

Research Article

Probability of risk in the recommendation of wheat cultivars for the northwest region of the state of Rio Grande do Sul

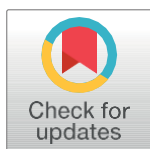
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Abstract

This study aimed to assess the probability of risk in recommending wheat (*Triticum aestivum* L.) cultivars for the northwestern region of Rio Grande do Sul, Brazil, during the 2023 and 2024 growing seasons. The experiments were conducted in two locations, Augusto Pestana and Entre-Ijuís, using a randomized complete block design with three replications in a factorial arrangement of four environments $\times$ thirty-nine cultivars. Agronomic traits, including plant height, ear insertion height, ear length, ear and grain weight, thousand-grain weight, and grain yield, were evaluated. Data were analyzed through the REML/BLUP approach using the *metan* package, and the probabilistic analysis of cultivar performance and risk was performed using the *Probreed* package in R software. Significant genotype $\times$ environment interactions were detected for most traits, particularly for grain yield, which exhibited low heritability ($H^2 = 0.17$) and high environmental influence. Plant height and ear insertion height showed high heritability ($H^2 = 0.40$ and 0.41 , respectively) and strong genotypic correlation between environments ($r_{ge} > 0.70$), indicating stability. Conversely, ear length and yield exhibited greater environmental sensitivity ($r_{ge} < 0.50$). Genotypes G6 (BRS Xiru Capataz), G7 (FPS Certero), G23 (TBIO Blanc), G27 (TBIO Ponteiro), and G33 (TBIO Trunfo) stood out for superior and stable performance across environments. The probabilistic model effectively identified genotypes with lower risk of unstable performance, providing reliable recommendations for regional cultivar positioning. Overall, the results highlight the importance of integrating environmental information and genetic stability analysis to optimize wheat production in southern Brazil.

Keywords: Bayesian inference; multi-environment trials; genetic correlation; risk analysis; adaptability; food security; reducing import dependence.

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Introduction

Wheat (*Triticum aestivum* L.) stands out as one of the most widely consumed cereals globally, followed by rice and corn (Sand et al., 2026). This widespread acceptance is facilitated by its use in cooking, animal feed, and forage, as well as its energy potential through ethanol production. Nutritionally, it is an important energy source due to its high concentration of carbohydrates, proteins, fiber, lipids, terpenoid compounds, vitamins, and minerals (Scheuer, Francisco, Miranda, & Limberger, 2011; Coêlho, 2021). Additionally, other important species have been studied in Brazil (Moraes et al., 2025; Silva et al., 2025; Kroth et al., 2026; Ribeiro et al., 2026; Ruediger et al., 2026).

In Brazil, wheat is of great strategic importance, especially in the context of food security and reducing import dependence. Its cultivation is growing through the exploitation of its adaptability to develop in more severe temperature conditions, specific to the Southeast and Central-West regions of the country. Production is concentrated mainly in the South, encompassing the states of Paraná and Rio Grande do Sul, which account for over 90% of national production. The 2024 wheat harvest in Rio Grande do Sul produced 4.12 million tons, with a planted area of 1,322,167 hectares and an expected mean yield of 3,116 kg/ha, representing a 62% increase compared to 2023 (Companhia Nacional de Abastecimento [CONAB], 2024).

The cultivation of this cereal in Brazil is influenced by the selection of cultivars that exhibit good adaptability and stability, considering the edaphoclimatic diversity across all growing environments. In this context, significant advances have been made through genetic improvement in the correct positioning of new cultivars for each region, contributing to improvements in grain production and quality (Szareski et al., 2021). In recent years, genetic advances in cultivars have led to significant improvements in breadmaking and animal feed characteristics, as well as in the crop's tolerance to biotic factors that could compromise the nutritional and industrial quality of the grains.

Among the producing states, Rio Grande do Sul stands out for its particularly favorable soil and climate conditions for wheat cultivation, such as a humid subtropical climate (Cfa), well-distributed precipitation throughout the year, mean temperatures between 14°C and 25°C, and deep, well-drained soils. Even so, the crop remains vulnerable to climatic stresses, such as frost and excessive precipitation during the ripening period (Feldmann, Vargas, Mühl, Cassol, & Somavilla, 2023). In general, ideal wheat development occurs at mean temperatures between 10°C and 19°C, at altitudes above 700 meters. These characteristics justify the concentration of national production in the states of the Southern Region, where winters have milder temperatures, conducive to the crop cycle (Battisti, Sentelhas, Pilau, & Wollmann, 2013; Santi et al., 2017).

Cultivar trials are essential tools for identifying superior genotypes in terms of productivity, disease tolerance, and regional adaptability, and consequently, their correct positioning. These experiments generate data that support technical recommendations and contribute to the sustainability of wheat farming (Ribeiro et al., 2024). The expansion of wheat cultivation, especially in non-traditional regions, depends on the integration of genetics, management practices, and logistical infrastructure (Soares Sobrinho et al., 2022). The selection of adapted and productive genotypes requires methodological rigor and analysis of the genotype $\times$ environment (G $\times$ E) interaction, which directly influences phenotypic expression in different soil and climate contexts, reducing the likelihood of low cultivar yields (Bornhofen et al., 2018; Dias et al., 2022).

Risk probability analysis applied to cultivar recommendations has gained prominence in modern agriculture, especially given technological advancements and the growing demand for safer, more informed decision-making. This analysis of cultivar performance probability has proven effective in the appropriate positioning of crops such as corn hybrids in Nepal (Basnet, Kunwar, & Upreti, 2025), common bean varieties (Miranda et al., 2024), and white oat cultivars (Roza et al., 2025) in Brazil.

Trials conducted in multiple locations, with controlled variables such as irrigation,

population density, and fertilization, allow for the evaluation of genotype performance under different environments. This approach provides essential information to guide farmers and genetic improvement programs (Silva et al., 2015). In general, wheat productivity and quality are determined by genetic, environmental, and management factors, and integrating these dimensions is essential in research and development programs for more efficient, stable, and nutritious cultivars. Based on these factors, this study aims to assess the risk of recommending the positioning of different wheat genotypes under real-world growing conditions in the northwestern region of the state of Rio Grande do Sul during the 2023 and 2024 growing seasons.

Materials and Methods

The study was carried out in the agricultural years of 2023 and 2024 in two locations in the northwest region of the state of Rio Grande do Sul. Field 1 is located at the Escola Fazenda (Farm School) of the Regional University of Northwest Rio Grande do Sul in the municipality of Augusto Pestana/RS, under coordinates 28° 02' 30" South and 54° 00' 58" West, altitude of 390 meters. Field 2 is located at the Center for Research and Agronomic Results of the Missions (Centro de Pesquisa e Resultados Agronômicos das Missões - CPRAM) in Entre-Ijuís/RS, under coordinates 28°23'17" South and 54°19'13" West, altitude of 213 meters. For both locations, the climate of the region is characterized as humid subtropical Cfa and the soil is classified as typical Dystrophic Red Latosol.

The experimental design used was a randomized complete block design organized in a factorial scheme, with cultivation environments (4) x wheat cultivars (39 - Table 1), arranged in three replicates. The environments were the following: E1: agricultural year 2023 in the Augusto Pestana/RS field; E2: agricultural year 2023 in the Entre-Ijuís/RS field; E3: agricultural year 2024 in the Augusto Pestana/RS field; and E4: agricultural year 2024 in the Entre-Ijuís/RS field. The experimental units were composed of 17 rows, spaced 0.17 meters between rows and 15 meters in length. For both environments, sowing was carried out on May 15, the fertilization used was 250 kg ha⁻¹ of the formula 10-20-20 (NPK) and 150 kg ha⁻¹ of urea (45N) at tillering, and the phytosanitary management of fungicides, insecticides and herbicides was carried out preventively, in order to minimize the biotic effects in the experiment.

The variables analyzed at harvest time were: plant height (PH, centimeters), ear insertion height (EIH, centimeters), ear length (EL, centimeters), ear weight (EW, grams), ear grain weight (EGW, grams) and number of grains per ear (NGE, units), thousand-grain weight (TGW, grams) and grain yield (GY, kg ha⁻¹). The data obtained were subjected to analysis of variance assumptions, such as homogeneity of residual variances using the Bartlett test and normality of errors using the *Shapiro-Wilk* test. Subsequently, descriptive analysis was used to describe the behavior of the meteorological variables and understand the results obtained. Meteorological information for minimum temperature (Tmin, °C), maximum temperature (Tmax, °C), mean temperature (Tmed, °C), and precipitation (mm) were obtained from NASA POWER database (National Aeronautics and Space Administration [NASA], 2025).

