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Adaptability, stability, and productivity of soybeans in an organic multi-environment system

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Abstract: Organic soybean production requires genotypes capable of maintaining high performance under variable environmental conditions and without synthetic inputs. This study evaluated 22 soybean genotypes grown in 24 environments across different regions of Brazil over five growing seasons (2019/2020 to 2023/2024) to identify materials with superior productivity, adaptability, and stability. The genotype × environment (G×E) interaction, analyzed using mixed models (REML/BLUP), was the only significant source of variation, indicating a strong environmental influence on genotype performance. Selection indices based on genotypic values (HMGV, RPGV, and HMRPGV) were applied to simultaneously assess yield, stability, and adaptability. Genotype BRSMG534 showed the best overall performance, with high productivity, stability, and broad adaptability. Additional promising genotypes included SOYPLENASG7401, BRS6013, LIN16, and IPR115. Conversely, BRS531, BRS573, and BRS391 exhibited low performance in the organic system. The results demonstrate that biometric modeling and BLUP-based indices are effective in recommending genotypes adapted to organic farming, highlighting that only a limited group of materials combines high yield, phenotypic stability, and environmental responsiveness.

Keywords: Genotype × environment interaction; Mixed models; REML/BLUP; Yield performance; Multi-environment trials; Organic agriculture; Genotypic stability indices.
Abbreviations: G×E - Genotype × environment interaction; GY - Grain yield; REML - Restricted Maximum Likelihood; BLUP - Best Linear Unbiased Prediction; HMGV - Harmonic Mean of Genotypic Values; RPGV - Relative Performance of Genotypic Values; HMRPGV - Harmonic Mean of Relative Performance of Genotypic Values; AIC - Akaike Information Criterion; LRT - Likelihood Ratio Test; rge - Genotypic correlation across environments; $GEIr^2$ - Coefficient of determination of G×E interaction; μ - Overall mean; g - Genotypic effect; e - Environmental effect; ge - Genotype × environment interaction effect; ε - Random error.

Introduction

The introduction of soybean [*Glycine max* L. (Merr.)] in Brazil has changed the prospects for agribusiness, currently accounting for a significant portion of the national economy (Carvalho et al., 2016). In the 2024/2025 crop season, the planted area reached 47.35 million hectares, resulting in 171.5 million tons of grain and a mean productivity of 3,621 kg ha^{-1} (CONAB, 2025). The soybean production chain also plays a relevant role in generating direct and indirect jobs, boosting regional and national development (Toloi et al., 2021).

Currently, three main cultivation systems are employed: conventional, based on the use of chemical fertilizers and pesticides; transgenic, which uses genetically modified seeds; and organic, which dispenses with chemical molecules and depends on ecological management, nutrient cycling, and biological control. Recent studies highlight the advantages of

integrated systems for soybean sustainability (Silva et al., 2023) and the viability of the organic system as a less environmentally impactful alternative (Reginatto et al., 2025). The growing global interest in healthier foods has increased the demand for organic products, opening new market opportunities for Brazilian soybeans. However, for this segment, it is necessary to identify genotypes appropriate to the organic system, with high competitiveness, tolerance to pests and diseases, lower nutritional requirements, and stable performance in environments with greater variability (Feledyn-Szewczyk and Jończyk, 2016; Borja Reis et al., 2022).

Recommending genotypes for this system requires specific trials, since synthetic fertilizers and chemical pesticides are not used (Pradebon et al., 2023). Organic production depends directly on cultivars adapted to low-input environments, capable of resisting biotic and abiotic stress, exhibiting vigorous initial growth, and demonstrating greater symbiotic efficiency (Venancio et al., 2024). Thus, it becomes fundamental to conduct multi-environment trials to identify genotypes suitable for such conditions. Studies in different crops, such as cowpea, show that biometric models applied to multi-environment trials allow the selection of genotypes that are simultaneously productive, stable, and adaptable (Sousa et al., 2019).

The use of these models has promoted advances in the positioning of soybean genotypes, allowing the identification of agronomically superior materials in different environments (Carvalho et al., 2016; Sousa et al., 2019; Rother et al., 2019). This approach is crucial because the same cultivar can exhibit contrasting performance depending on the growing environment, due to genetic and environmental effects and their interaction, called genotype × environment interaction (G×E). Recent studies indicate that G×E reduces the association between phenotypic and genotypic values and makes it difficult to recommend superior materials (Happ et al., 2021; Abebe et al., 2024). Thus, methods based on genotypic values, such as those that simultaneously integrate productivity, stability, and adaptability, become essential to guide selection in systems with greater environmental variability, such as organic farming (Colombari Filho et al., 2013).

Based on the above, it is hypothesized that adaptability and stability indices are efficient tools for recommending promising soybean genotypes for organic farming systems. The objective of this work was to evaluate the G×E interaction in an organic system, identifying genotypes with greater adaptability, stability, and productive performance in different environments.

Results and discussion

When comparing the overall mean air temperature among the environments, it is noted that Bela Vista do Norte/PY, Maracaju/MS, and Rio Verde/GO presented values above 25 °C (Fig. 1). Diamante D'Oeste/PR, Dourados/MS, Jaboticabal/SP, and Laguna/MS exhibited temperatures below 25 °C for most of the cycle, while São Francisco de Paula/RS and Major Vieira/SC presented values around 17 °C, being the environments with the mildest temperatures in the study. Thus, air temperature did not appear to be a limiting factor for soybean development, since soybeans require values between 20 °C and 30 °C, with an ideal temperature around 25 °C (Alsajri et al., 2022).

