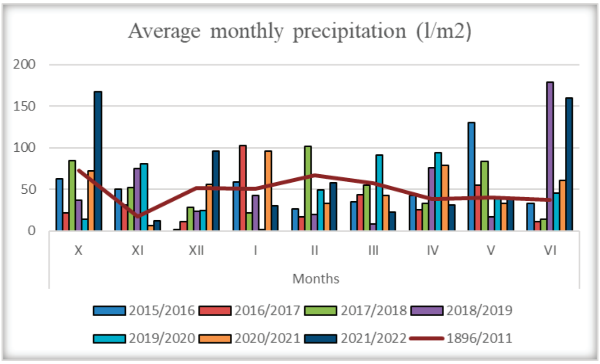

Figure 2. Average monthly precipitation (l/m^2) for the IPGR-Sadovo area

Grafikon 2. Prosječna količina oborina (l/m^2) na produčju IPGR-Sadovo

The grain yield (t ha^{-1}) data from the seven years of genotype testing were processed mathematically by a one-factor and a two-factor analysis of variance. The differences between the means of the genotypes were evaluated using the least significant difference (LSD) test at statistical significance levels of $p \leq 0.05$ (Lidansky, 1988). The *Dunav* variety, widely distributed and cultivated in Bulgaria and designated as a national yield standard by the Bulgarian Executive Agency for Variety Testing, Approval, and Seed Control, was used as standard check. In the two-factor analysis of variance, the strength of the influence of the sources of variation-genotype, year, the genotype x year interaction was estimated by Plochinsky's method (1970), according to the formula: $\eta^2 = Ci/Cy$, where η^2 is the strength of the influence of the sources of variation-genotype, year and genotype x year interaction, Ci is the variance of the respective factor (genotype, year or genotype × year interaction), and Cy is the total variance. Statistical and mathematical data processing was performed using IBM's *SPSS Statistics 22 for Windows* software.

Sixteen parameters of grain yield stability were determined. Parametric stability estimates include: a mean variance component (θ_i) (Plaisted and Peterson, 1959), GE variance component ($\theta_{(i)}$) (Plaisted, 1960), Wricke's (1962) ecovariance (W_i^2), regression coefficient (b_i) (Finlay and Wilkinson, 1963), deviation from regression (S^2_{di}) (Eberhart and Russel, 1966), Shukla's stability variance (σ^2_i) (Shukla, 1972) and coefficient of variance (CV_i; Francis and Kannenberg, 1978). Nonparametric statistical estimates of phenotypic stability include the parameters proposed by Nassar and Huehn (1987) ($S^{(1)}$-the mean of absolute rank differences of the genotype across all environments tested, $S^{(2)}$-the variance between ranks across all environments tested, $S^{(3)}$-sum of the absolute deviations for each genotype relative to the mean of the ranks, and the $S^{(6)}$-sum of the squares of the ranks for each genotype relative to the mean of the ranks), Thennarasu (1995; $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, and $NP^{(4)}$), Kang (1988; Kang's rank-sum (KR). Stabilitysoft statistical program was used to calculate the aforementioned parameters.

Table 2. List of winter oat genotypes included in the study

Tablica 2. Genotipovi zobi uključeni u istraživanje

№ of genotype	**Species** / *Vrsta*	**Accession number** / *Broj pristupa*	**Name of accession** / *Naziv pristupa*	**Biological status**	**Origin**
G1	*Avena sativa* L.	83106202	Dunav	Cultivar	BGR
G2	*Avena sativa* L.	83106008	Pennsylvania 822-7329	Breeding line	USA
G3	*Avena sativa* L.	84106082	local	Landraces	ITA
G4	*Avena sativa* L.	83106200	Dunav 1	Breeding line	BGR
G5	*Avena sativa* L.	84106172	Fringante	Cultivar	FRA
G6	*Avena sativa* L.	85106002	Pennline 6571	Breeding line	USA
G7	*Avena sativa* L.	86106024	PC 55	Breeding line	CZE
G8	*Avena sativa* L.	97106024	Ky 78/443	Breeding line	GBR
G9	*Avena sativa* L.	A3BM0578	F-21	Breeding line	BGR
G10	*Avena sativa* L.	A3BM0579	269/407	Breeding line	BGR
G11	*Avena sativa* L.	A3BM0580	281	Breeding line	BGR
G12	*Avena sativa* L.	A3BM0581	315	Breeding line	BGR
G13	*Avena sativa* L.	A3BM0582	318	Breeding line	BGR
G14	*Avena sativa* L.	A3BM0583	221	Breeding line	BGR

The AMMI stability value (ASV) was calculated based on the AMMI model interaction's principal component axis (IPCA1 and IPCA2 values) for each genotype and each environment, as suggested by Purchase (1997) while using the *PBTools* software and *Microsoft Excel 2010*.

