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Study Gene-environment Interactions and Ecological Stability for Common Bean (*Phaseolus vulgaris* L.)

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ABSTRACT

Background: Crop productivity is determined by genotype, environmental effects and their interactions. Comprehensive evaluation of crop varieties based on their adaptability, plasticity and stability makes it possible to select the most promising varieties, high-yielding and adapted to many environmental conditions to improve productivity.

Methods: Five common bean varieties were tested in a randomized complete block design with three replications during two growing periods in (2022 and 2023) in the experimental field of Novosibirsk State Agrarian University, Russia.

Result: Varieties, seasons and gene-environment interactions had a significant impact on the average yield of experimental varieties. Solnyshko, Viola and Kormilitsa varieties had a high average net yield in all environments, ranging from (2.29 - 2.71 kg/m^2). Analysis of the interaction between genotype and environment (G × E) by the mathematical model of Elberhart and Russell and the GGE biplot chart shows that: Solnyshko and Kormilitsa varieties have stable yields and high adaptability to the environment.

Key words: Adaptive ability, Environmental sustainability, Genotype × environment interaction, GGE biplot, *Phaseolus vulgaris*.

INTRODUCTION

Common bean *Phaseolus vulgaris* was domesticated about 8000 years ago in the Americas and today is a staple food worldwide. Besides caloric intake, common bean is also an important source of protein and micronutrients and it is widely appreciated in developing countries for their affordability (compared to animal protein) and its long storage life (Castro *et al.,* 2016). As a legume, common bean also has a role in sustainable agriculture owing to its ability to fix atmospheric nitrogen (Schmutz *et al.,* 2014).

Increasing crop productivity mainly depends on seeds, fertilizers and agricultural practices, in which seeds are considered the leading driving force to increase productivity and output (Hoa, 2005). The main condition for the development of a high-quality variety is the combination of ecological plasticity and productivity. In this case, much attention is paid to the parameters that influence the potential productivity of a variety (Yakubenko *et al.,* 2020). In addition, evaluating the stability and adaptability of varieties in different ecological regions will help improve productivity of agricultural crops.

The GGE Biplot (Genotype by Environment Interaction Biplot) model proposed by Yan and Kang (2007), is a statistical model widely used to analyze genotype-environment interaction and stability of new crop varieties. Based on the GE Biplot model, many plant varieties with high stability and adaptability have been identified, such as studies on chickpea (Ravi *et al.,* 2024), wheat (Ajay *et al.,* 2024), maize (Nirmal *et al.,* 2024; Jovan *et al.,* 2024; Katsenios *et al.,* 2021) and common bean (Odireleng *et al.,* 2019). The study's objective is to determine the effects of growing seasons and the interaction between gene and environment on growth rate and yield of common bean under Siberian conditions.

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MATERIALS AND METHODS

Plant samples

The research was conducted during two growing periods in (2022 and 2023) at the experimental field of Novosibirsk State Agrarian University. Five promising breeding varieties (Solnyshko, Kormilitsa, Nika, Darina and Viola) were sown annually in four terms: May 16 (E_1), May 23 (E_2), May 30 (E_3) and June 6 (E_4).

Data collection

The phenological observation was taken according to Vishniyakova *et al.* (2018) and morphological description of plants was carried out according to Budanova *et al.* (1987). The number of pods per plant was counted directly from ten sample plants of each plot and an average was caculated after harvesting. Pod weight (g) and one hundred seeds weight (g) are obtained from a random sample of 100 pods and 100 seeds, respectively and weighed. In each experimental plot, data on pod yield were recorded on ten randomly selected plants harvested. An effective method for assessing the adaptability of genotypes was

developed by Kilchevsky and Khotyleva (1985). The indicator of ecological plasticity was described by Eberhart *et al.* (1966) and Korzun *et al.* (2011). Stability analysis using the GGE biplot model was described by Yan *et al.* (2007) and Olanrewaju *et al.* (2021).

Satistical analysis

Data collected were subjected to excel and subsequently analyses using IRRISTAT statistical package.

RESULTS AND DISCUSSION

Climate change in novosibirsk during research

The studies were conducted in (2022 and 2023) at the experimental field of Novosibirsk State Agrarian University. Climatic conditions during the two growing periods are shown in Fig 1.