Mean daily rainfall values show a distribution between 3 and 4 mm day^{-1} for most of the soybean cycle, with values exceeding 5 mm day^{-1} only in October, with December being the month with the least rainfall (Fig. 1). Faxinal dos Guedes/SC, Capinzal/SC, Passo Fundo/RS, Augusto Pestana/RS, and Tiradentes do Sul/RS were among the environments with daily means exceeding 4.5 mm day^{-1}. Maracaju/MS and Jaboticabal/SP had the lowest averages. Soybeans require a total water volume ranging from 450 to 800 mm (Farias et al., 2007), being relatively tolerant to water deficit during the vegetative period, but very sensitive during flowering and grain filling (Sentelhas et al., 2015).

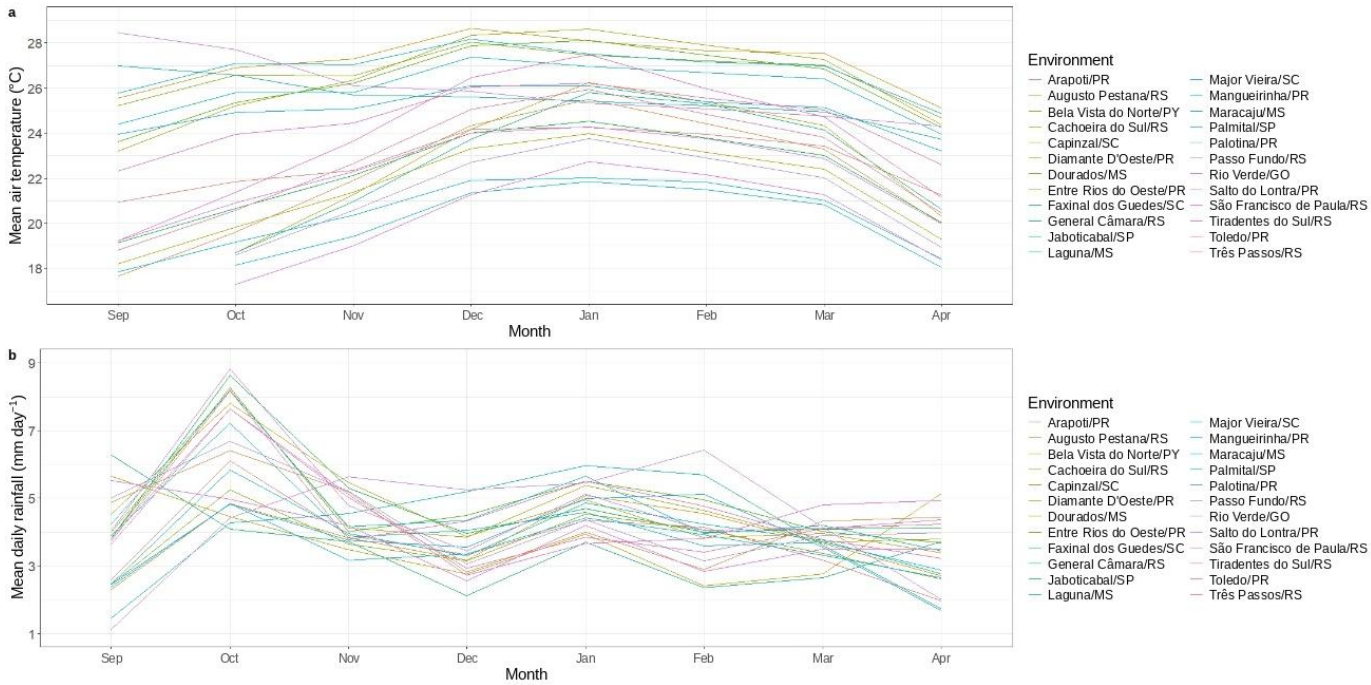


Fig. 1. Average monthly values of mean air temperature (°C) (a) and mean daily rainfall (mm day^{-1}) (b) for the environments evaluated in organic soybean cultivation in the 2019/2020, 2020/2021, 2021/2022, 2022/2023 and 2023/2024 growing seasons.

Deviance analysis based on the likelihood ratio test revealed statistically significant differences only for the G×E interaction effect on grain yield (Table 1). The estimated heritability value was 0.07, indicating a high influence of the environment on genotype performance. However, the genotypic correlation across environments (rge) and the coefficient of determination of the G×E interaction ($GEIr^2$) indicated a predominantly simple G×E interaction, with values of 0.77 and 0.71, respectively.

Table 1. Deviance analysis and genetic parameters obtained for the model.

Variable	Model	logLik	AIC	LRT	Pr(>Chisq)
GY	G	-445	1074	2.49	1.14×10^{-1}
GY	G×E	-529	1243	171	$3.69 \times 10^{-39*}$
Parameters			**Values**		
$\sigma^2 p$			0.65		
H^2			0.07		
$GEIr^2$			0.71		
$h^2 mg$			0.80		
Ac			0.89		
rge			0.77		
CV_g			7.29		
CV_r			12.60		
CV_{ratio}			0.58		

G: genotype effect; G×E: genotype × environment interaction effect; GY: grain yield (t ha^{-1}); logLik: Log Likelihood; AIC: Akaike Information Criterion; LRT: Likelihood Ratio Test; Pr(>Chisq): probability of the χ^2 test; $\sigma^2 p$: phenotypic variance; H^2: broad-sense heritability; $GEIr^2$: coefficient of determination of the G×E interaction; $h^2 mg$: average genotypic heritability; Ac: accuracy; rge: correlation coefficient of the G×E interaction; CV_g: coefficient of genotypic variation; CV_r: coefficient of residual variation; CV_{ratio}: Proportion between CV_g and CV_r.

High values for these coefficients suggest a proportional and predictable response from the genotypes (Pupin et al., 2015). In other words, this shows that the performance of a given genotype does not tend to change drastically in the face of the different environments evaluated. The selective accuracy obtained was 0.89, associated with an average genotypic heritability of 0.80. These values indicate high precision in predicting genotypic values and highlight the potential for selecting promising genotypes for the organic system.