The yield stability index (YSI) was also used to measure the stability of genotypes based on the rank of the mean yield of genotypes across environments and the rank of the ASV (Farshadfar et al., 2011).

The genotype selection index (GSI), as the sum of the ASV and yield stability index (YSI) ranking positions, were also calculated (Kose, 2022).

Spearman's rank correlation (Steel and Torrie, 1980) was determined based on the ranking procedures for the yield and stability parameters using the IBM's *SPSS Statistics 22 for Windows* software.

RESULTS AND DISCUSSION

A bivariate analysis of the variance of yield proved that the variation of the trait studied was dominated equally by the year and an interaction between the genotypes tested and the conditions under which they were grown (year) by 40.04 and 41.47%, respectively. The strength of influence of a genotype on the trait variability amounted to 12.31% of the total variation (Table 3).

Table 3. Two-way ANOVA and degree of influence of sources of variation on yield in 14 oat genotypes

Tablica 3. Dvosmjerna ANOVA i stupanj utjecaja izvora varijacije na prinos u 14 genotipova zobi

Source of variation / *Izvor vriranja*	SS	df	MS	F	P-value	F crit	η^2, %
Genotype / *Genotip*	672154.4	13	51704.19	45.03	3.98E-62	1.75	12.31
Year / *Godina*	2186951	6	364491.8	317.46	2.9E-125	2.13	40.04
GYI	2264719	78	29034.86	25.29	9.86E-94	1.33	41.47
Error / *Pogreška*	337559	294	1148.16				6.18
Total / *Ukupno*	5461383	391					

GYI-genotype × year interaction; SS-sum of squares; df-degree of freedom; MS-mean squared; η^2-strength of influence of sources of variation- genotype, year and genotype × year interaction; P-value-statistically significant values; F, F crit-Fisher's criteria

When assessing the stability and adaptability of genotypes in terms of the indicator grain yield per hectare, the presence of a proven interaction between the genotypes studied and the year in which they were grown is of particular importance for the reliability of the results obtained (Ahmad et al., 2013, 2016; Zeki et al., 2018). In our study, the genotype × year interaction was proven to have the highest influence, allowing genotypes to be evaluated for the grain yield stability and adaptability with the highest reliability (Mehraj et al., 2017, Zeki et al., 2018; Madosa et al., 2019; Singh et al., 2019; Devi et al., 2019). A cultivar's adaptability determines its stability, particularly in varying growing conditions (Chamurliyski and Tsenov, 2013).

Several studies emphasize the use of stability parameters to identify the widely adapted oat genotypes (Zeki et al., 2018; Singh et al., 2019; Madosa et al., 2022; Reginatto et al., 2022; Kebede et al., 2023a; Devi et al., 2023; Thiam et al., 2023). Comparing basic methods for the estimation of a level and stability of grain yield in winter wheat, Tsenov and Gubatov (2018) point out that using simple approaches, such as the regression coefficient (b_i), regression deviation (S^2_{di}), or the coefficient of variation (CV_i) are as effective as using the capabilities of large statistical programs developed specifically for these purposes.

Table 4 presents the average grain yield per hectare and parametric estimates of yield stability for the oat genotypes studied over a seven-year period. The average yield (t ha^{-1}) varied between 4.41 and 5.70 t ha^{-1}. The highest yield relative to the standard variety was achieved by the G12 (5.70 t ha^{-1}), followed by the G9 (5.43 t ha^{-1}), G14 (5.30 t ha^{-1}), G6 (5.29 t ha^{-1}), G11 (5.26 t ha^{-1}), G4 (5.22 t ha^{-1}), and the G13 (5.22 t ha^{-1}). The lowest yields were realized by the G2 (4.44 t ha^{-1}) and G5 (4.41 t ha^{-1}).