The Restricted Maximum Likelihood (REML) method was applied to estimate the variance components and genetic parameters, with significance based on deviance analysis at 5% probability using the chi-squared (χ^2) test. The significant model allowed estimating the following parameters: phenotypic variance (PV); broad-sense heritability (H^2); coefficient of determination of the genotype x environment interaction ($GEI r^2$); heritability of the genotype mean (H^2_{mg}); selection accuracy (Acc); genotype x environment correlation coefficient (rge); genetic coefficient of variation (CVg); residual coefficient of variation (CVr); and relative coefficient of variation ($CVratio$). Using these parameters, the Best Linear Unbiased Predictor (BLUP) was extracted for each variable analyzed in the progenies. The *REML/BLUP* procedure was performed using the *metan* package (Olivoto & Lúcio, 2020).

For the probabilistic approach to the data, the distribution of the effects of each variance

component, the lower and upper highest posterior density (HPD) intervals per genotype, the general, marginal, and conditional probability, and the performance and stability of the genotypes for grain yield were estimated using the *Probreed* package (Chaves, Krause, Dias, Garcia, & Dias, 2024). All analyses were performed using R software (R Core Team, 2025).

Table 1. Description of wheat cultivars grown in environments E1, E2, E3 and E4, in the northwest region of the state of Rio Grande do Sul.

Cultivars	Breeder	Cycle	Class
Bar 10 (G1)	Biotrigo/GDM	Very early	Bread/Improver
Bar 20 (G2)	Biotrigo/GDM	Early	Improver
Brs Reponte (G3)	Embrapa	Early	Domestic/Bread
Brs Belajóia (G4)	Embrapa	Early	Domestic
Brs Tr271 (G5)	Embrapa	Early	Bread
BrsTr874XiruCapataz (G6)	Embrapa/XiruAgrogenética	Médio	Bread
Fps Certero (G7)	Biotrigo Genética	Medium	Bread
Fps Luminus (G8)	Biotrigo Genética	Early	Bread
Fps Regente (G9)	Biotrigo Genética	Early	Improver
Fps Xerife (G10)	Biotrigo Genética	Medium	Improver
Ors Absoluto (G11)	Or Sementes	Medium/Early	Bread
Ors Feroz (G12)	Or Sementes	Early	Improver
Ors Guardiã (G13)	Or Sementes	Medium/Early	Bread
Ors Premium (G14)	Or Sementes	Medium/Early	Improver
Ors Selvagem (G15)	Or Sementes	Late	Improver
Ors Senna (G16)	Or Sementes	Very early	Improver
Ors Soberano (G17)	Or Sementes	Medium	Improver
Ors Turbo (G18)	Or Sementes	Very early	Bread
Tsz Vencitore (G19)	Semevinea	Early	Bread
Ors Falcão (G21)	Or Sementes	Very early	Improver
Ors Gladiador (G22)	Or Sementes	Medium/Late	Bread
Tbio Blanc (G23)	Biotrigo/GDM	Medium/Late	Bread/Improver/White
Tbio Calibre (G24)	Biotrigo/GDM	Very early	Bread/Improver
Tbio Motriz (G20)(G25)	Biotrigo/GDM	Medium/Late	Bread/Improver
Tbio Noble (G26)	Biotrigo/GDM	Medium/ Early	Improver/White
Tbio Ponteiro (G27)	Biotrigo/GDM	Late	Bread
Tbio Astro (G28)	Biotrigo/GDM	Very early	Improver
Tbio Audaz (G29)	Biotrigo/GDM	Early	Improver
Tbio Capaz (G30)	Biotrigo/GDM	Very early	Bread/White
Tbio Talismã (G31)	Biotrigo/GDM	Early	Improver
Tbio Titan (G32)	Biotrigo/GDM	Medium	Bread/Improver
Tbio Trunfo (G33)	Biotrigo/GDM	Early	Bread
Tsz Chiaro (G34)	Semevinea	Early	Bread
Tsz Dominare (G35)	Semevinea	Early	Bread
Xbio Fusão (G36)	Biotrigo/GDM	Early	Improver
Ors Agile (G37)	Or Sementes	Very early	Bread/Improver
Ors MadrePérola (G38)	Or Sementes	Medium/Early	Bread
Tbio Toruk (G39)	Biotrigo/GDM	Medium	Bread/Improver

Results and Discussion

When analyzing the climatic conditions of the environments during the study (Figure 1), a uniform distribution of precipitation was observed throughout the crop cycle, with lower volumes in 2024 for Entre-Ijuís and Augusto Pestana. On the other hand, in 2023,

for both environments, little precipitation was observed, with volumes below 30 millimeters up to 50 days after sowing. These conditions result in low efficiency of nutrient use, especially nitrogen, for which the presence of moisture in the soil is necessary for its absorption, reducing its volatilization (Arenhardt et al., 2015; Yokamo et al., 2023).

Still regarding precipitation, the two environments in 2023 presented high volumes and frequencies of rainfall during the flowering periods of the plants, favoring the occurrence of diseases such as head blight and blast on the ears (Singh, Chhabra, Raza, Yang, & Sandhu, 2023), and also on the filling and maturation of the grains, impacting their weight and quality (Jolánkai & Birkás, 2013).

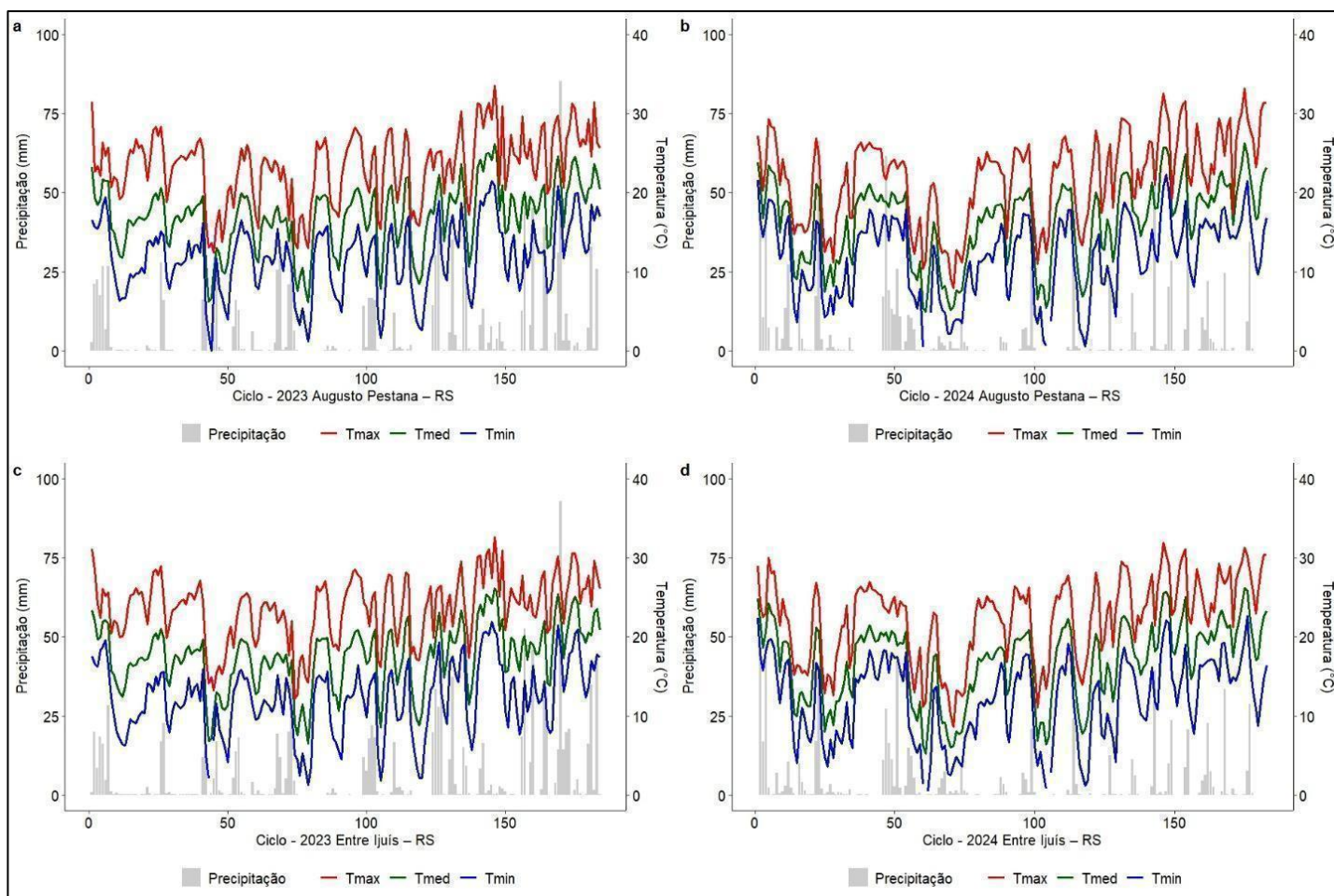


Figure 1. Performance of precipitation (mm), maximum temperature (Tmax, °C), mean temperature (Tmed, °C) and minimum temperature (Tmin °C) of the air during the crop cycle in the study environments. A) Augusto Pestana- 2023; B) Augusto Pestana- 2024; C) Entre- Ijuís- 2023; D) Entre- Ijuís- 2024.