Weather conditions varied greatly during the different growing seasons. During 2022, the weather was rather dry compared to the long-term average, with low average precipitation (2.5 to 58.8 mm) and average day and night temperatures ranging from (11 to 19°C), whereas 2023 was wetter in July and August (62.3 mm and 112.3 mm, respectively) and warmer throughout the season (Fig 1). During the experiment, the average temperature tended to gradually increase from May to July and gradually decrease from August to September. The recorded temperatures in June and July were lower in 2022 (17.3°C and 18.9°C, respectively) compared to 2023 (19.0°C and 21.6°C, respectively).

In 2023, characterized by a warm spring-summer period with increased precipitation, allowed the development of seedlings to take place in favorable condi-tions for heat-loving crops - in the second decade of June, the temperature exceeds the long-term average of 6°C, which leads to the formation of a high yield. In general, agro-climatic conditions in Novosibirsk during the experiment in 2023 are more favorable for bean growth and development than in 2022.

Adaptive capacity and ecological stability

Two factors analysis of variance was used to identify significant differences between genotypes and environments for all studied traits at 1 and 5% significance levels (Table 1).

The phenotypic variability in the number of beans per plant is largely contributed by environmental effects (mean squares of the means exceed the mean squares of the genotypes), while bean weight and 100-seed weight are contributed by genotypic effects (mean squares of the genotypes prevail over mean squares of the means).

Table 1 showed that the total squared variance of environment accounts for a larger proportion than genotype and gene-environment correlation. This shows that the actual yield of bean varieties depends largely on the farming environment and then on the nature of the genotype.

Table 2 showed the main indicators of adaptive capacity and stability of bean samples. One of the important elements of crop productivity is the number of beans per plant. The trait is influenced by both the genotype of the variety and soil and climatic conditions (Parkina *et al.,* 2023).

The total number of pod per plant in the varieties reached an average of 21.68, the highest in the variety Solnyshko - 31.83 and the lowest in the variety Viola - only 17.88 beans per plant.

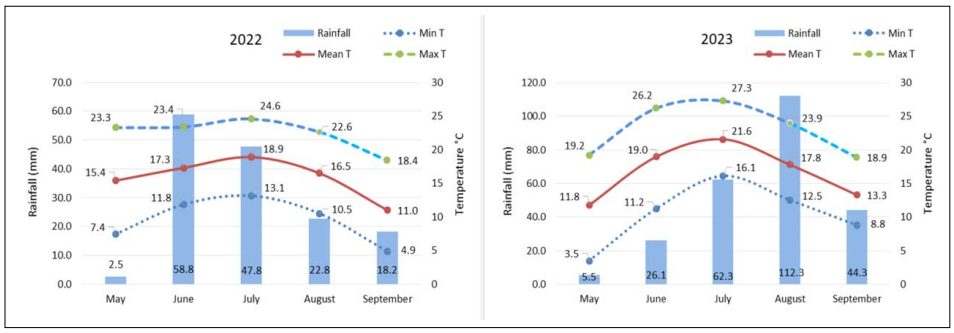


Fig 1: Climatic conditions during the two cultivation periods.

Table 1: Analysis of variance of the studied features.

Source of variation	Mean square			
	NPP	*WP*	*HSW*	*NY*
Environment	2338.81*	1.15	0.41	15.73*
Genotype	98.68*	4.28*	143.11*	0.21*
Genotype environment interaction	55.41*	0.52	12.81*	0.22*
Error	5.64	0.33	2.36	0.01

NPP: Number of pod per plant; WP: Weight of pod; HSW: Hundred seed weight; NY: Net yield; *Significant at p<0.01%.

Variety Solnyshko on the trait "Number of pod per plant" stands out for its general adaptive ability (9.07). Variance of specific adaptive ability in the studied samples ranged from 1.15 (Solnyshko) to 5.42 (Viola). Relative genotype stability varied from 3.6 (Solnyshko) to 30.33 (Viola), the best in this parameter were varieties Solnyshko and Kormilitsa.

According to the trait "Number of pod per plant", the Solnyshko variety shows general adaptability and high breeding value of the genotype (GAA_i = 9.07, SVG_i = 31.03).