Francis and Kannenberg (1987) suggest using the coefficient of variation as a stability statistic, which combines the mean yield, coefficient of variation, and environmental variance. The most desirable genotypes are those with a low CV_i, low environmental variance, and a high mean yield. In our study, the CV_i values ranged from 11.67 to 33.35%. The genotype with the lowest coefficient of variation in the grain yield per hectare was the G12, which had a higher productivity than the average of other genotypes. Therefore, it demonstrates better stability if compared to the remaining genotypes. On the other hand, the G9 and G8 had the highest CV_i values across the test years (Table 4).

Plaisted and Peterson (1959) proposed a measure of stability for genotype environment interactions by calculating the variance component of interactions between each possible pair of genotypes. They considered the average of the estimate for all combinations with a common genotype to be a measure of stability ($\theta_{i;}$ Pour-Aboughadareh et al., 2019). Plaisted (1960) recommended calculating the GE variance component ($\theta(i)$). In this modified form of stability measurement, a genotype with an environment-interaction variance subsequent to a deletion of the ith genotype from the entire data set was considered to be a stability index of the ith genotype (Afzal et al., 2021). Based on these two parametric stability estimates, the genotypes with the lower values for the mean variance component (θ_i) of Plaisted and Peterson (1959) and with the higher values for the GE variance component $\theta_{(i)}$ of Plaisted (1960) are deemed more stable. Our study identified the G11, G12, G13, G1, and G4 as meeting these criteria. With the exception of G12, which was ranked as the highest yielding genotype, the remaining two were ranked, fifth, sixth, seventh, and eighth, respectively (Table 4; Table 6).

The parameters based on Wricke's (1962) ecovariance (W_i^2) and Shukla's (1972) stability variance σ^2_i, also identified G11 as the most stable, followed by the G12, G13, G1, and the G4. Kılıç (2012), Ohunakin and colleagues (2021), and Kebede and colleagues (2023a) reported that the stability estimates of the σ^2_i and the W_i^2 provide a similar ranking of genotypes, which was also confirmed by the presence of a positive Spearman rank correlation between these stability parameters.

A genotype-year interaction corresponds to the variations in genotype phenotypic plasticity. The regression coefficient b_i presents the most accurate way to express this quality. A higher coefficient value indicates a higher sensitivity of the variety to the alterations in environmental conditions. If the value of b_i is not significantly different from 1, then the genotype is adaptable to all environments. If the value of b_i is greater than 1, the genotype manifests a higher sensitivity to the changing environmental conditions and a greater specific adaptability to the high-diversity environments. Conversely, if the value of b_i is less than 1, the genotypes are more resistant to the environmental changes, thereby increasing their specific adaptability to the low-yielding environments (Mehraj et al., 2017; Singh et al., 2019; Pour-Aboughadareh et al., 2022; Kumar et al., 2022). Based on the data obtained, it was found that G11 and G5 were the most adaptive. G9 (A3BM0578) and G8 (97106024) were the most sensitive because they exhibited significant b_i values ($b_i > 1$), indicating specific adaptation to congenial climatic conditions. Therefore, in these specimens, a slight change in the environment could result in a major impact. The study found that there was a change in genotypic response, indicating sufficient variation in genotypic performance across different environmental conditions (Devi et al., 2023). In addition to the regression, a deviance variance of regression (S^2_{di}) is suggested as one of the most commonly used parameters for identifying stable genotypes. The genotypes with $S^2_{di} = 0$ are regarded as the most stable, while those with $S^2_{di} > 0$ indicate a lower stability in all environments. Thus, the genotypes with the lower S^2_{di} values are the most desirable ones (Ahmad et al., 2017; Pour-Aboughadareh et al., 2022; Kumar et al., 2022). Our research revealed that, when it comes to the studied trait, the G11 and the G12 were the most desirable options, followed by the G1 and the G13.

Table 4. The average grain yield (t ha^{-1}) and parametric stability estimates in 14 genotypes of winter oat

Tablica 4. Prosječan prinos zrna (t ha^{-1}) i procjene parametarske stabilnosti u 14 genotipova ozime zobi