The largest GY ranges were observed in the 2022/2023 and 2020/2021 growing seasons (5.62 and 5.14 t ha^{-1}, respectively), with the smallest for the 2019/2020 growing season (3.64 t ha^{-1}). This information can be extracted from the predicted values for grain yield ($\hat{y}_{ij}$) in Tables 2 and 3. This suggests a greater environmental effect in crops with larger amplitudes. In the 2019/2020 crop season, the best genotypes were BRS284, DF 2353, and BRS523, grown in Jaboticabal/SP, Três Passos/RS, and Diamante D'Oeste/PR, with GY between 3.4 and 5.0 t ha^{-1} (Table 2). However, the genotypes BRS523 and DF 2353, along with BRS511, also showed the worst performance when grown in General Câmara/RS, which shows that the specific edaphoclimatic conditions of each environment were decisive for the success of organic farming in the 2019/2020 crop season. The genotypes BRS511, IPR122, BRS525, BRS539, and BRS511 evaluated In Augusto Pestana/RS, Três Passos/RS and General Câmara/RS, GY yields ranged between 4.6 and 6.5 t ha^{-1} in the 2020/2021 crop season, while BRS391 and BRS525 in Entre Rios do Oeste/PR, Salto do Lontra/PR, Major Vieira/SC and Toledo/PR were the worst genotypes.

Table 2. Predicted values for grain yield ($\hat{y}_{ij}$, in t ha^{-1}) of 22 soybean genotypes (G) evaluated in 24 environments (E), conducted in an organic farming system. Data extracted for the 2019/2020 and 2020/2021 growing seasons.

2019/2020					2020/2021					2020/2021 (continued)				
E	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$
E17	G1	0.1	1.3	5.0	E2	G3	0.1	1.8	6.5	E14	G2	-0.3	0.3	3.3
E17	G13	0.1	0.2	3.9	E24	G20	0.1	1.9	5.8	E14	G8	0.1	-0.2	3.2
E24	G1	0.1	0.7	3.8	E10	G5	0.0	0.9	5.1	E24	G8	0.1	-0.7	3.2
E17	G4	-0.1	0.1	3.6	E10	G8	0.1	0.4	4.7	E18	G21	0.2	-0.4	3.2
E6	G4	-0.1	0.5	3.4	E10	G3	0.1	0.3	4.6	E24	G2	-0.3	-0.4	3.2
E24	G13	0.1	0.2	3.4	E18	G5	0.0	1.2	4.6	E18	G2	-0.3	0.1	3.2
E20	G14	-0.2	0.0	3.3	E3	G21	0.2	0.7	4.6	E3	G14	-0.2	-0.4	3.1
E24	G3	0.1	0.2	3.3	E10	G21	0.2	0.2	4.6	E20	G8	0.1	0.5	3.1
E6	G3	0.1	0.1	3.2	E2	G8	0.1	-0.1	4.6	E10	G4	-0.1	-1.0	3.1
E22	G13	0.1	0.3	3.2	E24	G21	0.2	0.4	4.4	E24	G5	0.0	-0.8	3.0
E17	G14	-0.2	-0.3	3.1	E17	G8	0.1	0.3	4.3	E14	G4	-0.1	-0.2	3.0
E5	G13	0.1	0.5	2.9	E2	G11	0.0	-0.2	4.3	E23	G13	0.1	0.2	3.0
E24	G14	-0.2	0.0	2.8	E14	G1	0.1	0.9	4.3	E14	G14	-0.2	-0.1	3.0

2019/2020					2020/2021					2020/2021 (continued)				
E	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$
E16	G4	-0.1	0.7	2.8	E17	G5	0.0	0.4	4.2	E18	G8	0.1	-0.5	3.0
E22	G3	0.1	-0.3	2.6	E3	G1	0.1	0.4	4.2	E14	G5	0.0	-0.4	3.0
E6	G1	0.1	-0.6	2.5	E3	G5	0.0	0.4	4.2	E8	G8	0.1	0.6	2.9
E17	G3	0.1	-1.3	2.4	E3	G8	0.1	0.3	4.1	E17	G2	-0.3	-0.6	2.9
E5	G14	-0.2	0.2	2.3	E24	G19	0.1	0.2	4.1	E13	G1	0.1	0.1	2.9
E16	G3	0.1	-0.2	2.1	E3	G13	0.1	0.2	4.0	E13	G8	0.1	0.1	2.9
E5	G3	0.1	-0.3	2.1	E18	G4	-0.1	0.7	4.0	E18	G18	-0.2	-0.4	2.8
E10	G1	0.1	0.2	1.9	E2	G7	0.0	-0.5	4.0	E14	G3	0.1	-0.7	2.8
E5	G4	-0.1	-0.4	1.8	E24	G14	-0.2	0.3	4.0	E13	G3	0.1	-0.1	2.7
E24	G18	-0.2	-1.1	1.7	E23	G3	0.1	1.2	4.0	E5	G3	0.1	-0.5	2.7
E16	G1	0.1	-0.6	1.6	E24	G3	0.1	-0.1	3.8	E13	G4	-0.1	0.1	2.7
E10	G13	0.1	-0.1	1.6	E14	G13	0.1	0.4	3.8	E5	G13	0.1	-0.7	2.5
E10	G3	0.1	-0.1	1.6	E18	G19	0.1	0.3	3.8	E13	G2	-0.3	0.1	2.5
E10	G4	-0.1	-0.1	1.4	E5	G8	0.1	0.6	3.7	E3	G2	-0.3	-1.1	2.3
					E18	G3	0.1	0.2	3.7	E23	G14	-0.2	-0.2	2.3
					E17	G4	-0.1	-0.1	3.7	E23	G4	-0.1	-0.4	2.2
					E24	G18	-0.2	0.0	3.7	E8	G13	0.1	-0.1	2.2
					E20	G4	-0.1	1.2	3.7	E18	G20	0.1	-1.4	2.0
					E3	G4	-0.1	0.0	3.6	E23	G1	0.1	-0.8	2.0
					E5	G5	0.0	0.6	3.6	E8	G14	-0.2	0.0	1.9
					E18	G1	0.1	0.1	3.6	E8	G21	0.2	-0.4	1.9
					E13	G21	0.2	0.7	3.6	E8	G1	0.1	-0.4	1.9
					E24	G1	0.1	-0.4	3.5	E20	G3	0.1	-0.8	1.8
					E10	G1	0.1	-0.8	3.5	E8	G3	0.1	-0.4	1.8
					E24	G4	-0.1	-0.3	3.5	E23	G2	-0.3	-0.6	1.8
					E23	G21	0.2	0.7	3.5	E23	G5	0.0	-0.9	1.7
					E3	G3	0.1	-0.4	3.5	E13	G5	0.0	-1.1	1.6
					E23	G8	0.1	0.7	3.5	E20	G5	0.0	-1.0	1.5
					E2	G5	0.0	-1.1	3.4	E8	G2	-0.3	-0.5	1.3
					E8	G5	0.0	1.2	3.4					