Maximum temperatures were higher in 2023, specifically for Augusto Pestana, followed by Entre-Ijuís, with greater frequency throughout the crop cycle, compared to 2024. During the initial development phase, especially seed germination, wheat performs best at temperatures between 12°C and 25°C. During the grain filling stage, considered critical for yield, the ideal range is between 25°C and 28°C. Temperatures above these limits can accelerate the plant's phenological cycle, resulting in early flowering and shortening the grain filling period, which culminates in productivity losses (McMaster & Wilhelm, 2003; Ribeiro, Pimente, Souza, Rocha, & Fonseca, 2012).

Low minimum temperatures, close to zero degrees Celsius, were observed in 2024 for both environments, especially in Augusto Pestana, favoring the formation of frosts. When these occur during the tillering stages, they do not affect the development of wheat

plants (Silva, Cunha, Pires, Dalmago, & Pasinato, 2008). However, frost formation during the booting and earing stages compromises grain formation, compromising grain yield (Donato et al., 2024).

The restricted maximum likelihood test determined a significant effect of the cultivars for PH and EIH (Table 2), characteristics that are specific to each cultivar, and significance in the interaction between genotype and environment for the variables PH, EIH, EL, EW, NGE, TGW and GY. Based on the genetic parameters obtained, a high environmental effect was observed on the variables EL, EW, NGE, TGW and GY, which presented low genetic effect values ($H^2 < 30$) of 0.20, 0.27, 0.26, 0.04 and 0.17, respectively.

Considering the search for more assertive positioning of cultivars, it is of interest to obtain genotypes that present greater stability in their morphological and productive performance between environments (Szareski et al., 2021), shown by the genotypic correlation value of genotype performance between environments ($rge > 70.0$). Thus, the variables PH and EIH demonstrated high correlation values, 0.71 and 0.78, respectively. In contrast, low correlations were observed for EL (0.47) and GY (0.45), indicating greater discretion in the positioning of genotypes in multi-environments and in the adequacy of crop management for the expression of these traits (Rosado et al., 2012).

Table 2. Estimates of variance components and genetic parameters for the variables plant height (PH, cm), ear insertion height (EIH, cm), ear length (EL, cm), ear weight (EW, gr), number of grains per ear (NGE, un), thousand-grain weight (TGW, gr) and grain yield (GY kg ha⁻¹) for wheat cultivars grown in the northwest of Rio Grande do Sul state.

Parameters	PH	EIH	EL	EW	NGE	TGW	GY	
σ^2P^1	41.11	34.12	0.65	0.04	20.02	30.35	510244.4	
H ²	0.40	0.41	0.20	0.27	0.26	0.04	0.17	
GEIr ²	0.42	0.46	0.37	0.44	0.40	0.57	0.37	
H ² mg	0.77	0.77	0.62	0.68	0.69	0.22	0.58	
Acc	0.88	0.88	0.79	0.82	0.83	0.47	0.76	
Rge	0.71	0.78	0.47	0.59	0.54	0.60	0.45	
CVg	6.03	6.16	4.99	9.99	9.75	4.12	9.55	
CVr	3.86	3.43	7.30	10.56	11.03	11.40	15.41	
CVratio	1.56	1.79	0.68	0.95	0.88	0.36	0.61	
Deviance								
Pr(>Chisq)	GEN	0,011*	0,014*	0,078	0,107	0,099	0,712	0,174
	GEN:ENV	0,000*	0,000*	0,000*	0,000*	0,000*	0,000*	0,000*

¹ σ^2P : phenotypic variance; H^2 : heritability; $GEIr^2$: coefficient of determination of genotype-environment interaction; H^2mg : heritability of the genotype mean; Acc: selection accuracy; rge : genotype-environment correlation coefficient; CVg: genetic coefficient of variation; CVr: residual coefficient of variation; CVratio: relative coefficient of variation; *: significant at 5% by the χ^2 test.

The genetic parameters obtained are reliable, demonstrating experimental precision and positive selection of superior genotypes through accuracy values (Acc), demonstrating high (Acc > 70.0) for PH, EIH, EL, EW, NGE and GY. In contrast, the residual coefficient of variation (CVr), which measures the experimental pattern, was high for EW (10.56), NGE (11.03), TGW (11.40) and GY (15.41), demonstrating that these traits, although genetically promising, are also sensitive to environmental factors.

The genetic coefficient of variation (CVg) was higher than the residual (CVr) for PH and EIH, indicating high relative genetic variability for these traits. In contrast, the residual coefficient of variation (CVr), which measures the experimental pattern, was also high for grain yield (15.41) and ear weight (10.56), demonstrating a high environmental effect on the variables (Resende et al., 2007).

For the selected traits, the overall mean performance value of the genotypes was extracted, stratified by the four growing environments (BLUP), when they presented significance for the

variable. Significant variations in the performance of the plant height variable (Figure 2) between environments were expressed, reflecting the strong influence of the genotype $\times$ environment (G $\times$ E) interaction. In the 2023 harvest, most genotypes grown in Entre-Ijuís showed below-mean performance (67 cm). However, in the 2024 agricultural year, both in Augusto Pestana and Entre-Ijuís, superior genotype performance was observed for plant height.

Genotypes G6, G7, G23, G27, and G33 were superior for plant height in both 2024 environments, with measurements above 75 cm. In the 2023 environment, only genotype G3 showed superiority for this variable, above 70 cm. Larger wheat plants have greater accumulation of photoassimilates throughout the cycle, providing greater grain weight and consequently higher productivity, but at the same time, they are more prone to lodging (Zhang et al., 2017).

In contrast, genotypes G22, G21, and G25 showed plant heights lower than 60 cm in both years in Entre-Ijuís. Genotype G22 also showed shorter plants in the Augusto Pestana 2024 environment. Plant height performance of wheat cultivars can be influenced by heat and water stress, nitrogen fertilization management, and the use of growth regulators and herbicides on the crop (Costa, Vilela, Sousa, Paz, & Moura, 2018; Gazola et al., 2024).

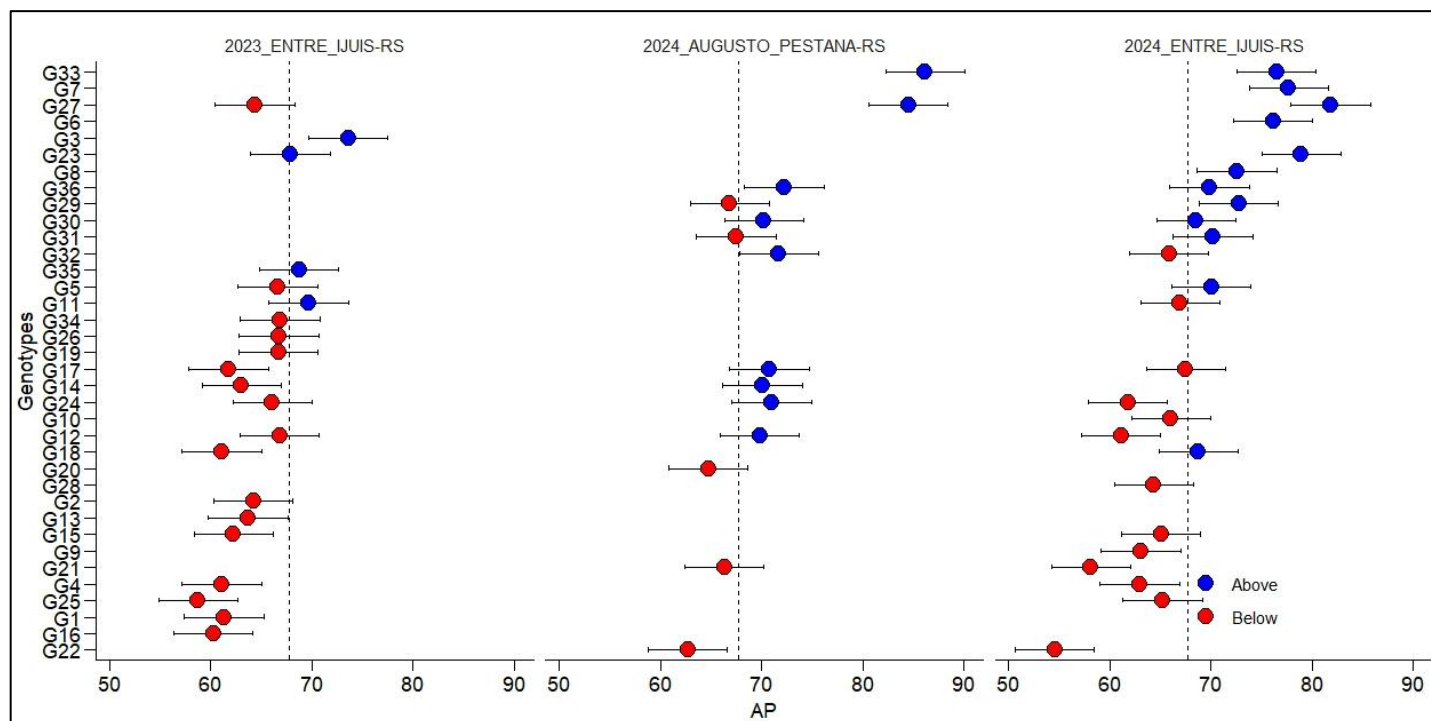


Figure 2. Prediction of the overall mean value of genotype performance (BLUP), stratified by environments for plant height (PH, cm). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

