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Positioning of wheat cultivars and its relationship with grain nutritional quality

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ABSTRACT

The objective of this study was to select wheat genotypes with potential to improve grain nutritional quality. An experiment was conducted in 10 environments in the state of Rio Grande do Sul, Brazil. Five wheat genotypes were sown (BRS Parrudo, LG ORO, Mirante, ORS 1403, and TBIO Sinuelo), using a randomized block experimental design with two replications. Grain crude protein, lipid, crude fiber, mineral matter, and non-structural carbohydrate contents were evaluated. The data were subjected to analysis of variance and Tukey's test at a 5% significance level. The method proposed by Annicchiarico and the additive main effects and multiplicative interaction (AMMI) model were used to analyze the adaptability and stability of the genotypes. The genotype LG ORO was identified as the agronomic and nutritional ideotype, demonstrating stability and superiority in crude proteins, lipids, and non-structural carbohydrates in grains.

Keywords: *Triticum aestivum*; Nutritional traits; Grain biofortification; Adaptability; Stability.

Posicionamento de cultivares de trigo e suas relações com a qualidade nutricional dos grãos

RESUMO

O objetivo deste trabalho foi selecionar genótipos de trigo para aumentar a qualidade nutricional dos grãos. O estudo foi realizado em 10 ambientes, localizados no estado do Rio Grande do Sul, Brasil. Foram semeados cinco genótipos de trigo: BRS Parrudo, LG ORO, Mirante, ORS 1403 e TBIO Sinuelo, em delineamento experimental de blocos casualizados com duas repetições. Posteriormente, foram avaliados os percentuais de proteína bruta, lipídios, fibra bruta, matéria mineral e carboidratos não estruturais. Análise de variância e teste de Tukey foram realizados a 5% de probabilidade. Os métodos Annicchiarico e *Additive Main Effect Interaction* (AMMI) foram utilizados para estudar a adaptabilidade e estabilidade dos genótipos. O ideótipo agronômico e nutricional é dado ao genótipo LG ORO, sendo estável e superior para proteína bruta, lipídios e carboidratos não estruturais em grãos de trigo.

Palavras-chave: *Triticum aestivum*; Caracteres nutricionais; Biofortificação de grãos; Adaptabilidade; Estabilidade.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereals grown worldwide (Bayissa et al., 2022), contributing significantly to food security, as it provides substantial dietary calories, mainly from carbohydrates and proteins (Segatto et al., 2022; Loro et al., 2023), and is a source of iron, calcium, and several vitamins (Zain et al., 2021) The composition and proportions of individual gluten fractions are the main determinants of the dough rheological properties, which determine wheat quality (Filip et al., 2023). In this context, wheat flour quality and, consequently, the dough quality, is closely connected to grain physical and chemical quality. Therefore, the effect of the environment and management practices are among the main factors that influence the performance of wheat genotypes in terms of grain quality.

Environmental conditions, agronomic traits of genotypes, cultural practices, and their interactions can affect the quality, processing, performance, final products, and nutritional traits of wheat grains and flour (Bhatta et al., 2017; Tozatti et al., 2020). Regarding technological properties, wheat genotypes strongly affect grain hardness and the composition of gluten-forming proteins (gliadin and glutenin), while environmental conditions affect protein and mineral contents (Johansson et al., 2020). Protein concentrations and the amino acid profile are crucial for the economic value of wheat crops (Marcos-Barbero et al., 2021).

Wheat proteins and amino acids can undergo modifications due to genotypic traits (G), environment (E), and the G × E interaction (Segatto et al., 2022). Loro et al. (2023) observed G × E interactions in the expression of essential amino acids in wheat grains. Therefore, determining and quantifying the factors contributing to these variations in wheat quality parameters is essential (Kaya and Akcura, 2014).

Different biometric approaches can be used to define the yield potential and strategic positioning of genotypes for phenotypic stability and adaptability (Kehl et al., 2022). The additive main effect and multiplicative interaction (AMMI) model is widely used to evaluate the stability of genotypes grown in different environments (Bayissa et al., 2022; Loro et al., 2023). Similarly, the methodology proposed by Annicchiarico (1992) evaluates the stability of genotypes based on the average traits in each environment (Carvalho et al., 2016). Furthermore, the Multi-Trait Stability Index (MTSI) has been successfully used to select superior genotypes based on multiple traits (Lima et al., 2022). In this context, the objective of this study was to select wheat genotypes with potential to improve grain nutritional quality.