g: predicted value for the i-th genotype ($BLUP_g$); ge: predicted value for the interaction of the i-th genotype with the j-th environment (BLUP); E1: Arapoti/PR; E2: Augusto Pestana/RS; E3: Bela Vista do Norte/PY; E4: Cachoeira do Sul/RS; E5: Capinzal/SC; E6: Diamante D'Oeste/PR; E7: Dourados/MS; E8: Entre Rios do Oeste/PR; E9: Faxinal dos Guedes/SC; E10: General Câmara/RS; E11: Jaboticabal/SP; E12: Laguna/MS; E13: Major Vieira/SC; E14: Mangueirinha/PR; E15: Maracaju/MS; E16: Palmital/SP; E17: Palotina/PR; E18: Passo Fundo/RS; E19: Rio Verde/GO; E20: Salto do Lontra/PR; E21: São Francisco de Paula/RS; E22: Tiradentes do Sul/RS; E23: Toledo/PR; E24: Três Passos/RS; G1: BRS284; G2: BRS391; G3: BRS511; G4: BRS523; G5: BRS525; G6: BRS531; G7: BRS537; G8: BRS539; G9: BRS546; G10: BRS573; G11: BRS6013; G12: BRSMG534; G13: DF 2353; G14: GE; G15: IDRBASALTO; G16: IDRPETROVITA; G17: IDRPÉVERMELHO; G18: IPR110; G19: IPR115; G20: IPR122; G21: LIN16; G22: SOYPLENASG7401.

These results highlight that choosing the best genotype or the most assertive growing environment for the organic system in just a few harvests can lead to erroneous deductions. In this study, for example, the environment of General Câmara/RS went from the worst position to the top of the ranking due to a change in the influence of the harvest effect. The G×E interaction constitutes one of the main challenges faced by breeders when identifying, selecting, and recommending genotypes, since it can lead to inconsistencies in the classification of materials between environments and reduce the association between phenotypic and genotypic values. Recent studies have reinforced this complexity, demonstrating that environmental variation substantially modifies the relative performance of genotypes and demands robust analytical methodologies (Abebe et al., 2024; Happ et al., 2021).

In the 2021/2022 growing season, the genotypes DF 2353, BRS546, BRS539, BRS284, and BRS525 showed GY greater than 4.0 t ha^{-1} when cultivated in São Francisco de Paula/RS, Passo Fundo/RS, Jaboticabal/SP, and São Francisco de Paula/RS, respectively (Table 3). The worst performance was attributed to the genotypes BRS525, BRS523, and BRS531 in Laguna/MS, with GY between 0.6 and 0.8 t ha^{-1}, being 87 to 82% lower than the GY of the best genotype in this growing season, highlighting the importance of evaluating the stability of the genotypes. Similarly, the highest predicted values for the 2022/2023 crop occurred in Três Passos/RS, where BRS546, BRS539, and BRS511 showed superior performance (6.6; 6.4; 5.6 t ha^{-1}). However, these same genotypes exhibited a decrease in GY when compared to other environments, e.g., the

BRS546 genotype, which led in Três Passos/RS (6.6 t ha^{-1}), fell to 2.9 t ha^{-1} in Palotina/PR and reached 1.6 t ha^{-1} in Augusto Pestana/RS.

Table 3. Predicted values for grain yield ($\hat{y}_{ij}$, in t ha^{-1}) of 22 soybean genotypes (G) evaluated in 24 environments (E), conducted in an organic farming system. Data extracted from the 2021/2022, 2022/2023 and 2023/2024 growing seasons.