The highest ear insertion heights, above 65 cm, were observed for genotypes G6, G7, G23, G27, and G33 in Entre-Ijuís and Augusto Pestana, in the 2024 harvest, with the mean value of the study being 61 cm. For these environments, the lowest ear insertion heights were expressed by G22, G20, and G25 (Figure 3). This variable is directly correlated with plant height and also depends on ear length (Loro et al., 2021).

A predominance of genotypes with ear insertion height below the mean for the Entre-Ijuís 2023 environment was observed, with emphasis on G25, G16, G4, G1, and G16, which expressed ear insertion heights below 55 cm. Ear insertion height is associated with

resistance to lodging, light interception, and harvesting efficiency, especially mechanized harvesting. Genotypes with adequate ear insertion height tend to present greater stability in environments with high precipitation and intensive fertilizer management (Zhang et al., 2017; Pasa et al., 2024).

Ear length (Figure 4) is a morphoagronomic trait strongly related to the number of spikelets and, consequently, to grain accumulation per ear. It is one of the primary components of wheat yield. In the 2023 harvest, the Augusto Pestana environment showed an above-mean length of 7.2 cm for all genotypes sown there, with G4 standing out, with ear length above 9 cm. In contrast, the 2024 harvest in the Augusto Pestana environment showed below-mean values for most genotypes, with the exception of G27.

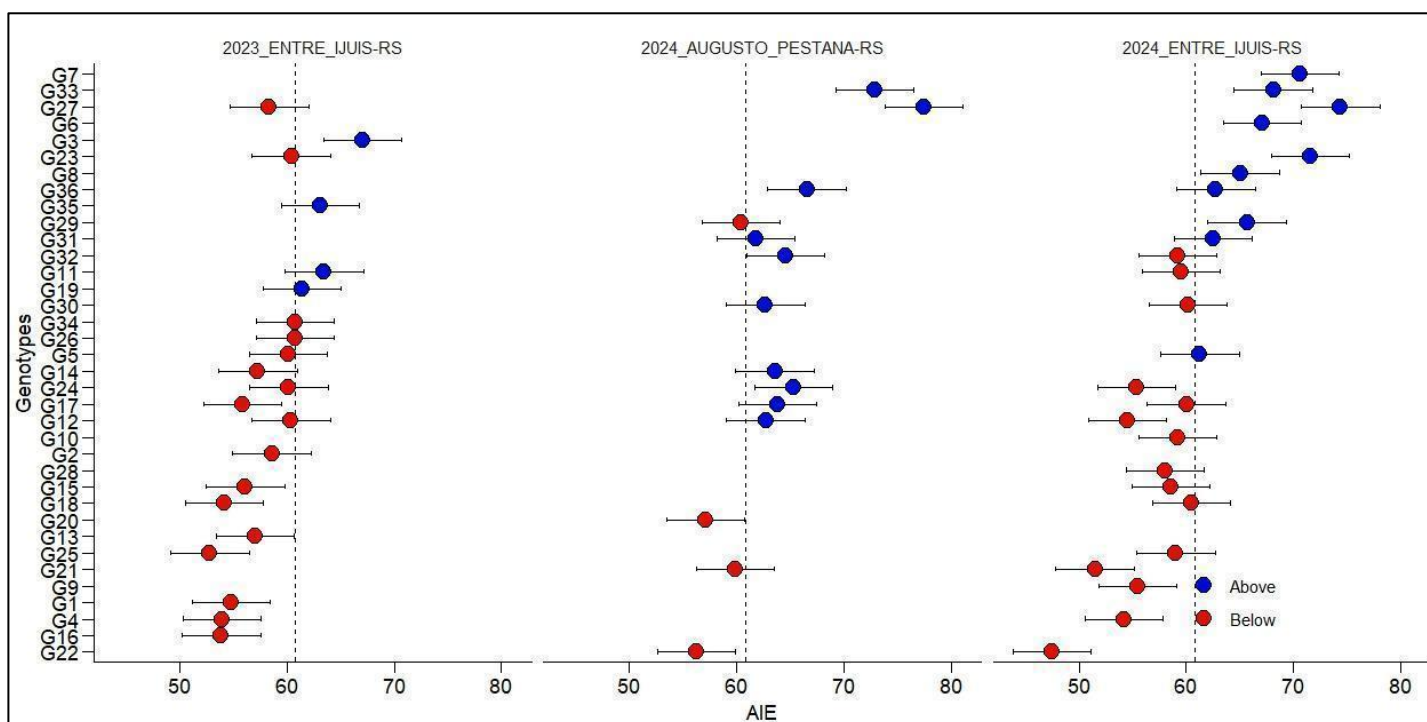


Figure 3. Prediction of the overall mean performance value of the genotypes (BLUP), stratified by environments for ear insertion height (EIH, cm). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

For Entre-Ijuí 2023, most cultivars expressed ear lengths below 7 cm, with G2 showing greater genotypic variability and range in EL values. Genotypes such as G18 (ORS Turbo) and G23 (TBIO Blanc) demonstrated outstanding performance, indicating that the environment was more favorable for trait expression. On the other hand, Entre-Ijuí 2024 showed good overall genotypic performance for the variable, with G18, G30, G33, G4, and G5 expressing lengths greater than 8 cm, and G6 expressing lengths greater than 9 cm. On the other hand, Entre-Ijuí 2024 showed good overall genotypic performance for the variable, with G18, G30, G33, G4, and G5 expressing lengths greater than 8 cm, and G6 expressing lengths greater than 9 cm. Environments with greater selectivity, as pointed out by Teixeira et al. (2022), favor better differentiation between genotypes and provide more robust estimates of adaptability and genetic stability.

For ear weight (Figure 5), the Augusto Pestana 2023 environment showed the highest mean ear weight values, above 1.5g, with emphasis on genotypes G38, G33, and G4, with weights above 2.0g. Similarly, G33 showed superior performance in the Entre-Ijuí 2024

environment, with the highest mean ear weight (1.44g), indicating high responsiveness and stability of this genotype for positioning in different environments. Furthermore, the Entre-Ijuís 2024 environment showed intermediate performance for ear weight, where 60% of the genotypes expressed values above the mean of 1.5g.

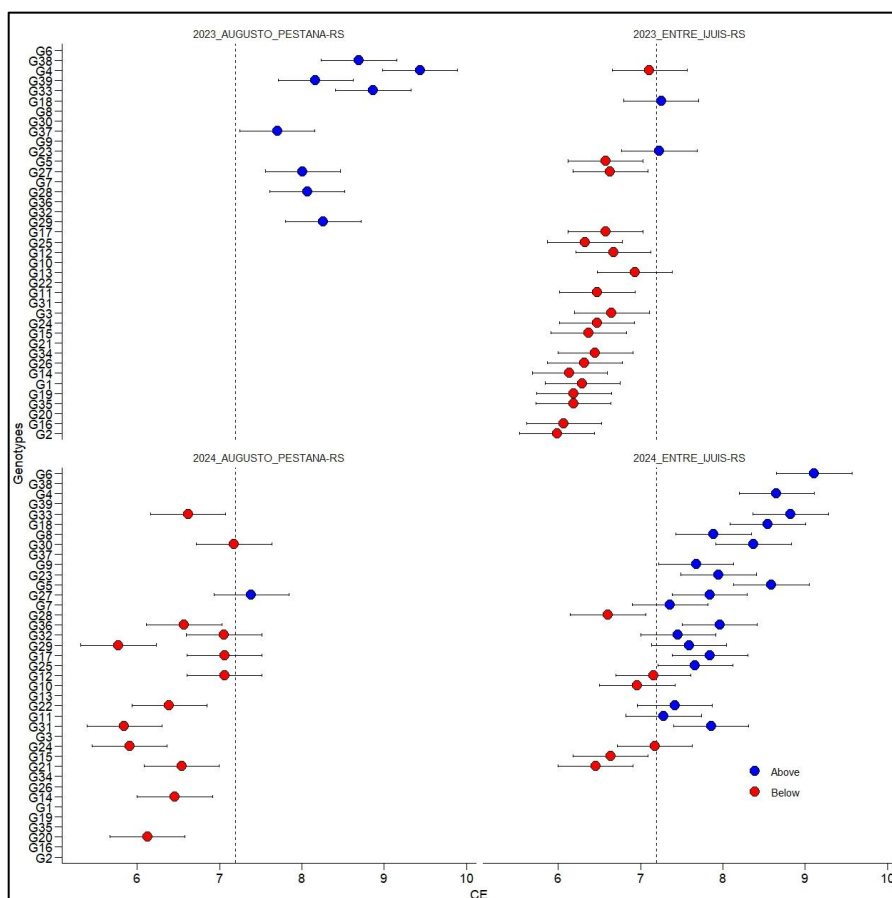


Figure 4. Prediction of the overall mean performance value of the genotypes (BLUP), stratified by environments for ear length (EL, cm). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérula (G38); Tbio Toruk (G39).