2. Material and Methods

The experiment was conducted in five municipalities in the state of Rio Grande do Sul, Brazil: Cachoeira do Sul (27°52'15"S, 54°28'53"W, 277 m altitude), Cruz Alta (27°22'16"S, 53°45'30"W, 390 m altitude), Santo Augusto (27°56'38"S, 52°55'23"W, 503 m altitude), São Gabriel (30°20'03"S, 54°19'18"W, 114 m altitude), and Vacaria (28°53'10"S, 52°59'55"W, 710 m altitude) (Figure 1). Wheat seeds were sown under a non-tillage system at two different sowing times (May 15 and June 15), resulting in ten distinct growing environments. A randomized block experimental design (random effect) with two replications was used, in a 10×5 factorial arrangement consisting of ten growing environments and five wheat genotypes: BRS Parrudo (G1), LG ORO (G2), Mirante (G3), ORS 1403 (G4), and TBIO Sinuelo (G5).

The experimental units consisted of seven 5-m rows spaced 0.17 m apart, with a sowing density of 300 plants m^{-2}. Basal fertilizers were applied at rates of 12.5 kg ha^{-1} of N, 50 kg ha^{-1} of P205, and 50 kg ha^{-1} of K2O, followed by a topdressing application of 67.5 kg ha^{-1} of N. Weed, insect pest, and disease controls were conducted preventively.

Plants at full physiological maturity were harvested from each experimental unit. The harvested grains were stored for two months in a cold chamber at 20 °C for subsequent milling to obtain the flour for evaluating the wheat nutritional quality based on crude protein, lipid, crude fiber, mineral matter, and non-structural carbohydrate percentages (Rosa-Campos et al., 2014). Mean daily maximum, mean, and minimum air temperatures (°C), relative air humidity (%), rainfall (mm), and solar radiation (Mj m^{-2} s^{-1}) were recorded for each location (Nasa Power, 2023).

The obtained data were analyzed for normality and homogeneity using the Shapiro-Wilk and Bartlett tests, respectively, followed by statistical modeling. Analysis of variance was conducted at a 5% significance level using the F-test to assess the genotype × environment (G × E) interaction for all grain nutritional quality parameters evaluated. The variables that demonstrated significant effects were compared between and within environments and genotypes, using the Tukey's test at a 5% significance level to further analyze the simple effects.

Based on the significance of the variables, the method proposed by Annicchiarico (1992) was used to calculate the stability parameter, defined as $I_j = X_j - \mu$, where I_j is the environmental index; X_j is the mean of the variable in j-th environment; and μ is the overall mean of the variable. Subsequently, the additive main effect and multiplicative interaction (AMMI) model was applied; it combines the additive effects of genotypes (G) and environments (E) with the multiplicative effects of the G × E interaction. The model is represented by $yij = \mu + \alpha i + \tau j + \sum k = 1p\lambda kaiktjk + \rho ij + \varepsilon ij$, where μ is the grand mean; αi is the effect of the i-th genotype; τj is the effect of the i-th environment; λk is the singular value for the k-th interaction principal component axis (IPCA); aik is the i-th element of the k-th eigenvector; ρij is the remaining residual if not all IPCAs are used, and εij is the standard error. The identification of the wheat stability ideotype involved predicting an increase in crude protein, lipid, and non-structural carbohydrate contents, while reducing crude fiber and mineral material contents. This was based on the Multi-trait Stability Index (MTSI) (Olivoto et al., 2019), using the equation: $\mathrm{MTSI}_i = \left[\sum_{j=1}^{f}\left(F_{ij} - F_j\right)^2\right]^{0.5}$ where, MTSIi is the index for the i-th genotype; F_{ij} is the score of the i-th genotype; e F_j is the ideotype score.

Subsequently, Pearson correlation analysis was performed to evaluate the relationship between grain nutritional quality parameters and meteorological variables. All statistical analyses were conducted using R software (R Core Team, 2023).