2021/2022					2021/2022 (continued)					2022/2023					2023/2024				
E	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$	**E**	**G**	**g**	**ge**	$\hat{y}_{ij}$
E21	G13	0.1	0.9	4.6	E15	G14	-0.2	0	2.1	E24	G9	0.2	0.4	6.6	E2	G17	-0.1	1.3	6.1
E18	G9	0.2	0.7	4.4	E7	G13	0.1	0.1	2	E24	G8	0.1	0.2	6.4	E2	G3	0.1	0.9	5.9
E11	G8	0.1	0.6	4.3	E7	G14	-0.2	0.4	2	E24	G3	0.1	-0.5	5.6	E2	G5	0	0.4	5.3
E21	G1	0.1	0.6	4.3	E12	G8	0.1	0.6	1.9	E15	G5	0	0.9	5.4	E2	G15	-0.1	0	4.8
E21	G5	0	0.4	4	E15	G4	-0.1	-0.2	1.9	E19	G12	0.1	0.7	5	E2	G9	0.2	-0.5	4.6
E18	G5	0	0.4	3.9	E24	G3	0.1	0.3	1.9	E15	G3	0.1	0.2	4.9	E2	G16	0	-0.6	4.3
E11	G7	0	0.3	3.8	E9	G4	-0.1	-0.9	1.7	E15	G9	0.2	-0.1	4.6	E1	G3	0.1	0.2	3.6
E11	G5	0	0.3	3.8	E7	G4	-0.1	0	1.7	E19	G22	0	0	4.4	E2	G8	0.1	-1.4	3.6
E10	G9	0.2	1	3.8	E7	G3	0.1	-0.2	1.7	E19	G9	0.2	-0.2	4.3	E1	G9	0.2	0.1	3.6
E11	G3	0.1	0.1	3.8	E12	G1	0.1	0.4	1.7	E19	G10	-0.2	-0.5	3.7	E24	G9	0.2	0.6	3.5
E18	G3	0.1	0.2	3.8	E15	G5	0	-0.6	1.7	E15	G8	0.1	-1	3.6	E18	G5	0	0.3	3.4
E18	G4	-0.1	0.3	3.7	E7	G5	0	-0.1	1.7	E18	G9	0.2	0	3.6	E18	G15	-0.1	0.3	3.4
E2	G1	0.1	0	3.6	E7	G1	0.1	-0.2	1.6	E17	G9	0.2	0.4	2.9	E18	G3	0.1	0.1	3.3
E9	G5	0	0.9	3.6	E24	G9	0.2	-0.1	1.6	E4	G9	0.2	0.6	2.1	E18	G8	0.1	0	3.2
E11	G4	-0.1	-0.1	3.4	E12	G9	0.2	0.1	1.5	E17	G8	0.1	-0.4	2	E23	G3	0.1	0.9	3.2
E21	G4	-0.1	-0.2	3.3	E12	G7	0	0.3	1.5	E8	G4	-0.1	0.3	1.7	E1	G8	0.1	-0.3	3.2
E15	G3	0.1	0.9	3.2	E24	G1	0.1	-0.1	1.4	E2	G8	0.1	0.2	1.7	E24	G16	0	0.5	3.1
E10	G3	0.1	0.5	3.2	E12	G13	0.1	0.1	1.4	E8	G3	0.1	0	1.6	E23	G9	0.2	0.7	3.1
E9	G8	0.1	0.3	3.1	E12	G3	0.1	-0.1	1.3	E8	G8	0.1	0	1.6	E18	G16	0	0.1	3.1
E18	G1	0.1	-0.6	3	E24	G5	0	-0.3	1.2	E2	G9	0.2	0.1	1.6	E18	G1	0.1	-0.1	3.1
E10	G8	0.1	0.2	2.9	E10	G5	0	-1.5	1.2	E8	G5	0	0	1.6	E24	G3	0.1	0.2	3
E11	G6	-0.1	-0.5	2.9	E15	G10	-0.2	-1	1.1	E4	G3	0.1	-0.1	1.4	E24	G1	0.1	0.3	3
E11	G1	0.1	-0.7	2.9	E12	G14	-0.2	-0.1	1	E2	G5	0	0	1.3	E18	G9	0.2	-0.3	3
E21	G14	-0.2	-0.6	2.8	E24	G4	-0.1	-0.4	1	E2	G1	0.1	0	1.3	E24	G8	0.1	0.1	2.9
E15	G8	0.1	0.5	2.8	E12	G6	-0.1	-0.4	0.8	E2	G3	0.1	-0.4	1	E17	G1	0.1	0.8	2.7
E9	G9	0.2	-0.1	2.8	E12	G4	-0.1	-0.4	0.7	E4	G8	0.1	-0.5	1	E18	G17	-0.1	-0.4	2.6
E9	G14	-0.2	0.2	2.7	E12	G5	0	-0.6	0.6	E8	G2	-0.3	-0.2	1	E15	G9	0.2	0.2	2.2
E15	G9	0.2	0.2	2.7	-	-	-	-	-	-	-	-	-	-	E23	G15	-0.1	-0.1	2
E15	G1	0.1	0.3	2.7	-	-	-	-	-	-	-	-	-	-	E15	G8	0.1	0	1.9
E21	G9	0.2	-1.2	2.6	-	-	-	-	-	-	-	-	-	-	E23	G8	0.1	-0.4	1.9
E10	G1	0.1	-0.1	2.6	-	-	-	-	-	-	-	-	-	-	E24	G15	-0.1	-0.7	1.8
E10	G13	0.1	-0.1	2.6	-	-	-	-	-	-	-	-	-	-	E17	G3	0.1	-0.1	1.8
E10	G4	-0.1	0	2.5	-	-	-	-	-	-	-	-	-	-	E23	G16	0	-0.4	1.8
E9	G13	0.1	-0.4	2.4	-	-	-	-	-	-	-	-	-	-	E17	G8	0.1	-0.2	1.7
E15	G6	-0.1	0.1	2.3	-	-	-	-	-	-	-	-	-	-	E15	G3	0.1	-0.2	1.7
E18	G14	-0.2	-1	2.3	-	-	-	-	-	-	-	-	-	-	E17	G9	0.2	-0.5	1.5
E24	G8	0.1	0.6	2.2	-	-	-	-	-	-	-	-	-	-	E24	G17	-0.1	-1.1	1.5
E15	G13	0.1	-0.2	2.1	-	-	-	-	-	-	-	-	-	-	E23	G17	-0.1	-0.7	1.4