On the other hand, in Entre-Ijuís 2023, the performance of the genotypes was substantially lower, with ear weight predominantly between 0.42 and 0.70 g, all below the study mean, with G16 and G17 being lower (0.42 g) and G18 higher (0.70 g) in this environment. This result suggests strong environmental limitations, possibly resulting from biotic and/or abiotic stresses, such as water and nutritional restrictions, or extreme temperatures during critical developmental stages. As pointed out by Singh, Kingra, Pal, and Singh (2024), environments with adverse conditions negatively impact ear biomass, directly affecting grain filling potential and, consequently, final yield. Furthermore, wheat ears exhibit different flowering and grain filling times, resulting in great variability in grain weight within a crop (Baillot, Girousse, Allard, Piquet-Pissaloux, & Le Gouis, 2018).

In the municipality of Entre-Ijuís, in 2023, virtually all genotypes performed below the mean of 30g for thousand-grain weight (Figure 6), with the exception of G13, which

the mean was 30.6g. Genotypes G27 and G23 had the lowest thousand-grain weights, 18.05g and 19.98g, respectively. G27 also showed lower values for the other environments, being characterized by low responsiveness between environments. Thousand-grain weight is one of the most direct components of wheat yield, representing the genotype's ability to accumulate dry matter in the grains during filling, and is influenced by environmental factors, especially in the final phenological stages of the crop (Pérez, Viegas & Castro, 2020).

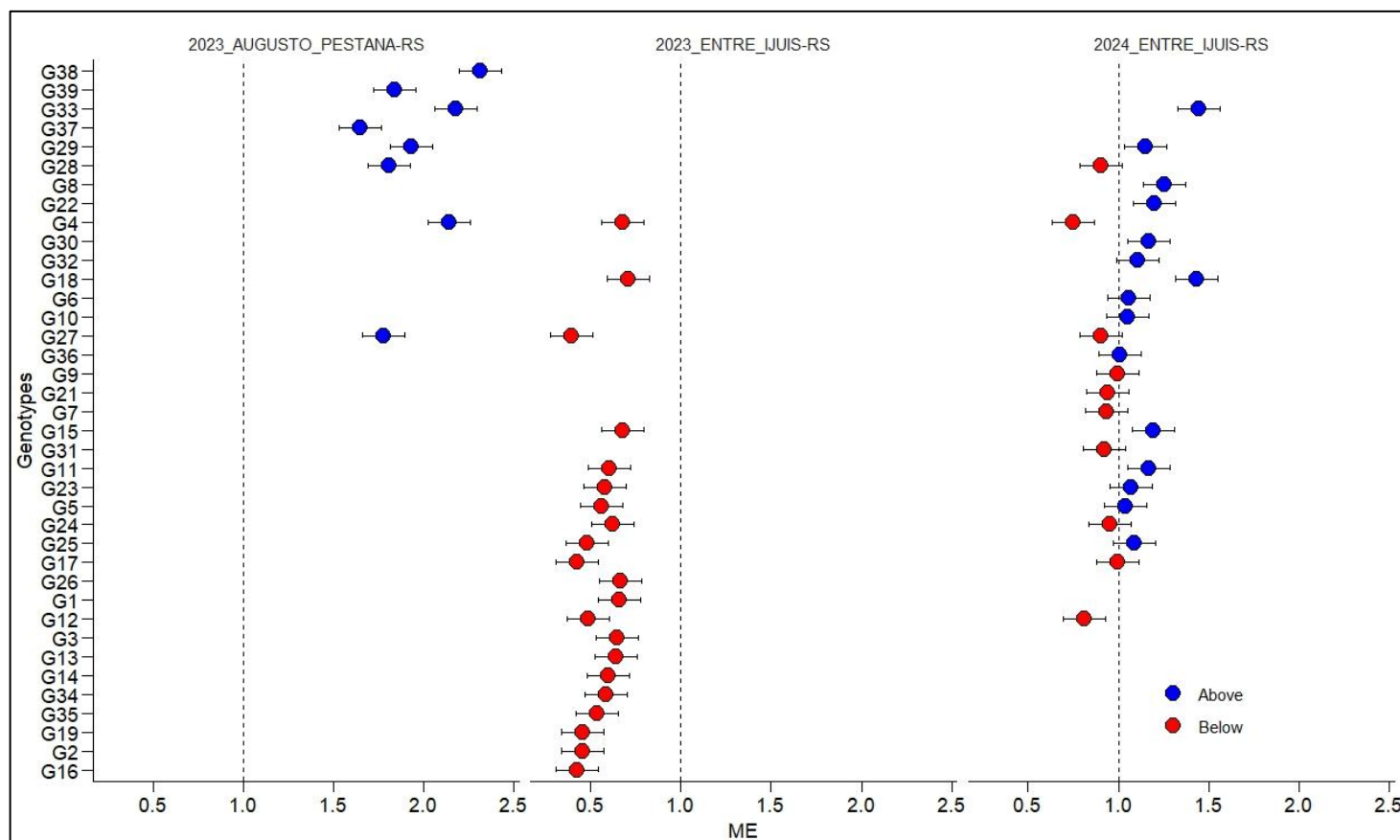


Figure 5. Prediction of the overall mean performance value of the genotypes (BLUP), stratified by environments for ear weight (EW, gr). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

In the Entre-Ijuís 2024 environment, greater variability was obtained among genotypes for thousand-grain weight. Values below 25g were observed for G4, G6, and G5 (17.51, 23.29, and 24.02g, respectively) and above 35g for G18, G8, G33, and G36 (35.29, 36.86, 37.74, and 37.75g, respectively). In contrast, all genotypes in the Augusto Pestana 2024 environment obtained thousand-grain weight above the general mean of 30g, with values above 40g being obtained by G32, G21, G12, G17, G22, and G24. The genotypes G33 and G36 stand out as environmentally responsive for high thousand-grain weight performance.

In pursuit of high grain yields in wheat cultivation, the positioning of genotypes that present high weight and number of grains per ear is an alternative, being merely a decision-making practice for the producer. According to Vesohoski, Marchioro, Franco, and Cantelle (2011) and Bellinaso et al. (2025), these variables have a strong direct correlation with wheat grain yield. The number of grains per ear (Figure 7) was higher

than the mean of 24 grains in the Augusto Pestana 2023 environment, where the genotypes G39, G4, G29, G33, and G38 presented means of 40.78, 41.77, 43.85, 44.91, and 46.63 grains per ear, respectively.