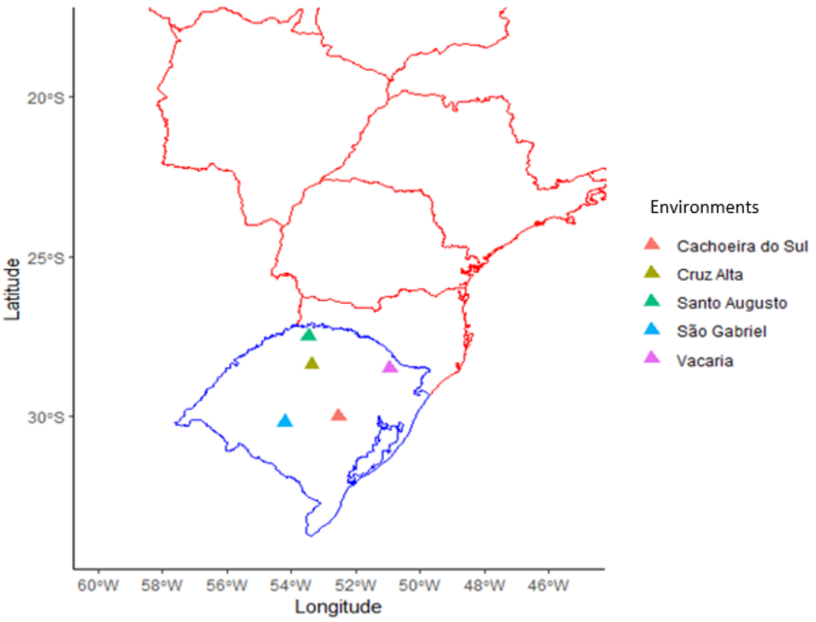

Figure 1. Geographic location of the experimental sites in municipalities of Rio Grande do Sul, Brazil.

3. Results and Discussion

Meteorological data for the different environments used to evaluate wheat genotypes are presented in Figure 2. Vacaria exhibited the lowest air temperatures among the evaluated environments, with temperatures below 5 °C during June and mean temperatures below 18 °C throughout the crop cycle. Contrastingly, air temperatures in the other environments were similar, with mean temperatures exceeding 20 °C in May and ranging between 10 and 18 °C throughout the crop cycle. The optimum temperature range for growing wheat crops is 12 to 25 °C (Farooq et al., 2011; Flato et al., 2013).

The highest relative air humidity values were recorded for Vacaria, followed by Cachoeira do Sul and São Gabriel. Rainfall was lower in all environments during May, June, and September. High grain yield is associated with adequate availability of water and nutrients, which are essential for enhancing metabolism and minimizing losses in wheat crops (Turek et al., 2018).

Incident radiation values were similar in Santo Augusto, Cruz Alta, and Vacaria but lower in Cachoeira do Sul. The analysis of variance revealed significant G × E interactions for all evaluated parameters (Table 1).

The comparison between and within genotypes and environments for the evaluated parameters are shown in Table 2. Crude protein contents were significant higher for the wheat genotypes BRS Parrudo, LG ORO, Mirante, and ORS 1403 sown on June 15 in Santo Augusto.

Lipid content was significantly higher when the genotypes were sown in June in São Gabriel. BRS Parrudo was superior for this aspect in Cruz Alta and Vacaria. Crude fiber contents exhibited smaller fluctuations across the environments; BRS Parrudo exhibited significantly higher means in Cruz Alta and Santo Augusto, whereas LG ORO was superior in São Gabriel and Vacaria. TBIO Sinuelo sown in June in São Gabriel had the highest non-structural carbohydrate content.