The average value of the trait "Hundred seed weight" ranged from [(21.19 g (Solnyshko) to 36.79 g (Darina)]. The Kormilitsa and Nika varieties are characterized by a high rate of general adaptability (2.21-4.28), selection value of the genotype (17.28-20.29) and coefficient bi regression > 1, this means that their seed weight increases as farming conditions improve. However, it is necessary to consider the results of the analysis of variance of the studied traits, according to which the phenotypic expression of seed weight depends more not on the environment but on the genotype.

The yield of the varieties ranges from (2.2 (Nika) to 2.71 kg/m^2 (Solnyshko)) and reaches an average of 2.36 kg/m^2. The Solnyshko variety has the highest general adaptive ability (*GAAi*), reaching a value of 0.35. A variety is considered stable when it simultaneously has a regression coefficient (*bi*) close to 1 and a low *Sgi* [Olga *et al.,* 2023]. Varieties Solnyshko, Viola and Kormilitsa have regression coefficients reaching a value of 1, respectively; 0.98 and 0.92 and the *Sgi* index is lower than the other varieties. These breeds also have a positive and higher genotype selection value than the remaining breeds.

Genotype-environment interaction

Compared to statistical measures, the GGE biplot has several advantages for characterizing genotype-environment interactions. This graphical model allows visualizing the ranking of environments by differentiation ability and representativeness, as well as highlighting genotypes both specifically adapted and with an optimal combination of yield potential and stability in a set of environments (Gudzenko, 2019).

Genotype × environment interaction was evaluated using the GGE biplot model with 97.5% of the total variation distributed as 72.2% and 25.3% of the sum of squares between the principal component PC1 and PC2, respectively (Fig 2).

A comparative depiction of the environment in terms of differentiation and representativeness is shown in Fig 2. The line through the center of the GGE biplot represents the mean axis of the environment. The lines connecting the centers of the GGE biplot with the experimental

Table 2: Parameters of adaptive ability and stability of bean samples.

Variety		X_i	GAA_i	σSAA_i	Sg_i	b_i	SVG_i
			Number of pod per plant				
G1	Solnyshko	31.83	9.07	1.15	3.60	0.19	31.03
G2	Kormilitsa	20.87	-1.90	3.27	15.65	0.41	18.59
G3	Nika	19.43	-3.34	3.74	19.26	0.46	16.82
G4	Darina	18.40	-4.37	5.10	27.70	0.61	14.85
G5	Viola	17.88	-4.89	5.42	30.33	0.65	14.10
			Weight of pod (g)				
G1	Solnyshko	4.26	-1.11	0.15	3.58	1.46	3.24
G2	Kormilitsa	5.48	0.10	0.10	1.82	-1.37	4.81
G3	Nika	6.25	0.88	0.57	9.05	2.85	2.46
G4	Darina	6.51	1.14	0.75	11.55	3.62	1.48
G5	Viola	6.21	0.84	0.56	8.98	2.82	2.48
			Hundred seed weight (g)				
G1	Solnyshko	21.19	-8.31	4.60	21.73	21.51	-7.73
G2	Kormilitsa	33.78	4.28	2.63	7.78	12.61	17.28
G3	Nika	31.71	2.21	1.82	5.73	9.09	20.29
G4	Darina	36.79	7.29	1.03	2.81	-5.93	30.30
G5	Viola	34.02	4.52	3.07	9.01	14.57	14.75
			Yield (Kg/m^2)				
G1	Solnyshko	2.71	0.35	0.02	0.64	0.99	2.35
G2	Kormilitsa	2.29	-0.08	0.10	4.18	0.91	0.21
G3	Nika	2.22	-0.15	0.30	13.38	1.04	-3.29
G4	Darina	2.26	-0.11	0.38	16.61	1.06	-4.70
G5	Viola	2.34	-0.03	0.05	2.09	0.98	1.44

X_i: Average genotype value; GAA_i: General adaptive ability; σSAA_i: Variance of specific adaptive ability; Sg_i: Relative stability of the genotype; b_i: Regression coefficient; SVG_i: Selection value of the genotype.