Genotype / *Genotip*	GY	W_i^2	$\sigma_i^{\ 2}$	s^2_{di}	b_i	CV_i	$\theta_{(i)}$	θ_i
G1	5.06	20273.55	3366.374	2702.04	1.21	20.33	7180.93	5561.51
G2	4.44*	40645.23	7327.53	3134.73	0.21	14.04	6876.23	7389.73
G3	4.73	37635.68	6742.34	4970.06	0.69	19.18	6921.24	7119.65
G4	5.22	24407.79	4170.25	2902.26	0.63	14.09	7119.10	5932.53
G5	4.41*	38056.28	6824.13	5435.59	0.98	23.99	6914.95	7157.39
G6	5.29	46270.13	8421.26	6354.88	1.24	23.31	6792.10	7894.53
G7	4.97	65581.44	12176.24	9318.99	0.89	24.54	6503.25	9627.60
G8	5.04	54192.66	9961.76	6450.03	1.55	27.74	6673.60	8605.53
G9	5.43	98593.82	18595.31	8665.55	2.12	33.35	6009.48	12590.25
G10	4.97	40154.25	7232.07	5609.10	0.83	20.12	6883.57	7345.67
G11	5.26	4015.906	205.17	572.54	1.02	14.59	7424.10	4102.49
G12	5.70*	13470.24	2043.51	1575.56	0.72	11.67	7282.69	4950.95
G13	5.16	19252.02	3167.74	2740.24	0.95	17.07	7196.21	5469.83
G14	5.30	36311.23	6484.81	5176.27	0.95	19.41	6941.05	7000.79
Average	5.07							
LSD 0.05	0.59							
LSD 0.01	0.77							
LSD 0.001	0.99							

GY-grain yield per hectare (t ha^{-1}), W_i^2 - Wricke's covariance, σ^2_i - Shukla stability variance, S^2_{di} - regression variance, b_i - regression coefficient, CV_i - coefficient of variation, $\theta_{(i)}$ - GE variance component, θ_i - mean-variance component; * statistically proven differences at $p \leq 0.05$

The rank–based nonparametric measures of stability are a useful alternative to the currently used parametric measures, which are based on absolute data (Kaya and Geri, 2003). In this study, the first two nonparametric estimates of phenotypic stability, the $S^{(1)}$ and the $S^{(2)}$ by Nassar Huehn (1987) were identified as the most stable genotypes—the G11, G12, G5, and the G1. The $S^{(3)}$ identified the G11, G12, G1, and the G13, while the $S^{(6)}$ identified the G11, 12, G1, and the G10, respectively. On the other hand, the genotypes having a lower value of Thennarasu's parameters (1995) are considered to be the most stable. According to the $NP^{(1)}$, the genotypes G11, G13, G1, and G4 were the most stable. The $NP^{(2)}$ ranked the G11 as the most stable, followed by the G12, G13, and the G9, whereas it was G12, G13, G9, and the G1according to the $NP^{(3)}$, and the $NP^{(4)}$ ranked the G11, followed by the G12, G1, and the G13 (Table 5). According to the KR (i.e., Kang's rank-sum Kang, 1988), which uses both yields and the σ_i^2 as the selection criteria, the G12, ranked as the most stable genotype, followed by the G11, G13, and the G14, which were also distinguished by the higher yields than the average in the set of genotypes studied. The genotypes with the highest rank sums were the G2, G7, and the G5, which were deemed undesirable (Table 5).

Table 6 figures the ranking of the studied genotypes based on the calculated stability parameters. The ranking by different indices in each of the tested genotypes affects differently its rank relative to the whole group; therefore, the sum-rank average (ASR) was calculated for all statistics to select the potentially better stable genotypes. A genotype with a low ASR value is considered the most superior and stable genotype (Pour-Aboughadareh et al., 2022). Based on the results obtained, it can be summarized that the most stable genotype in the sample of the studied genotypes was the G11 (ASR = 2.31; SD = 3.34), followed by the G12 (ASR = 2.75; SD = 2.96), G13 (ASR = 4.69; SD = 2.33), and the G1 (ASR = 4.88; SD = 2.47).

AMMI stability value (ASV) is genotypes' stability considering its distance from the IPCA1 and IPCA2 axes. It quantifies and ranks the genotypes based on their yield stability (Wodebo et al., 2023). The genotype with the least ASV score is the most stable one (Farshadfar et al., 2011; Kyratzis et al., 2022; Kebede et al., 2023a). Our result confirmed that the G14 was the most stable, followed by the G8 and G12. Thiam and colleagues (2023) note that combining the ASV and the yield into a single index represents a better way to assess the potential of a genotype in different locations. The genotype with the smallest YSI is considered to be the most stable and the one with a high grain yield. On the basis of the YSI, the most stable genotypes with a grain yield higher than 5.07 tha^{-1} were the G14, G12, G11, and the G9, respectively. The Genotype Selection Index (GSI) enables ranking and creating clear classifications of the genotypes' breeding value. The genotypes with the lowest GSI coefficient had the broad adaptation (Jędzura et al., 2023; Wodebo et al., 2023). In our study, these genotypes were the G14 (GSI=2), G12 (GSI=4), G8 (GSI=5), and the G11 (GSI=6; Table 7).