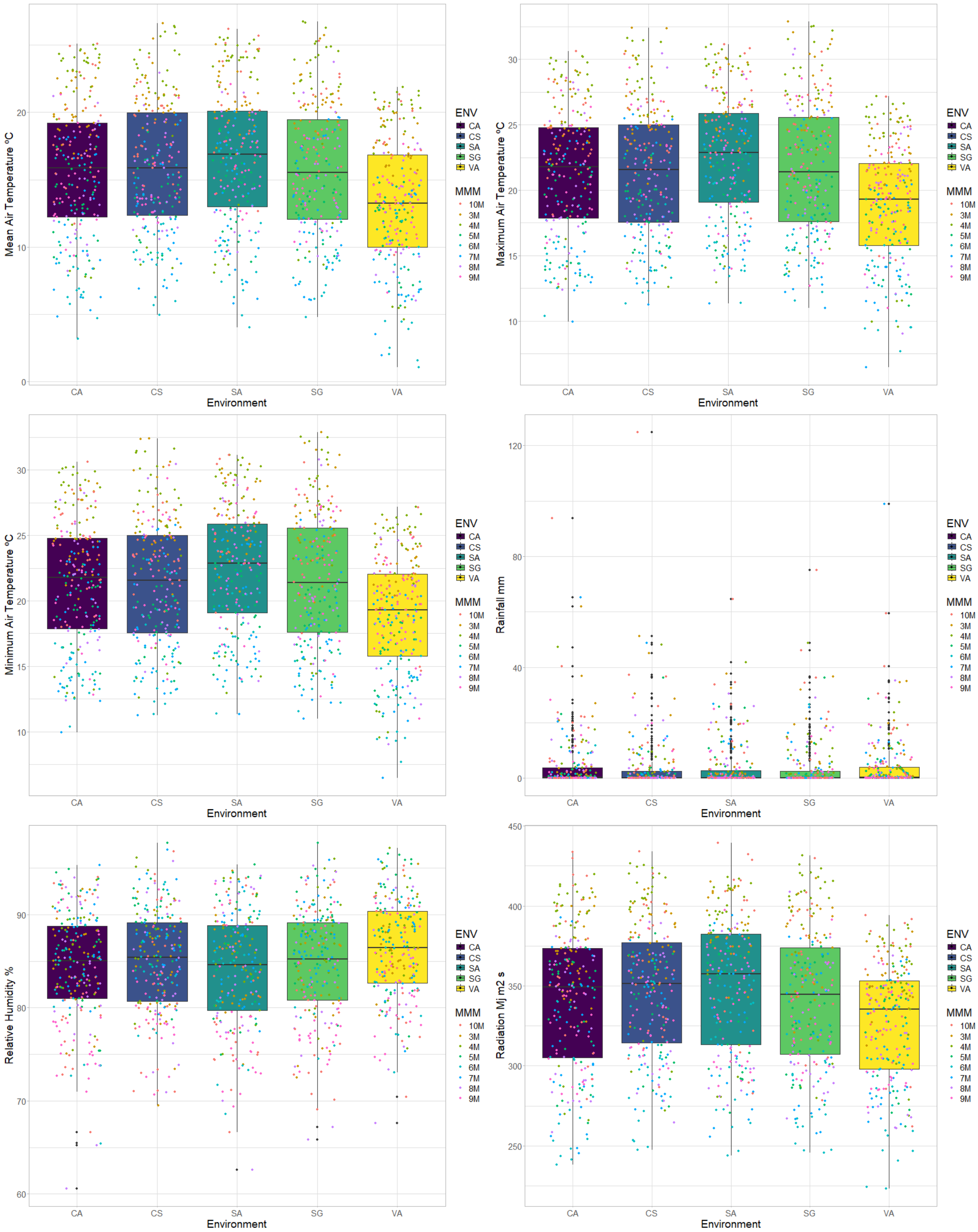

Figure 2. Maximum, mean, and minimum air temperatures (°C), rainfall (mm), relative air humidity (%), and solar radiation (Mj m^{-2} s^{-1}) for the different environments used for growing wheat crops in Rio Grande do Sul, Brazil: CA = Cruz Alta; CS = Cachoeira do Sul; SA = Santo Augusto; SG = São Gabriel; VA = Vacaria.

Table 1. Analysis of variance (ANOVA) for grain nutritional quality parameters in wheat genotypes.

Source of variation	Degrees of freedom	Sum of squares				
		TPN	LIP	CF	MM	CHO
Environments (E)	9	168.87*	2.08*	0.66*	0.73*	192.00*
Genotypes (G)	4	116.50*	0.49*	2.02*	1.21*	475.70*
Blocks (A)	20	0.47	0.11	0.08	0.02	0.7
E × G	36	34.10*	0.97*	0.90*	0.25*	52.30*
Residual	80	1.11	0.34	0.36	0.07	5.7
Mean	-	13.42	1.66	2.51	1.69	56.85
CV (%)	-	0.88	3.94	2.67	1.74	0.47

Blocks (A) = nested block; TPN = crude protein; LIP = lipids; CF = crude fiber; MM = mineral matter; CHO = non-structural carbohydrates; * = significant at a 5% significance level by the F-test; CV = coefficient of variation.

Table 2. Simple effects of five wheat genotypes grown in five different environments based on two different sowing times [May 15 (1) and June 15 (2)]. Rio Grande do Sul, Brazil.