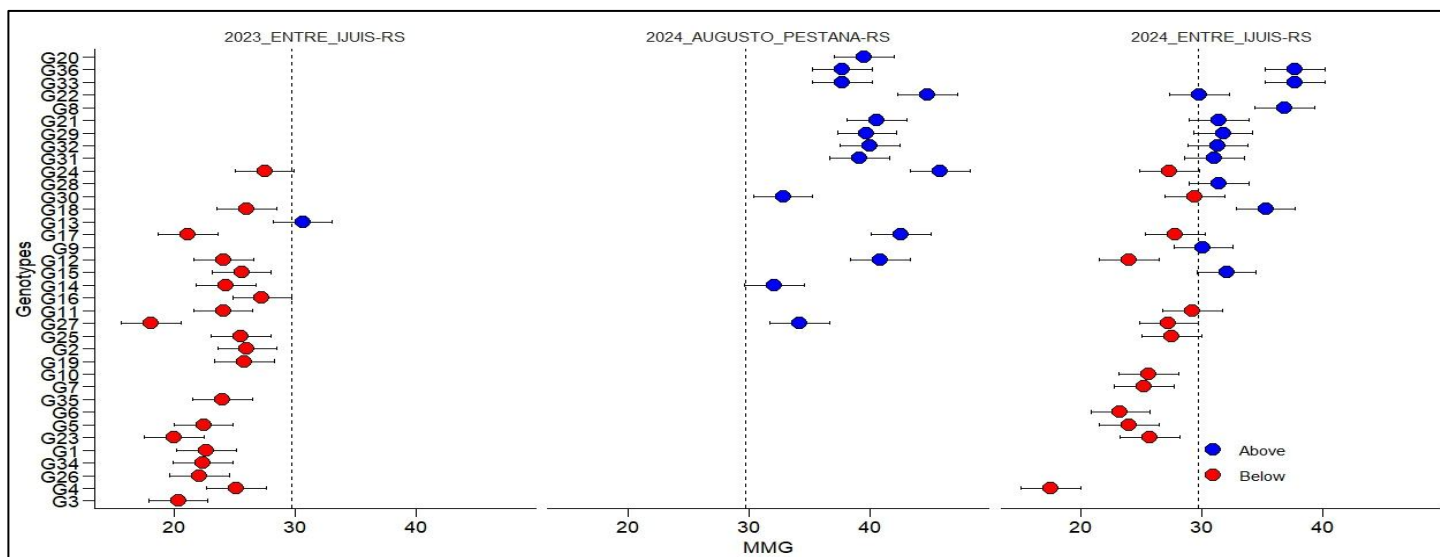


Figure 6. Prediction of the overall mean performance value of the genotypes (BLUP), stratified by environments for thousand-grain weight (TGW, gr). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardião (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

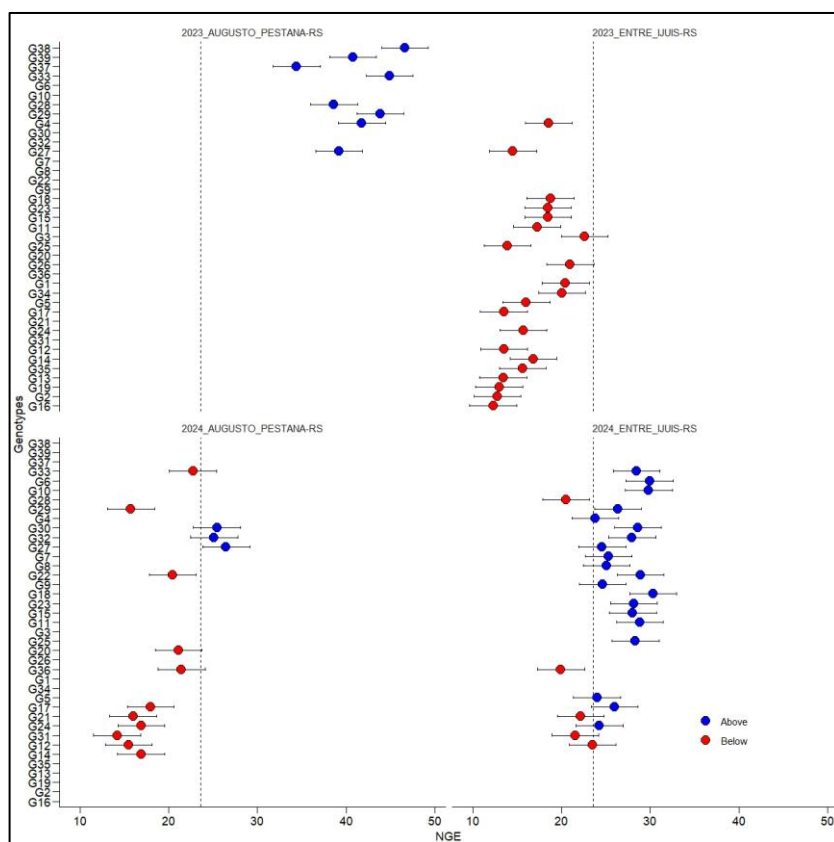


Figure 7. Prediction of the overall mean performance value of the genotypes (BLUP).

stratified by environments for number of grains per ear (NGE, gr). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

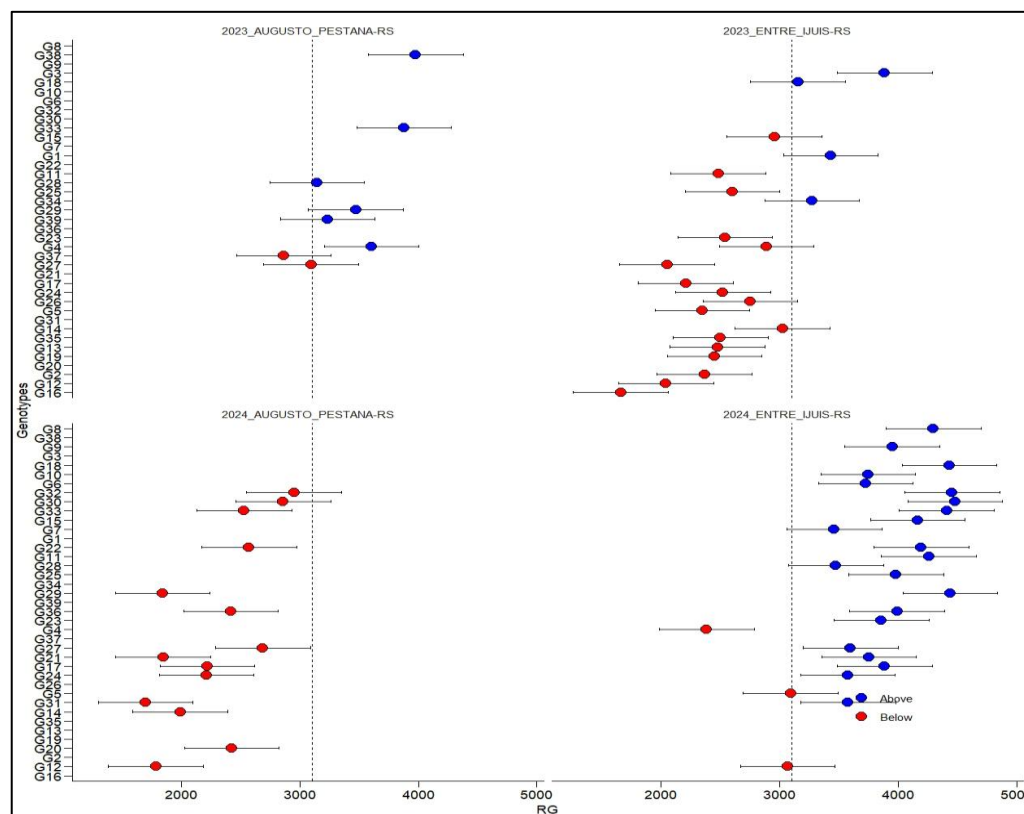


Figure 8. Prediction of the overall mean value of genotype performance (BLUP), stratified by environments for grain yield (GY, kg ha⁻¹). Bar 10 (G1); Bar 20 (G2); Brs Reponte (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

In contrast, Augusto Pestana 2023 and Entre-Ijuís 2024 presented high grain yields, with emphasis on Entre-Ijuís 2024, where 88% of the genotypes resulted in above-mean values, with G11, G15, G18, G22, G29, G30, G32, G33 and G8 being superior, with grain yields above 4,000 kg ha⁻¹. High grain yields in wheat crops are essential to support the high cost of inputs in the face of low cereal prices in Brazil, ensuring economic sustainability for producers (Sobrinho, Cardoso & Tavares, 2022).

Considering the genotype's stability and responsiveness for high grain yield across different years and environments, G33 and G18 stood out, enabling their positioning in multiple environments, regardless of the soil and climate conditions of the site and harvest. On the other hand, G12 and G27 demonstrated inferiority for the variable, requiring greater discretion in their positioning. According to Segatto et al. (2022), genotypes that combine superior performance and stability in the face of environmental

variability are essential to ensure production security in the face of increasing climate uncertainty.

Based on the general *posteriori* analysis, the variance components and probabilistic indicators were estimated for the 39 wheat genotypes evaluated in four different environments (Table 3). A strong environmental effect on grain yield was observed, influencing the genetic performance of the genotypes in their interaction with the environment. The probabilistic analysis indicated a good model fit, with a maximum probability of 0.45 and a minimum of 0.43, resulting in a mean of 0.50.

Table 3. Decomposition of variance effects and probability diagnosis for grain yield (kg ha⁻¹).