Table 5. Nonparametric stability estimates in 14 winter oat genotypes

Tablica 5. Neparametrijska procjena stabilnosti u 14 genotipova ozime zobi

Genotype/ *Genotip*	$S^{(1)}$	Z_1	$S^{(2)}$	Z_2	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	KR
G1	3.62	1.02	10.62	0.75	8.58	2.08	3.14	0.38	0.45	0.49	12
G2	5.24	0.35	21.14	0.57	24.67	4.50	3.86	1.00	0.84	1.02	23
G3	4.57	0.00	17.67	0.05	17.67	4.00	4.29	1.26	0.69	0.76	19
G4	4.86	0.04	16.24	0.00	13.37	3.06	3.14	0.35	0.50	0.67	11
G5	3.62	1.02	9.81	0.98	14.21	4.21	4.00	1.96	0.98	0.87	22
G6	6.38	2.94	29.14	3.93	22.25	4.22	4.43	0.39	0.58	0.81	15
G7	6.19	2.33	25.81	2.16	19.02	3.58	4.57	0.43	0.59	0.76	23
G8	5.14	0.24	18.48	0.12	15.52	3.48	4.00	0.46	0.58	0.72	21
G9	5.43	0.60	21.48	0.65	14.09	2.72	3.43	0.32	0.44	0.59	16
G10	4.10	0.29	11.48	0.54	10.04	2.50	4.14	0.63	0.57	0.60	20
G11	2.29	5.41	3.67	3.74	2.20	1.00	1.29	0.17	0.13	0.23	6
G12	2.86	3.11	5.57	2.70	3.12	1.28	3.57	0.19	0.39	0.27	3
G13	4.10	0.29	11.62	0.51	9.38	2.62	3.00	0.30	0.46	0.55	10
G14	4.86	0.04	15.95	0.00	12.64	2.98	4.43	0.38	0.59	0.64	9

$S^{(1)}$, $S^{(2)}$, $S^{(3)}$, and $S^{(6)}$-Nassar and Huehn's nonparametric estimates of phenotypic stability, $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, and $NP^{(4)}$-Thennarasu's nonparametric estimates, KR - Kang's rank sum

Table 6. Ranking of 14 genotypes of winter oat by parametric and nonparametric stability assessments

Tablica 6. Rangiranje 14 genotipova ozime zobi prema parametarskoj i neparametarskoj procjeni stabilnosti

G	GY	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	W_i^2	σ^2_i	S^2_{di}	CV_i	*K*R	$\theta_{(i)}$	θ_i	SR	ASR	SD
G1	8	**3**	**4**	**3**	**3**	**3**	6	4	**3**	4	4	**3**	9	6	**4**	**11**	78	4.88	2.47
G2	13	11	11	14	14	7	12	13	14	10	10	6	**2**	13	10	5	165	10.31	3.59
G3	12	7	9	11	11	11	13	12	11	7	7	7	6	9	7	8	148	9.25	2.29
G4	6	8	8	7	8	3	5	6	8	5	5	5	**3**	5	5	10	97	6.06	1.95
G5	14	**3**	**3**	9	12	8	14	14	13	8	8	9	11	12	8	7	153	9.56	3.54
G6	4	14	14	13	13	12	8	9	12	11	11	11	10	7	11	4	164	10.25	3.13
G7	10	13	13	12	10	14	9	10	10	13	13	14	12	13	13	2	181	11.31	2.96
G8	9	10	10	10	9	8	10	8	9	12	12	12	13	11	12	3	158	9.88	2.39
G9	**2**	12	12	8	6	5	4	**3**	5	14	14	13	14	8	14	1	135	8.44	4.80
G10	11	5	5	5	4	10	11	7	6	9	9	10	8	10	9	6	125	7.81	2.37
G11	5	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	4	**2**	**1**	**14**	**37**	**2.31**	3.34
G12	**1**	**2**	**2**	**2**	**2**	6	**2**	**2**	**2**	**2**	**2**	**2**	**1**	**1**	**2**	**13**	**44**	**2.75**	2.96
G13	7	5	6	4	5	**2**	**3**	5	4	**3**	**3**	4	5	4	**3**	**12**	**75**	**4.69**	2.33
G14	**3**	8	7	6	7	12	7	11	7	6	6	8	7	**3**	6	9	113	7.06	2.35