Growing environment	BRS Parrudo	LG ORO	Mirante	ORS 1403	Tbio Sinuelo
			Crude protein		
Cachoeira do Sul 1	12.08 gB	12.03 eB	11.94deB	13.10 efA	11.42 fC
Cachoeira do Sul 2	15.16 cA	13.56 dB	12.14 cdD	13.33 eB	12.68 cC
Cruz Alta 1	14.45 dB	15.6 bA	13.14 bE	14.11 cC	13.42 bD
Cruz Alta 2	14.57 dB	15.11 cA	12.44 cD	14.03 cC	12.35 dD
Vacaria 1	13.97 eA	13.60 dB	12,39 cC	13.65 dB	11.97 eD
Vacaria 2	13.03 fB	13.60 dA	11.83 deD	12.58 gC	10.38 gE
Santo Augusto 1	15.64 bA	15.32 dcB	13.02 bE	14.55 bC	13.33 bD
Santa Augusto 2	17.26 aA	16.48 aB	14.25 aD	16.12 aC	14.48 Ad
São Gabriel 1	15.16 cA	13.79 dB	12.13 cdD	12.84 fgC	11.34 fE
São Gabriel 2	13.73 eA	12.09 eC	11.66 eD	12.54 gB	11.42 fD
			Lipids		
Cachoeira do Sul 1	1.57 bcC	1.92 aA	1.75 bcB	1.68 bBC	1.81 abAB
Cachoeira do Sul 2	1.53 cdB	1.54 dB	1.54 defB	1.8 bA	1.49 cdeB
Cruz Alta 1	1.53 bcdB	1.53 dB	1.60 cdeAB	1.72 bA	1.48 deB
Cruz Alta 2	1.60 abcB	1.60 cdB	1.78 bA	1.80 bA	1.65 bcAB
Vacaria 1	1.37 dB	1.77 bcA	1.67 bcdA	1.69 bA	1.65 bcaA
Vacaria 2	1.65 abcA	1.77 bcA	1.66 bcdA	1.72 bA	1.80 abA
Santo Augusto 1	1.59 bcAB	1.55 dBC	1.38 fD	1.71 bA	1.41 eCD
Santa Augusto 2	1.5 cdABC	1.60 cdAB	1.48 efBC	1.63 bA	1.44 eC
São Gabriel 1	1.71 abAB	1.58 dB	1.59 cdeB	1.79 bA	1.64 bcdAB
São Gabriel 2	1.77 aB	1.97 aA	2.01 aA	1.98 aA	1.95 aA
			Crude fiber		
Cachoeira do Sul 1	2.62 bcA	2.64 aA	2.40 bcdeB	2.46 abcB	2.50 abcAB
Cachoeira do Sul 2	2.78 abA	2.48 abB	2.22 eC	2.33 cdBC	2.25 dC
Cruz Alta 1	2.92 aA	2.53 abB	2.59 aB	2.53 abB	2.55 aB
Cruz Alta 2	2.73 bA	2.53 abB	2.42 abcB	2.5 abcB	2.44 abcB
Vacaria 1	2.69 bcA	2.56 aAB	2.54 abAB	2.54 aAB	2.44 abcB
Vacaria 2	2.66 bcA	2.56 aA	2.41 bcdBC	2.56 aAB	2.34 cdC
Santo Augusto 1	2.94 aA	2.53 abB	2.24 deC	2.40 abcdB	2.48 abcB
Santa Augusto 2	2.68 bcA	2.48 abB	2.52 abB	2.46 abcB	2.52 abB
São Gabriel 1	2.55 cA	2.62 aA	2.33 cdeB	2.27 dB	2.34 bcdB
São Gabriel 2	2.61 bcA	2.36 bB	2.36 bcdeB	2.36 bcdB	2.33 cdB
			Mineral material		
Cachoeira do Sul 1	1.65 efA	1.59 dAB	1.56 bB	1.65 deA	1.49 eC
Cachoeira do Sul 2	1.74 dA	1.79 bcA	1.53 bC	1.66 cdeB	1.61 bcdB
Cruz Alta 1	1.72 deB	1.86 abA	1.57 abC	1.74 bcB	1.60 bcdC
Cruz Alta 2	1.76 cdB	1.87 abA	1.64 abD	1.7 bcdBC	1.64 bcCD
Vacaria 1	1.82 bcA	1.86 abA	1.57 abC	1.66 cdeB	1.56 deC
Vacaria 2	1.76 cdB	1.86 abA	1.59 abC	1.74 bB	1.57 cdeC
Santo Augusto 1	1.85 Ba	1.90 aA	1.61 abC	1.72 bcdB	1.67 Bbc
Santa Augusto 2	1.95 aA	1.90 aAB	1.64 aD	1.86 aB	1.77 aC
São Gabriel 1	1.76 cdA	1.77 cA	1.54 bB	1.58 eB	1.55 deB
São Gabriel 2	1.64 fA	1.60 dA	1.53 bB	1.60 eA	1.51 eB
			Non-structural carbohydrates		
Cachoeira do Sul 1	56.14 bD	58.19 aC	59.28 abB	57.92 abC	59.94 abA
Cachoeira do Sul 2	53.94 fgD	54.91 bC	59.11 abcA	57.83 abB	57.97 cB
Cruz Alta 1	54.72 deD	53.40 cE	59.41 abA	57.23 bcC	57.97 cB
Cruz Alta 2	53.70 fgC	53.15 cC	58.84 bcA	56.71 cdB	58.27 cB
Vacaria 1	54.1 efD	55.16 bC	58.51 cdA	56.29 dB	58.52 cA
Vacaria 2	55.78 bcD	55.16 bE	59.46 abB	57.43 bC	60.23 abA
Santo Augusto 1	53.34 Gc	53.29 cC	57.13 eA	55.11 eB	57.16 dA
Santa Augusto 2	52.56 hE	53.17 cD	58.12 dA	55.26 eC	56.91 dB
São Gabriel 1	55.19 cdC	55.42 bC	59.34 abA	57.83 abB	59.61 bA
São Gabriel 2	57.11 aD	58.08 aC	59.72 aB	58.46 aC	60.38 aA