Components	Variance	SD ¹	Naive se	HPD_0.05	HPD_0.95
Block	2982.58	4648.10	23.24	13.29	11399.5
Genotype (G)	77062.46	66086.90	330.43	963.56	202845.40
Environment (E)	4905327.01	31650036.76	158250.18	242730.47	14748254.91
<i>G x E</i>	227376.98	69391.87	346.96	127811.51	353521.52
error_env1	15523.80	5116.62	25.58	9184.87	25091.38
error_env2	518022.56	93037.67	465.19	384233.77	684871.99
error_env3	51997.03	12000.55	60.00	35673.85	73974.04
error_env4	192010.17	32526.92	162.64	145223.48	251251.30
Probability diagnosis				Value	
<i>P</i> -val_max				0.45	
<i>P</i> -val_min				0.43	
<i>P</i> -val_median				0.80	
<i>P</i> -val_mean				0.50	
<i>P</i> -val_sd				0.53	
Effective number of parameters				31.72	
WAIC2				4172.11	
mean_Rhat				1.00	
Effective number of sample size				0.83	

¹SD: standard deviation; Naive SE: naive standard error; HPD: lower (HPD_0.05) and upper (HPD_0.95) posterior density intervals; *P*-values: Bayesian test values (maximum, minimum, median, mean, and standard deviation); WAIC: Watanabe–Akaike Information Criterion (WAIC); mean_Rhat: potential scaling reduction factor (*R*).

The standard deviation of the probability was also 0.53, suggesting significant variation in the estimates. Bayesian *p*-values closer to 0.50 indicate greater statistical similarity between the generated and collected data. The effective number of fitted parameters was 31.72, and the Watanabe-Akaike information criterion (WAIC) was 4172.11, which was used as a reference for validating the statistical models employed. Furthermore, the *R* value: 1.00 also indicates a strong similarity between the phenotypic data generated and those collected in the study (Dias et al., 2022; Chaves et al., 2024).

In the Bayesian chain analysis, the two density plots presented in Figure 9 allowed us to interpret the estimated effects based on the grain yield variable. Graph (a) presented a density of the posterior value. Histogram (9-b) represents the genotypic effect (GEN), presenting an approximately normal distribution and centered near zero, with an estimated variation between -1000 and 1000. This configuration indicates that most of the genotypes evaluated presented genetic effects within a moderate range, with no extreme values. This pattern suggests genetic variability among genotypes, but with a predominance of small- to medium-magnitude effects, which may be beneficial for breeding programs focused on selecting materials with consistent performance.

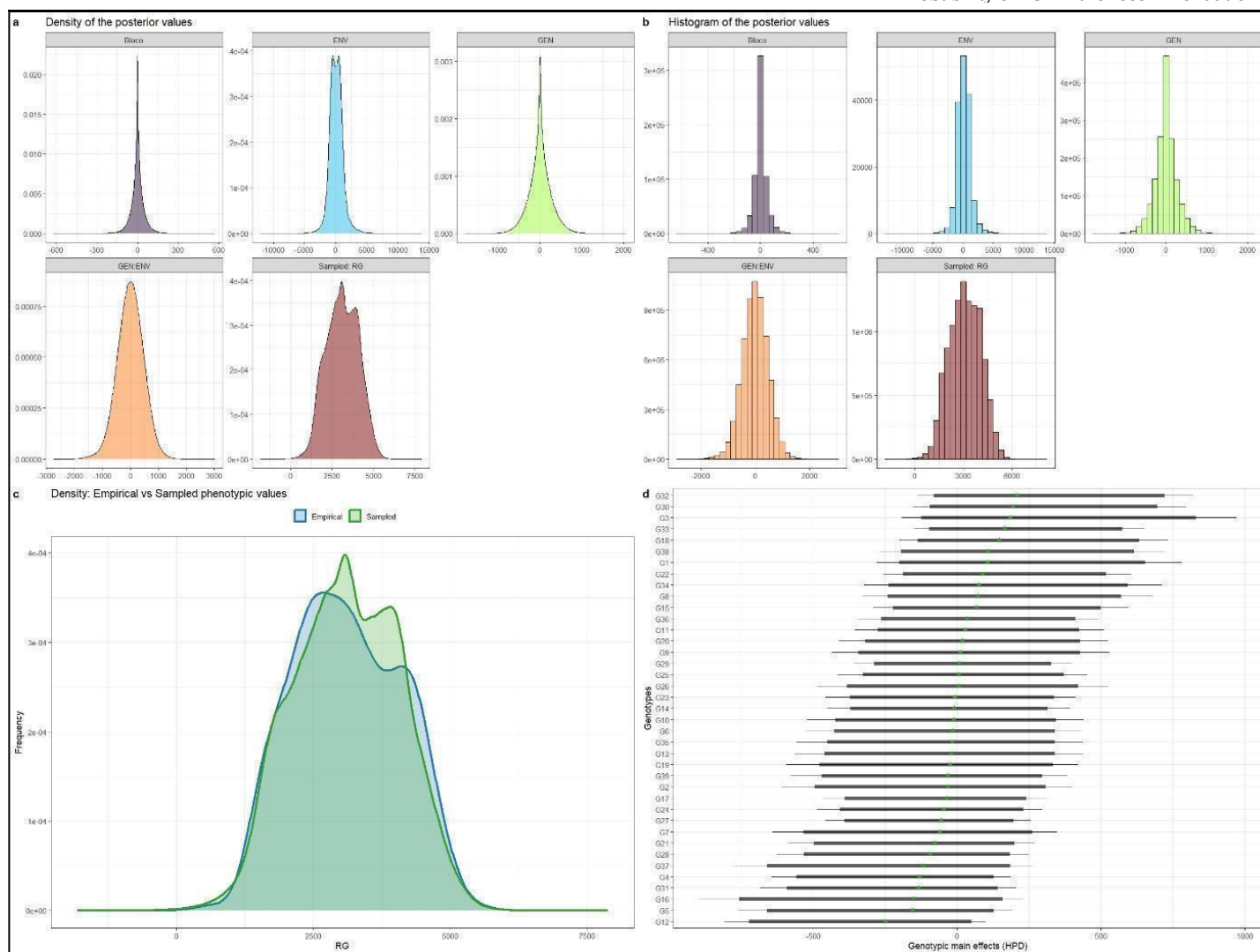


Figure 9. Density plots (a) and histogram (b) of posterior values of density of generated data compared with the distribution of actual data for grain yield (GY, kg ha⁻¹) (c) and main genotypic posterior effects HPD (d). Bar 10 (G1); Bar 20 (G2); Brs Reponete (G3); Brs Belajóia (G4); Brs Tr271 (G5); BrsTr874XiruCapataz (G6); Fps Certero (G7); Fps Luminus (G8); Fps Regente (G9); Fps Xerife (G10); Ors Absoluto (G11); Ors Feroz (G12); Ors Guardiã (G13); Ors Premium (G14); Ors Selvagem (G15); Ors Senna (G16); Ors Soberano (G17); Ors Turbo (G18); Tsz Vencitore (G19); Ors Falcão (G21); Ors Gladiador (G22); Tbio Blanc (G23); Tbio Calibre (G24); Tbio Motriz (G20)(G25); Tbio Noble (G26); Tbio Ponteiro (G27); Tbio Astro (G28); Tbio Audaz (G29); Tbio Capaz (G30); Tbio Talismã (G31); Tbio Titan (G32); Tbio Trunfo (G33); Tsz Chiaro (G34); Tsz Dominare (G35); Xbio Fusão (G36); Ors Agile (G37); Ors MadrePérola (G38); Tbio Toruk (G39).

The identified histogram refers to the environmental effect (ENV), it presents an asymmetric distribution, with values accumulating close to zero, but with a longer tail to the right. This indicates the presence of some environments with strong positive effects, which may be related to more favorable soil and climate conditions or a specific year effect that benefited genotype productivity. This asymmetry may reflect the influence of seasonal and regional factors on plant response, being relevant for interpreting the adaptability of the tested genetic materials.

The genotypic effect (g) also presented values centered or close to zero, indicating equilibrium among the genotypes. The genotype $\times$ environment ($g \times l$) and genotype $\times$ year ($g \times m$) interactions presented distributions with values very close to the zero line, indicating low interaction and, therefore, phenotypic stability of the genotypes in the face of environmental and seasonal variations. Genotypes G32, G30, and G3 presented the highest genetic values, and genotypes G12, G5, and G16 presented the lowest genetic performance (9-d). The symmetry of the distributions and the proximity of the values

around zero further indicate convergence of the Bayesian chains, which ensures statistical robustness to the inferences made.

Thus, the results obtained in this study reinforce the applicability of Bayesian methods in the analysis of genotype $\times$ environment interactions, favoring the identification of promising and stable genetic materials for growing environments. Azevedo et al. (2023) obtained promising responsiveness and adaptability of wheat cultivars when dividing the state of Rio Grande do Sul into four megaenvironments with specific soil and climate conditions. Furthermore, Loro et al., (2021), evaluating wheat cultivars for four consecutive years in the same environment in Rio Grande do Sul, observed that the cultivation year factor contributed most to the phenotypic variation of the cultivars.