G-genotype / *genotip*; Ranks of W_i^2 - Wricke's covariance, σ^2_i - Shukla stability variance, S^2_{di} - regression variance, b_i - regression coefficient, CV_i - coefficient of variation, $\theta_{(i)}$ - GE variance component, θ_i - mean-variance component; $S^{(1)}$, $S^{(2)}$, $S^{(3)}$), and S(6)-Nassar and Huehn's nonparametric estimates of phenotypic stability, $N^{P(1)}$, $NP^{(2)}$, $NP^{(3)}$, and $NP^{(4)}$-Thennarasu's nonparametric estimates, KR - Kang's rank sum; SR-sum of ranks; ASR-mean sum of ranks; SD-standard deviation

The relationships between the mean grain yield and the studied stability parameters were established by Spearman's rank correlation analysis (Table 8). If the stability parameters are positively associated with each other, they can be used interchangeably. This is because they provide a similar pattern in genotype ranking (Temesgen et al., 2015).

Among stability parameters, the $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, KR, and YSI demonstrated significant positive associations with the grain yield. This suggests that the selection of winter oat genotypes based on these stability parameters would result in the development of high-yielding genotypes with a stable performance across different environments (Kebede et al., 2023a). Various research in oats also demonstrated significant positive associations between the yield and the YSI (Yusuff et al., 2017; Kebede et al., 2023a, 2023b). The $S^{(1)}$ positively associated with the W_i^2, σ^2_i, S^2_{di}, $\theta_{(i)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$, $NP^{(4)}$, SR, and the ASR and negatively with the θ_i. A highly significant positive correlation was recorded between the $S^{(2)}$ and $S^{(3)}$, $S^{(6)}$, $NP^{(4)}$, W_i^2, σ^2_i, S^2_{di}, $\theta_{(i)}$, SR, and the ASR. In turn, the $S^{(3)}$ and $S^{(6)}$ correlated positively with Thennarasu's nonparametric estimates—namely, with the $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, W_i^2, σ^2_i, KR, $\theta_{(i)}$, SR, ASR, and the YSI. The $NP^{(1)}$ had a significant positive association with the $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, W_i^2, σ^2_i, S^2_{di}, and the $\theta_{(i)}$, and a negative relationship with the θ_i. $NP^{(2)}$, $NP^{(3)}$, and $NP^{(4)}$. It correlated significantly positively with the KR, SR, ASR, and the YSI. The W_i^2, σ^2_i and S^2_{di}, stability parameters that correlated positively with each other, had significant positive associations with the $\theta_{(i)}$, CV_i, KR, SR, and the ASR and negatively with the θ_i. Kılıç (2012) and Kebede and colleagues (2023a, 2023b) also indicated a close relationship between the W_i^2, σ^2_i, and the S^2_{di}. Ohunakin and colleagues (2021) recorded a highly significant positive correlation between the $S^{(1)}$ and $S^{(2)}$, $S^{(3)}$, $S^{(6)}$, and $NP^{(1)}$ and $NP^{(4)}$, as well as between the $S^{(1)}$ and W_i^2, σ^2_i, and the S^2_{di}. The relationships between the CV_i, $\theta_{(i)}$, and θ_i, were significantly positive and negative, respectively. Positive correlations were observed between the KR and the $\theta_{(i)}$, SR, ASR, YSI and the GSI, whereas they were negative between the KR and the θ_i. The association between the mean variance component—the θi—and the GE variance component $\theta_{(i)}$—was significantly negative. Negative correlations were detected between the SR, ASR, and the θ_i, while the relationships between the ASR, YSI, and the GSI were highly positive. The ASV had positive and significant correlations with YSI and GSI. YSI positively associated with GSI.