g: predicted value for the i-th genotype ($BLUP_g$); ge: predicted value for the interaction of the i-th genotype with the j-th environment ($BLUP$); E1: Arapoti/PR; E2: Augusto Pestana/RS; E3: Bela Vista do Norte/PY; E4: Cachoeira do Sul/RS; E5: Capinzal/SC; E6: Diamante D'Oeste/PR; E7: Dourados/MS; E8: Entre Rios do Oeste/PR; E9: Faxinal dos Guedes/SC; E10: General Câmara/RS; E11: Jaboticabal/SP; E12: Laguna/MS; E13: Major Vieira/SC; E14: Mangueirinha/PR; E15: Maracaju/MS; E16: Palmital/SP; E17: Palotina/PR; E18: Passo Fundo/RS; E19: Rio Verde/GO; E20: Salto do Lontra/PR; E21: São Francisco de Paula/RS; E22: Tiradentes do Sul/RS; E23: Toledo/PR; E24: Três Passos/RS; G1: BRS284; G2: BRS391; G3: BRS511; G4: BRS523; G5: BRS525; G6: BRS531; G7: BRS537; G8: BRS539; G9: BRS546; G10: BRS573; G11: BRS6013; G12: BRSMG534; G13: DF 2353; G14: GE; G15: IDRBASALTO; G16: IDRPETROVITA; G17: IDRPÉVERMELHO; G18: IPR110; G19: IPR115; G20: IPR122; G21: LIN16; G22: SOYPLENASG7401.

In the 2023/2024 growing season, Augusto Pestana/RS provided the best performance, especially for IDRPÉVERMELHO, BRS511, and BRS525 (Table 3). However, these same genotypes showed significant drops in other environments, where IDRPÉVERMELHO reduced GY from 6.1 t ha^{-1} to 1.5 t ha^{-1} in Três Passos/RS, and G3 from 5.9 t ha^{-1} (Augusto Pestana/RS)

to 1.7 and 1.8 t ha^{-1} in Maracaju/MS and Palotina/PR, respectively. This fluctuation reinforces the magnitude of the G×E interaction, with few genotypes maintaining consistent performance across environments.

The BRSMG534 genotype showed the best overall performance for mean GY considering all environments, exceeding 5 t ha^{-1} (Fig. 2a). Next, the SOYPLENASG7401 and BRS6013 genotypes stood out, with 4.34 and 4.28 t ha^{-1}, respectively. BRS531 and BRS573 were the least productive, with 1.94 and 2.28 t ha^{-1}, suggesting poor adaptation to the organic system. The study by Casarotto et al. (2025), also conducted in an organic system, identified the LIN 16, BRS 539, and IPR 115 genotypes as those with the highest GY values, while BRS 531 and BRS 573 also showed inferior performance, as reported in our study.