Means followed by the same lowercase letter in the columns or uppercase letter in the rows are not significantly different from each other by the Tukey's test a 5% significance level.

Segatto et al. (2023) evaluated nutritional quality traits of wheat grains and reported broad-sense heritability (h^2) values of 0.715 for crude protein, 0.169 for lipids, 0.566 for crude fiber, 0.751 for mineral matter, and 0.89 for non-structural carbohydrates. According to the classification of Resende and Alves (2021), all traits showed high heritability ($h^2 > 0.50$), except for lipids.

This information is crucial for interpreting the results obtained using the Annicchiarico method, as the environmental stability indices (I_j) (Table 3) identified the environments favorable for genotypes to express high crude fiber and mineral matter contents.

The Cruz Alta environment consistently improved the performance of genotypes for all grain quality parameters, regardless of the sowing time. São Gabriel was a favorable environment for genotypes to express the evaluated parameters, except for non-structural carbohydrates, when sown on May 15.

Table 3. Classification of 10 environments (ENV) in Rio Grande do Sul, Brazil, based on environmental indices (Annicchiarico, 1992) for parameters of wheat grain quality: crude protein (PTN), lipids (LIP), crude fiber (CF), mineral matter (MM), and non-structural carbohydrates (CHO).

TPN				LIP			
ENV	Mean	Index	Class	ENV	Mean	Index	Class
1	12.116	-1.301	Unfavorable	1	1.748	0.086	Favorable
2	13.376	-0.042	Unfavorable	2	1.582	-0.08	Unfavorable
3	14.124	0.707	Favorable	3	1.576	-0.086	Unfavorable
4	13.705	0.287	Favorable	4	1.69	0.0279	Favorable
5	13.118	-0.299	Unfavorable	5	1.632	-0.0301	Unfavorable
6	12.29	-1.127	Unfavorable	6	1.722	0.06	Favorable
7	14.376	0.958	Favorable	7	1.53	-0.132	Unfavorable
8	15.721	2.303	Favorable	8	1.532	-0.129	Unfavorable
9	13.058	-0.359	Unfavorable	9	1.665	0.003	Favorable
10	12.292	-1.125	Unfavorable	10	1.941	0.279	Favorable
CF				MM			
ENV	Mean	Index	Class	ENV	Mean	Index	Class
1	2.527	0.022	Favorable	1	1.591	-0.097	Unfavorable
2	2.414	-0.091	Unfavorable	2	1.67	-0.018	Unfavorable
3	2.628	0.123	Favorable	3	1.703	0.014	Favorable
4	2.528	0.022	Favorable	4	1.713	0.024	Favorable
5	2.556	0.051	Favorable	5	1.697	0.008	Favorable
6	2.508	0.003	Favorable	6	1.706	0.017	Favorable
7	2.519	0.014	Favorable	7	1.754	0.065	Favorable
8	2.536	0.03	Favorable	8	1.828	0.14	Favorable
9	2.425	-0.079	Unfavorable	9	1.642	-0.045	Unfavorable
10	2.408	-0.096	Unfavorable	10	1.579	-0.109	Unfavorable
CHO							
ENV	Mean	Index	Class				
1	58.296	1.444	Favorable				
2	56.754	-0.097	Unfavorable				
3	56.548	-0.303	Unfavorable				
4	56.138	-0.714	Unfavorable				
5	56.518	-0.333	Unfavorable				
6	57.616	0.763	Favorable				
7	55.212	-1.64	Unfavorable				
8	55.206	-1.646	Unfavorable				
9	57.478	0.626	Favorable				
10	58.752	1.90	Favorable				

Sowing on May 15: Cachoeira do Sul (1); Cruz Alta (2); Santo Augusto (3); São Gabriel (4); and Vacaria (5). Sowing on June 15: Cachoeira do Sul (6); Cruz Alta (7); Santo Augusto (8); São Gabriel (9); and Vacaria (10).