Analysis of genotypic effects and their interactions suggest that, although there are genotypes with superior performance, the magnitude of genotype $\times$ environment interactions are not high enough to compromise stability. This is positive for breeding programs aiming to recommend broadly adapted cultivars. Furthermore, Bayesian modeling proves effective, with chain convergence (evidenced by symmetric distributions) and good predictive ability (9-c).

Figure 10 allows us to identify superior and inferior genotypes based on the estimated values and the confidence associated with these estimates. In the search for genotypes that express greater stability, aiming at their positioning in contrasting multi-environments, G30, G36, and G22 stand out as the most stable (10_b). Probabilities of higher performance (10_a) were identified with genotypes G32, G30, and G3, with the first two being presented as highly stable genotypes, along with performance (10_c). It can be observed that the high-performing genotypes G3 and G33 did not achieve good stability, indicating that their positions should be rigorously analyzed based on the soil and climate conditions of the growing environments. This evaluation must be even more rigorous for the use of genotypes G27, G29, G1, G10, G13, G19, G2, G20, G26, G3, G34, G35, G37, G38, G39, G4, G6, G7, G8 and G9, which did not present a probability of performance and stability.

The selection decision should consider both genetic value (g) and precision (HPD range) (10_d). The genotypes that represent the estimated additive genetic effects, indicating the productive potential or performance of each, with the highest positive g values (best genotypes): G18: 145.85, G1: 106.23, G22: 89.23, and G15: 67.74, are promising for selection, as they indicate genetic superiority. The worst genotypes were: G12: -248.56, G16: -151.49, G21: -77.06, and G17: -35.40, presenting below-mean genetic performance and being unfavorable for selection. HPD intervals indicate the uncertainty associated with genetic estimates. Genotypes with narrower intervals suggest greater precision in the estimate, while wide intervals indicate greater uncertainty. Thus, the genotypes with the greatest precision were G10, G14, G13 (range between HPD97.5 and HPD5 close to 60 to 100). The genotypes with the greatest uncertainty were G18 (HPD5: -136.72 to HPD97.5: 733.97) and G1 (from -202.56 to 781.81).

Assessing risks associated with genetic, environmental, and seasonal factors contributes to more accurate selection, aiming to optimize productivity and promote the sustainability of agricultural systems. In this sense, adopting risk analysis methods strengthens agricultural resilience by reducing uncertainties related to cultivar performance and mitigating potential losses. Furthermore, it enables more efficient use of available resources, a strategic aspect for the sustainable development of Brazilian agriculture.

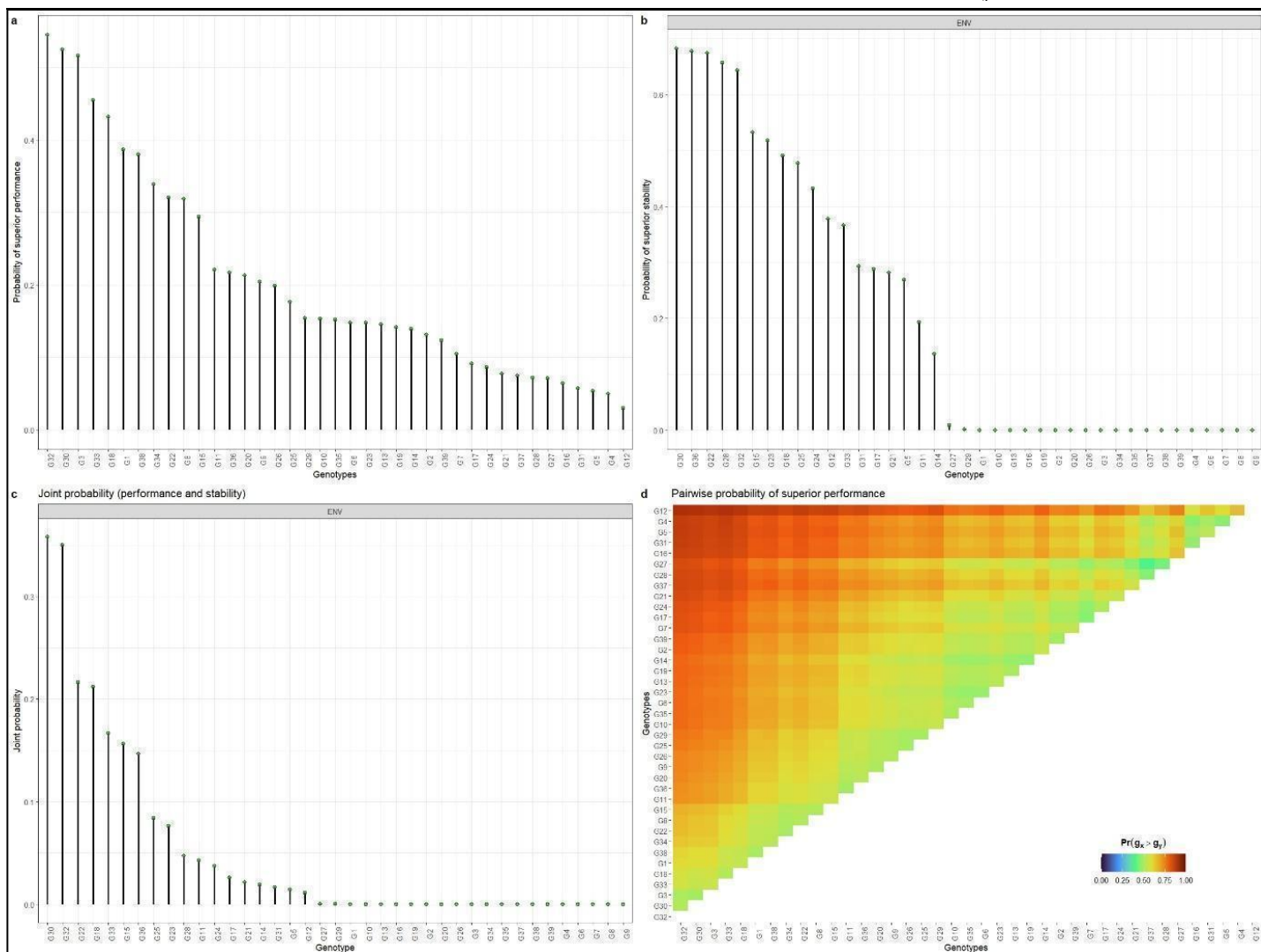


Figure 10. Superior probability plots of performance (a), stability (b), joint (c), and pairwise probability (d) of wheat genotypes in different environments, for grain yield kg ha^{-1} . BRS BELAJÓIA (G4), TBIO PONTEIRO (G27), TBIO ASTRO (G28), TBIO AUDAZ (G29), TBIO TRUNFO (G33), ORS AGILE (G37), ORS MADRE PÉROLA (G38), TBIO TORUK (G39), BAR 10 (G3), BRS TR271 (G5), ORS ABSOLUTO (G11), ORS FERROZ (G12), ORS GUARDIÃO (G13), ORS PREMIUM (G14), ORS SELVAGEM (G15), ORS SENNA (G16), ORS SOBERANO (G17), ORS TURBO (G18), ORS VENCITORE (G19), TBIO BLANC (G23), TBIO CALIBRE (G24), TBIO MOTRIZ (G25), TBIO NOBLE (G26), TBIO PONTEIRO (G27), TSZ CHIARO (G34), TSZ DOMINARE (G35), ORS PREMIUM (G14), ORS SOBERANO (G17), TBIO MOTRIZ (G20), ORS FALCÃO (G21), ORS GLADIADOR (G22), TBIO CALIBRE (G24), TBIO CAPAZ (G30), TBIO TALISMÃ (G31), TBIO TITAN (G32), XBIOFUSÃO (G36), BRS TR874XIRUCAPATAZ (G6), FPS CERTERO (G7), FPS LUMINUS (G8), FPS REGENTE (G9), FPS XERIFE (G10), ORS ABSOLUTO (G11), ORS FALCÃO (G21), ORS GLADIADOR (G22), TBIO BLANC (G23), TBIO CALIBRE (G24), TBIO MOTRIZ (G25), TBIO PONTEIRO (G27), TBIO ASTRO (G28).

Conclusions

Genotypic performance varied significantly among the evaluated environments, reflecting the influence of soil and climatic conditions. A low joint probability of performance and stability was observed for 51% of the evaluated genotypes. Genotypes G30 and G32 demonstrated the best probabilities of performance and stability for grain yield in the northwest region of the state of Rio Grande do Sul.

Conflict of interest

The authors declare that there is no conflict of interest with this article.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of use of AI Technologies

We hereby declare that no artificial intelligence (AI) technologies were used in the preparation of this manuscript. All research, data analysis, and manuscript preparation were conducted manually and without the assistance of AI tools or technologies

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