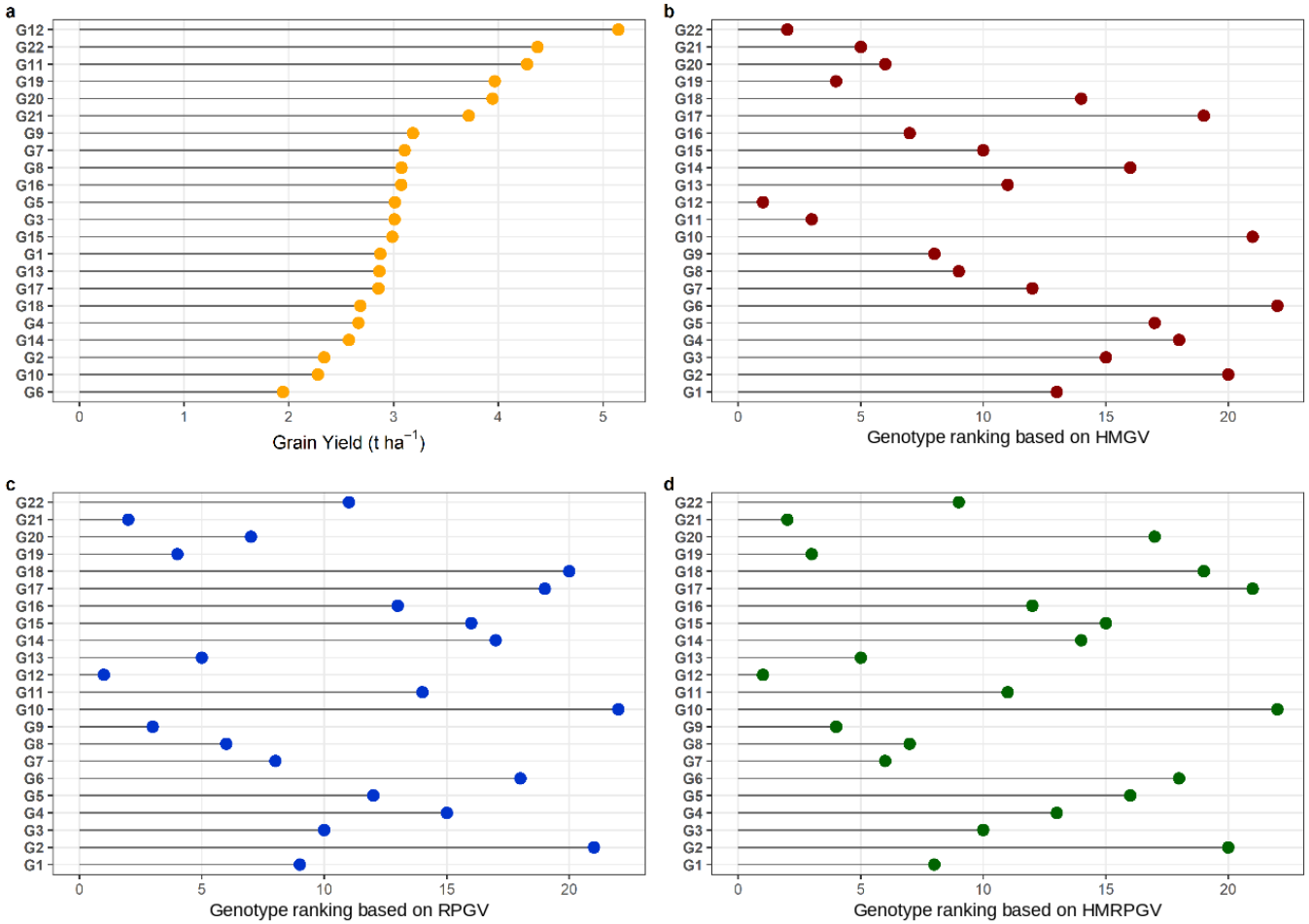


Fig. 2. Overall mean values of grain yield (a) and genotype ranking based on the harmonic mean of genotypic values (HMGV; b), relative performance of genotypic values (RPGV; c) and harmonic mean of the relative performance of genotypic values (HMRPGV; d), in which rank 1 indicates the best-performing genotype, for 22 soybean genotypes evaluated in 24 environments, conducted in an organic farming system. G1: BRS284; G2: BRS391; G3: BRS511; G4: BRS523; G5: BRS525; G6: BRS531; G7: BRS537; G8: BRS539; G9: BRS546; G10: BRS573; G11: BRS6013; G12: BRSMG534; G13: DF 2353; G14: GE; G15: IDRBASALTO; G16: IDRPETROVITA; G17: IDRPÉVERMELHO; G18: IPR110; G19: IPR115; G20: IPR122; G21: LIN16; G22: SOYPLENASG7401.

Adaptability and stability indices were evaluated by ranking the genotypes based on the obtained values. Thus, it was observed that the genotypes BRSMG534, SOYPLENASG7401, and BRS6013 demonstrated high stability, with HMGV values of 5.05 and 4.38 t ha^{-1}, respectively, while BRS531 and BRS573 were less stable, with HMGV of 1.94 and 2.28 t ha^{-1} (Fig. 2b). These values are weighted by the genotype's stability in the different environments. From the point of view of adaptability only (RPGV), which indicates the relative performance of genotypic values in relation to the environmental mean, BRSMG534, LIN16, BRS546, and IPR115 stood out, with respective RPGVs of 1.15, 1.13, 1.13, and 1.09 (Fig. 2c).

It can be inferred that these were the genotypes with the best response to environmental variations. In contrast, BRS573, BRS391, and IPR110 showed low adaptability (0.66, 0.78, and 0.79, respectively). Values greater than 1 indicate performance above the overall mean, while values below 1 show performance below the overall mean and low adaptability (Colombari Filho et al., 2013).

The harmonic mean of relative genotypic performance (HMRPGV) identifies genotypes with high genetic value, high stability, and good adaptability, simultaneously penalizing variations between environments (Fig. 2d). The BRSMG534 genotype again showed superiority, with an expected mean performance of 3.42 t ha^{-1}. LIN16 and IPR115 also stood out, with 3.27 and 3.21 t ha^{-1}, respectively, while BRS573, IDRPÉVERMELHO, and BRS391 obtained the worst performance in the organic system. For these genotypes, a mean performance of only 1.79, 2.17, and 2.23 t ha^{-1}, respectively, is expected.

The results show that only a limited set of genotypes combines high yield, stability, and good adaptability to the organic system, with BRSMG534 consistently standing out. This pattern is consistent with recent results by Pradebon et al. (2023), who demonstrated that the selection of genotypes adapted to the organic system depends on characteristics associated with physiological robustness, such as vigorous initial growth, efficient architecture, and good competitive ability. Similarly, Mushoriwa et al. (2022) and Gayosso Barragán et al. (2025) show that low-input environments intensify the G×E interaction, favoring genotypes with greater phenotypic plasticity and productive stability. Furthermore, the dependence on biological nitrogen fixation in the organic system reinforces the importance of genotypes with high nodulation efficiency and a positive response to inoculation (Borja Reis et al., 2022). In this context, the poor performance of BRS531, BRS573, and BRS391 can be attributed to low physiological robustness and reduced resource utilization efficiency under organic system conditions.

Materials and methods

Plant material, experimental design and environments

The study was conducted with soybean genotypes in an organic farming system (i.e., without the addition of synthetic molecules) over five growing seasons (2019/2020, 2020/2021, 2021/2022, 2022/2023, and 2023/2024). The experimental design used was a randomized block design organized in an incomplete factorial scheme with four replications, comprising 24 environments and 22 conventional genotypes (Table 4). The geographic distribution of the experimental environments is shown in Fig. 3.

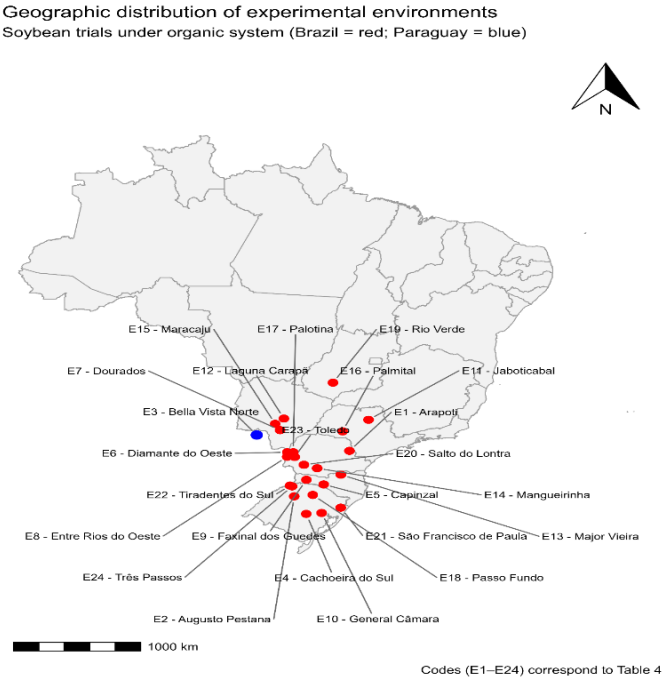


Fig. 3. Geographic distribution of experimental environments. Soybean trials under organic system (Brazil = red; Paraguay = blue). Codes (E1–E24) correspond to Table 4.