The analysis of variance for the AMMI model (Table 4) revealed that all evaluated wheat grain quality parameters were significantly affected by genotypic traits, environment, and G x E interaction, requiring an individual evaluation of each parameter. Principal components 1 and 2 (PC1 and PC2, respectively) were significant ($p < 0.05$) for all parameters and were incorporated into the model.

The AMMI analysis for crude protein contents identified three mega-environments (Figure 3a), with PC1 and PC2 explaining 46.8% and 34.7% of the total variance, respectively.

The genotype BRS Parrudo (G1) had superior performance in the mega-environment comprising Cruz Alta at both sowing times (2 and 7), as well as Santo Augusto and São Gabriel with sowing in June (8 and 9, respectively).

LG ORO (G2) was superior in the mega-environment comprising Santo Augusto and São Gabriel with sowing in May (3 and 4, respectively), as well as Cachoeira do Sul with sowing in June (6). Mirante (G3) and ORS 1403 (G4) exhibited superior performance with sowing in May at Cachoeira do Sul (1) and Vacaria (5).

According to Abdelaleem and Al-Azab (2021), intrinsic genotypic effects influence crude protein contents in wheat grains, which had higher levels than the flours obtained from them. The lipid content accounted for 86.7% of the total variance explained by PC1 (66.4%) and PC2 (20.3%).

Table 4. Analysis of variance for principal component analysis based on contents of crude protein (TPN), lipids (LIP), crude fiber (CF), mineral matter (MM), and non-structural carbohydrates (CHO) in five wheat genotypes grown in five different environments and sown on May 15 and June 15.

			TPN				
Source of variation	DF	SS	MS	F value	Pr(> F)	%	Accumulated
Environments (E)		168.874	18.764	804.551	0	.	.
Blocks (A)	20	0.466	0.023	1.674	0.055752	.	.
Genotypes (G)	4	116.498	29.125	2090.477	4.73E-80	.	.
E × G	36	34.101	0.947	67.991	8.48E-47	.	.
PC1	12	15.945	1.329	95.38	0	46.8	46.8
PC2	10	11.844	1.184	85.01	0	34.7	81.5
Residual	80	1.115	0.014			.	.
Total	149	321.054	2.155				
			LIP				
Source of variation	DF	SS	MS	F value	Pr(> F)	%	Accumulated
Environments (E)	9	2.082913	0.231435	42.911	3.9E-11	.	.
Blocks (A)	20	0.107867	0.005393	1.257	0.233388	.	.
Genotypes (G)	4	0.487063	0.121766	28.373	1.11E-14	.	.
E × G	36	0.969684	0.026936	6.276	4.71E-12	.	.
PC1	12	0.64371	0.05364	12.5	0	66.4	66.4
PC2	10	0.19639	0.01964	4.58	0	20.3	86.6
Residual	80	0.343333	0.004292			.	.
Total	149	3.990859	0.026784				
			CF				
Source of variation	DF	SS	MS	F value	Pr(> F)	%	Accumulated
Environments (E)	9	0.661	0.073	19.339	5.25E-08	.	.
Blocks (A)	20	0.076	0.004	0.849	0.648292	.	.
Genotypes (G)	4	2.024	0.506	113.134	4.11E-32	.	.
E × G	36	0.898	0.025	5.575	8.7E-11	.	.
PC1	12	0.461	0.038	8.59	0	51.4	51.4
PC2	10	0.267	0.027	5.97	0	29.8	81.1
Residual	80	0.358	0.004			.	.
Total	149	4.017	0.027				
			MM				
Source of variation	DF	SS	MS	F value	Pr(> F)	%	Accumulated
Environments (E)	9	0.734	0.082	86.196	5.07E-14	.	.
Blocks (A)	20	0.019	0.001	1.101	0.365631	.	.
Genotypes (G)	4	1.209	0.302	351.355	6.9E-50	.	.
E × G	36	0.249	0.007	8.056	6.21E-15	.	.
PC1	12	0.144	0.012	13.99	0	57.9	57.9
PC2	10	0.047	0.005	5.47	0	18.9	76.8
Residual	80	0.069	0.001			.	.
Total	149	2.280	0.015				
			CHO				
Source of variation	DF	SS	MS	F value	Pr(> F)	%	Accumulated
Environments (E)	9	191.960	21.329	631.517	0	.	.
Blocks (A)	20	0.675	0.034	0.472	0.970078	.	.
Genotypes (G)	4	475.730	118.932	1661.303	4.2E-76	.	.
E × G	36	52.319	1.453	20.300	1.46E-27	.	.
PC1	12	38.027	3.169	44.26	0	72.7	72.7
PC2	10	8.835	0.884	12.34	0	16.9	89.6
Residual	80	5.727	0.072			.	.
Total	149	726.411	4.875				

* = significant at a 5% significance level. DF = degrees of freedom; SS = sum of squares; MS = mean square; Blocks (A) = nested blocks; PC1 = principal component 1; PC2 = principal component 2.