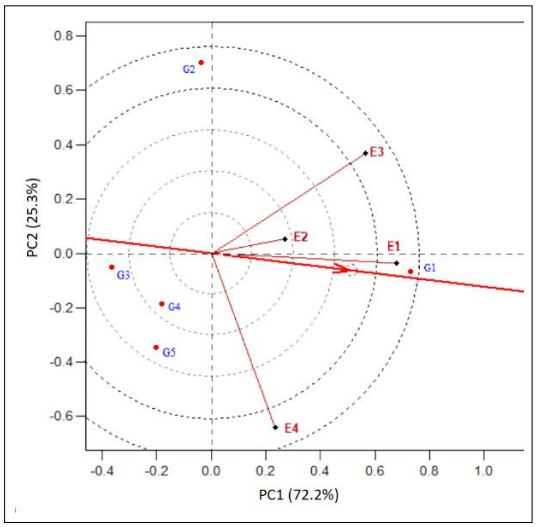


Fig 2: Discriminating ability against representativeness of test environments.

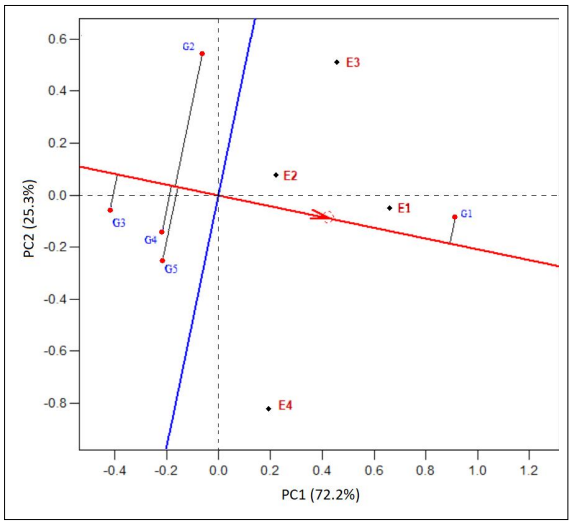


Fig 3: Ranking bean breeding lines based on both mean performance and stability.

seasons are vectors of the environment. A longer vector indicates greater variability of the respective environment. The angle between the mean axis of the media and the vector of a particular medium characterizes its representativeness. Smaller angle corresponds to higher representativeness. The maximum representativeness was observed in environment E1. In general, it should be noted that environment E1 combined high levels of differentiation ability and representativeness. The smaller the angle between the vectors of the environments, the more similar these environments were to each other in terms of yield and vice versa. The environments E1, E2 were the closest to each other, while E3 and E4 were the most different.

Fig 3 showed that the variety G1 has the highest net yield and dominates in environment E1. While G2 variety has an advantage in E3 environment and G3, G4, G5 varieties have more advantage in E4 environment compared to the remaining environments. Environment E2 is closer to the center of the model than environments E3, E4 and E5, which shows that the yield fluctuations of experimental varieties in environment E2 are lower than those in environments E3, E4 and E1. The G1 variety is closest to the midline and on the right side compared to the other varieties, so the G1 variety has high yield and stability. Variety G3 is located closer to the midline than varieties G2, G4, G5 and is at the far left, which means that although variety G3 has stable productivity under all conditions, its productivity is low compared to the other varieties. Although variety G2 is farthest from the center line, its yield is higher than varieties G3, G4 and G5. This indicates that stability and yield parameters are completely independent of each other.

The GGE (genotype ranking) biplot model used to rank the stability of varieties under different conditions, presented in Fig 3, shows that variety G1 is closest to the center of the small circle, thus line G1 optimally combines yield potential and adaptability.

CONCLUSION

The use of different sowing dates at the final stage of the bean breeding process is a simple but practical and effective way to evaluate and select genotypes that combine yield potential and higher stability under the weather fluctuations of different growing years.

Statistical indices characterize the studied genotypes in different ways. Most indices δ*SAAi, Sgi, bi* evaluate mainly stability, without taking into account the level of productivity. The *SVGi* index can be considered relatively balanced in terms of stability and productivity. These regularities should be taken into account when characterizing genotypes for objective interpretation of experimental data.

The combined use of both statistical parameters and GGE biplot visualizations contributes to maximum informativeness in assessing genotype-environment interactions, as well as to the selection of valuable genotypes. The Solnyshko variety with the optimal combination of yield and stability, as well as two high-yielding varieties, Viola and Kormilitsa, were identified. Therefore, they are classified as highly adaptable varieties and are encouraged to be included in breeding programs as a source of raw materials to create vegetable bean varieties adapted to Siberian conditions.

Conflict of interest

All authors declared that there is no conflict of interest.

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