Table 4. Code and name of the 24 environments and 22 genotypes used in the study.

Code	Environment	Code	Genotype
E1	Arapoti/PR	G1	BRS284
E2	Augusto Pestana/RS	G2	BRS391
E3	Bela Vista do Norte/PY	G3	BRS511
E4	Cachoeira do Sul/RS	G4	BRS523
E5	Capinzal/SC	G5	BRS525
E6	Diamante D'Oeste/PR	G6	BRS531
E7	Dourados/MS	G7	BRS537
E8	Entre Rios do Oeste/PR	G8	BRS539
E9	Faxinal dos Guedes/SC	G9	BRS546
E10	General Câmara/RS	G10	BRS573
E11	Jaboticabal/SP	G11	BRS6013
E12	Laguna/MS	G12	BRSMG534
E13	Major Vieira/SC	G13	DF2353
E14	Mangueirinha/PR	G14	GE
E15	Maracaju/MS	G15	IDRBASALTO

Code	Environment	Code	Genotype
E16	Palmital/SP	G16	IDRPETROVITA
E17	Palotina/PR	G17	IDRPÉVERMELHO
E18	Passo Fundo/RS	G18	IPR110
E19	Rio Verde/GO	G19	IPR115
E20	Salto do Lontra/PR	G20	IPR122
E21	São Francisco de Paula/RS	G21	LIN16
E22	Tiradentes do Sul/RS	G22	SOYPLENASG7401
E23	Toledo/PR		
E24	Três Passos/RS		

Crop management, trait measurement and environmental data

The experimental units were 15 meters long by 6 meters wide, with rows spaced 0.45 meters apart, totaling 90 m^2. Sowing was carried out in the first half of October of the respective growing seasons, with a density of 10 seeds per linear meter. Grain yield (GY, t ha^{-1}) was measured from the harvest of the two central rows of each experimental unit when the plants were at physiological maturity, with grain moisture corrected to 13%. The meteorological variables of mean air temperature (in °C) and rainfall (in mm) were extracted to aid in understanding the results obtained, with the help of the NASA Power platform (Sparks, 2018).

Statistical analysis, genotypic prediction and stability indices

The resulting data matrix was subjected to analysis of the normality of errors and homogeneity of variances using the Shapiro-Wilk and Bartlett tests, respectively. The variance components for the variable GY were obtained from the following model

$$y_{ijk} = \mu + g_i + e_j + (ge)_{ij} + b_{k(j)} + \varepsilon_{ijk},$$

where y_{ijk} is the response variable observed in the k-th block of the i-th genotype in the j-th environment; μ is the general mean; g_i is the effect of the i-th genotype, considered random; e_j is the effect of the j-th environment, considered fixed; $(ge)_{ij}$ is the effect of the interaction between the i-th genotype and the j-th environment, considered random; $b_{k(j)}$ is the effect of the k-th block within the j-th environment; and ε_{ijk} is the random error. Significance was obtained through deviance analysis at a 5% probability level, with the results supported by the test of χ^2.

The system of equations was solved using REML Expectation-Maximization (Henderson, 1975). This procedure allowed the estimation of the following parameters: phenotypic variance ($\sigma^2 p$), heritability in the broad sense (H^2), genotypic mean heritability ($h^2 mg$), coefficient of determination of the interaction G×E ($GEIr^2$), correlation coefficient of the interaction G×E (rge), genotypic coefficient of variation (CV_g), residual coefficient of variation (CV_r), and proportion between CV_g and CV_r (CV_{ratio}).

Predicted values ($\hat{y}_{ij}$) of the i-th genotype in the j-th environment were obtained by adding the BLUPs of the genotypic and genotype × environment interaction effects to the estimated mean of the j-th environment, as follows:

$$\hat{y}_{ij} = \hat{\mu} + \hat{e}_j + \hat{g}_i + (\widehat{ge})_{ij},$$

where $\hat{\mu} + \hat{e}_j$ is the estimated mean of the j-th environment (fixed effect); $\hat{g}_i$ is the BLUP of the genotypic effect of the i-th genotype; and $(\widehat{ge})_{ij}$ is the BLUP of the interaction effect between the i-th genotype and the j-th environment.

Subsequently, BLUP-based indices described by Colombari Filho et al. (2013) were used to select genotypes with performance and stability. The Harmonic Mean of Genotypic Values was calculated with:

$$HMGV = \frac{l}{\sum_{j=1}^{l} \frac{1}{G_{ij}}}$$

The Relative Performance of Genotypic Values was calculated with:

$$RPGV = \frac{1}{l} \sum_{j=1}^{l} \frac{G_{ij}}{M_j}$$

The Harmonic Mean of the Relative Performance of Genotypic Values was calculated with:

$$HMRPGV = \frac{l}{\sum_{j=1}^{l} \frac{1}{G_{ij}/M_j}}$$

where l is the number of test environments for the i-th genotype; G_{ij} is the genotypic value of the i-th genotype in the j-th environment; and M_j is the overall mean for each environment j. For the preparation of statistical analyses, the metan (Olivoto and Lúcio, 2020) and ggplot2 (Wickham, 2016) packages were used in the R software (R Core Team, 2026).

Conclusion

The HMGV, RPGV, and HMRPGV indices proved efficient in identifying genotypes with superior performance and responsiveness to environmental variations and the challenges of the organic farming system.

BRSMG534 showed the highest productivity and stability. SOYPLENASG7401, BRS6013, LIN16, and IPR115 also demonstrated good performance, with high adaptability and stability in different environments.

Author contributions

AA, MAC and LCP were responsible for preparing the field data, designing the experiments and conducting the evaluations.

LAG, IRC and WJAB provided methodological support, assisted with the organization of the experimental design and contributed to the technical interpretation of the data.

PB, MGM and CMB performed the statistical analyses, manuscript formatting, and technical and grammatical review.

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