Table 7. Mean performance of winter oat genotypes based on the AMMI Stability Value (ASV), Yield Stability Index (YSI), and Genotype Selection Index (GSI)

Tablica 7. Prosječne vrijednosti genotipova ozime zobi na temelju AMMI vrijednosti stabilnosti (ASV), indeksa stabilnosti prinosa (YSI) i indeksa selekcije genotipa (GSI)

G	Yield, t ha^{-1}	R	ASV	R	YSI	R	GSI
G1	5.06	8	11.96	11	19	6	17
G2	4.44	13	13.63	12	25	9	21
G3	4.73	12	5.83	5	17	5	10
G4	5.22	6	8.98	8	14	4	12
G5	4.41	14	9.69	9	23	7	16
G6	5.29	4	15.87	13	17	5	18
G7	4.97	10	21.32	14	24	8	22
G8	5.04	9	3.91	**2**	11	**3**	**5**
G9	5.43	**2**	8.78	7	9	**2**	9
G10	4.97	11	6.25	6	17	5	11
G11	5.26	5	5.56	**4**	9	**2**	**6**
G12	5.70	**1**	4.66	**3**	4	**1**	**4**
G13	5.16	7	9.94	10	17	5	15
G14	5.30	**3**	3.02	**1**	4	**1**	**2**

Table 8. Spearman's correlation coefficients among the ranks of grain yield and stability parameters for 14 winter oat genotypes

Tablica 8. Spearmanovi koeficijenti korelacije između rangova prinosa zrna i parametara stabilnosti za 14 genotipova ozime zobi

	GY	S$^{(1)}$	S$^{(2)}$	S$^{(3)}$	S$^{(6)}$	NP$^{(1)}$	NP$^{(2)}$	NP$^{(3)}$	NP$^{(4)}$	W_i^2	σ^2_i	s^2d_i	CVi	KR	$\theta_{(i)}$	θ_i	SR	ASR	SD	ASV	YSI	GSI
GY	1																					
S$^{(1)}$	-0.004	1																				
S$^{(2)}$	0.046	0.983**	1																			
S$^{(3)}$	0.459	0.814**	0.837**	1																		
S$^{(6)}$	0.521	0.670**	0.684**	0.952**	1																	
NP$^{(1)}$	0.232	0.555*	0.531	0.637*	0.580*	1																
NP$^{(2)}$	0.829**	0.293	0.314	0.705**	0.749**	0.637*	1															
NP$^{(3)}$	0.684**	0.397	0.389	0.763**	0.864**	0.686**	0.890**	1														
NP$^{(4)}$	0.622*	0.595*	0.600*	0.925**	0.982**	0.620*	0.842**	0.912**	1													
W_i^2	0.244	0.834**	0.820**	0.780**	0.618*	0.593*	0.530	0.442	0.609*	1												
σ^2_i	0.244	0.834**	0.820**	0.780**	0.618*	0.593*	0.530	0.442	0.609*	1.000**	1											
s^2d_i	0.182	0.767**	0.736**	0.670**	0.53	0.695**	0.499	0.437	0.534*	0.943**	0.943**	1										
CVi	0.108	0.454	0.442	0.341	0.231	0.393	0.305	0.169	0.222	0.732**	0.732**	0.815**	1									
KR	0.783**	0.510	0.530	0.777**	0.706**	0.486	0.823**	0.682**	0.763**	0.774**	.774**	0.675**	0.491	1								
$\theta_{(i)}$	0.244	0.834**	0.820**	0.780**	0.618*	0.593*	0.530	0.442	0.609*	1.000**	1.000**	0.943**	0.732**	0.774**	1							
θ_i	-0.244	-0.834**	-0.820**	-0.780**	-0.618*	-0.593*	-0.530	-0.442	-0.609*	-1.000**	-1.000**	-0.943**	-0.732**	-0.774**	-1.000**	1						
SR	0.516	0.781**	0.785**	0.952**	0.873**	0.717**	0.754**	0.749**	0.877**	0.868**	0.868**	0.789**	0.508	0.880**	0.868**	-0.868**	1					
ASR	0.516	0.781**	0.785**	0.952**	0.873**	0.717**	0.754**	0.749**	0.877**	0.868**	0.868**	0.789**	0.508	0.880**	0.868**	-0.868**	1.000**	1				
SD	-0.007	0.152	0.125	0.222	0.165	-0.033	0.024	-0.007	0.143	0.376	0.376	0.218	0.288	0.310	0.376	-0.376	0.314	0.314	1			
ASV	0.336	0.406	0.437	0.459	0.442	0.086	0.196	0.235	0.402	0.310	0.310	0.200	0.152	0.464	0.310	-0.310	0.464	0.464	0.305	1		
YSI	0.806**	0.225	0.274	0.541*	0.566*	0.210	0.624*	0.564*	0.604*	0.316	0.316	0.203	0.143	0.749**	0.316	-0.316	0.590*	0.590*	0.196	0.815**	1	
GSI	0.525	0.368	0.402	0.521	0.521	0.150	0.367	0.376	0.512	0.319	0.319	0.204	0.134	0.585*	0.319	-0.319	0.538*	0.538*	0.257	0.974**	0.915**	1

GY-grain yield per hectare / *prinos sjemena ha*$^{-1}$, S$^{(1)}$, S$^{(2)}$, S$^{(3)}$), and S(6)-Nassar and Huehn's nonparametric estimates of phenotypic stability, N$^{P(1)}$, NP$^{(2)}$, NP$^{(3)}$, and NP$^{(4)}$-Thennarasu's nonparametric estimates, W_i^2 - Wricke's covariance, σ^2_i - Shukla stability variance, S^2_{di} - regression variance, b_i - regression coefficient, CV_i - coefficient of variation, $\theta_{(i)}$ - GE variance component, θ_i - mean-variance component; KR - Kang's rank sum; SR-sum of ranks; ASR-mean sum of ranks; SD-standard deviation, ASV-AMMI Stability Value, YSI-Yield stability index, GSI-Genotype Selection Index

CONCLUSION

The strength of influence of the sources of variation—that is, year and year × genotype interaction—had an almost equally dominant effect on grain yield per hectare. The Spearman's rank correlation coefficients indicated that the grain yield had significant positive associations with the NP$^{(2)}$, NP$^{(3)}$, and NP$^{(4)}$, KR, and the YSI. The use of these stability parameters would efficiently aid the selection of winter oat genotypes for yield improvement. The genotypes G11, G12, G13, and G1 were characterized as the high-yielding and stable ones, suitable for cultivation in the Sadovo region. The G14, G12, G8, and the G11 were identified as the genotypes with the broadest adaptability to adverse climatic conditions that could be used as a starting material in oat-breeding programs. Yet, further research on genotypes at diverse locations is required to enhance the validity of these results.

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OCJENA STABILNOSTI PRINOSA I ADAPTIBILNOSTI GENOTIPOVA ZOBI (*Avena sativa* L.)

SAŽETAK

Glavni ciljevi ovoga istraživanja bili su sljedeći: (i) utvrditi stabilnost genotipova zobi za prinos zrna (t ha^{-1}), (ii) istražiti odnos parametara stabilnosti s prinosom zrna u analiziranome skupu genotipova, i (iii) identificirati visokoprinosne, stabilne i adaptabilne genotipove zobi. Istraživanje je provedeno u razdoblju od 2015. do 2022. godine i uključivalo je četrnaest genotipova ozime zobi koji se čuvaju u banci gena u Bugarskoj. Pokus je postavljen prema slučajnome blok-dizajnu u trima ponavljanjima, s veličinom pokusne parcele od 10 m^2. Utvrđeno je šesnaest parametara stabilnosti prinosa zrna. Izračunana je i vrijednost AMMI stabilnosti (ASV), indeks stabilnosti prinosa (YSI) i indeks selekcije genotipa (GSI). Interakcija godina i genotip × godina imala je gotovo jednako dominantan učinak na prinos zrna po hektaru. Spearmanovi koeficijenti korelacije pokazali su da je prinos zrna imao značajne pozitivne veze s Thennarasuovim neparametarskim statistikama — NP$^{(2)}$, NP$^{(3)}$ i NP$^{(4)}$ — te Kangovim zbrojem rangova (KR) i YSI. Parametri stabilnosti prinosa procijenili su genotipove G11, G12, G13 i G1 kao najstabilnije. ASV je identificirao G14, G8 i G12 kao najstabilnije genotipove, dok je YSI utvrđen za G14, G12, odnosno za G11. GSI je klasificirao G14, G12, G8 i G11 kao genotipove s najširom adaptabilnošću na nepovoljne klimatske uvjete. Navedeni genotipovi mogli bi poslužiti kao izvorni materijal u programima oplemenjivanja ozime zobi.

Ključne riječi: zob, prinos, adaptabilnost, analiza, stabilnost

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