Wheat grains typically contain 3% to 4% lipids, with approximately 1% to 2% retained in flours (Wrigley et al., 2016). In this context, BRS Parrudo (G1) had higher lipid contents in the mega-environment comprising Cruz Alta, Santo Augusto, and São Gabriel with sowing in June (7, 8, and 9, respectively), whereas LG ORO (G2) and TBIO Sinuelo (G5) demonstrated superior performance in the mega-environment comprising Cachoeira do Sul at both sowing times (1 and 6) and Vacaria with sowing in May (5). Mirante (G3) exhibited its high potential in the mega-environment consisting of São Grabriel (4) and Vacaria (5) with sowing in May and June, respectively, whereas ORS 1403 (G4) performed better under environmental conditions of Cruz Alta and Santo Augusto with sowing in May (2 and 3, respectively).

The crude fiber content accounted for 29.8% of the total variance explained by PC2 (Figure 4c). BRS Parrudo (G1) exhibited superior performance in Cruz Alta, regardless of the sowing time (2 and 7), and in Santo Augusto with sowing in May (3). Mirante (G3), ORS 1403 (G4), and TBIO Sinuelo (G5) showed superior performance in Vacaria, regardless of the sowing times (5 and 10). The mineral matter content accounted for 57.9% of the total variance explained by PC1 (Figure 4d). The genotype LG ORO (G2) can be positioned in various environments (2, 3, 4, 5, 6, and 7) and is characterized by broad adaptation.

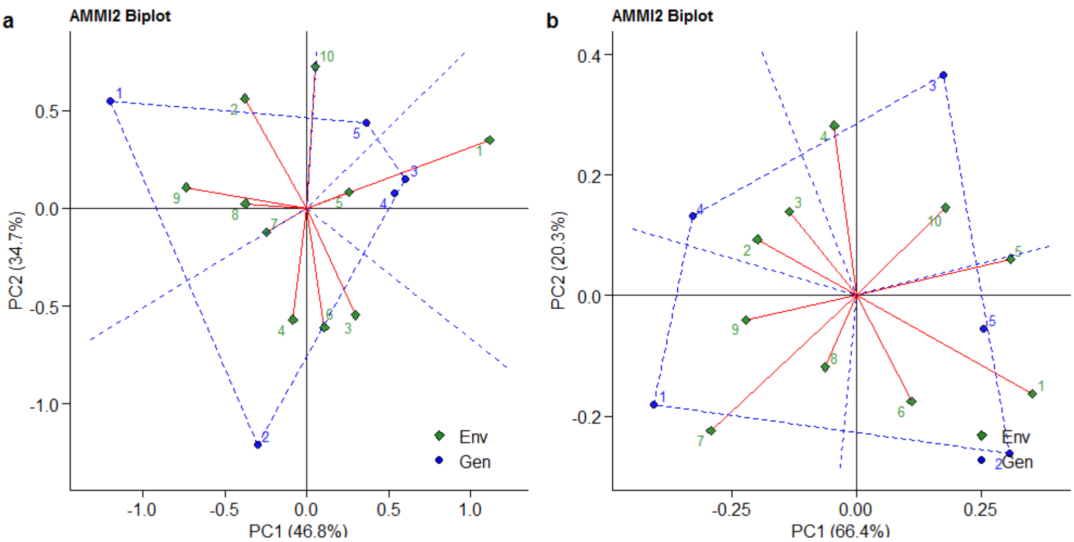

Figure 3. Additive main effects and multiplicative interaction (AMMI) analysis for crude protein (a) and lipid (b) contents in five wheat genotypes grown in five different environments based on two different sowing times. PC1 = principal component 1; PC2 = principal component 2; Environment (Env) in green, based on sowing on May 15 (1: Cachoeira do Sul; 2: Cruz Alta; 3: Santo Augusto; 4: São Gabriel; and 5: Vacaria) and June 15 (6: Cachoeira do Sul; 7: Cruz Alta; 8: Santo Augusto; 9: São Gabriel; and 10: Vacaria). Genotype (Gen) in blue: (1) BRS Parrudo, (2) LG ORO, (3) Mirante, (4) ORS 1403, and (5) TBIO Sinuelo.

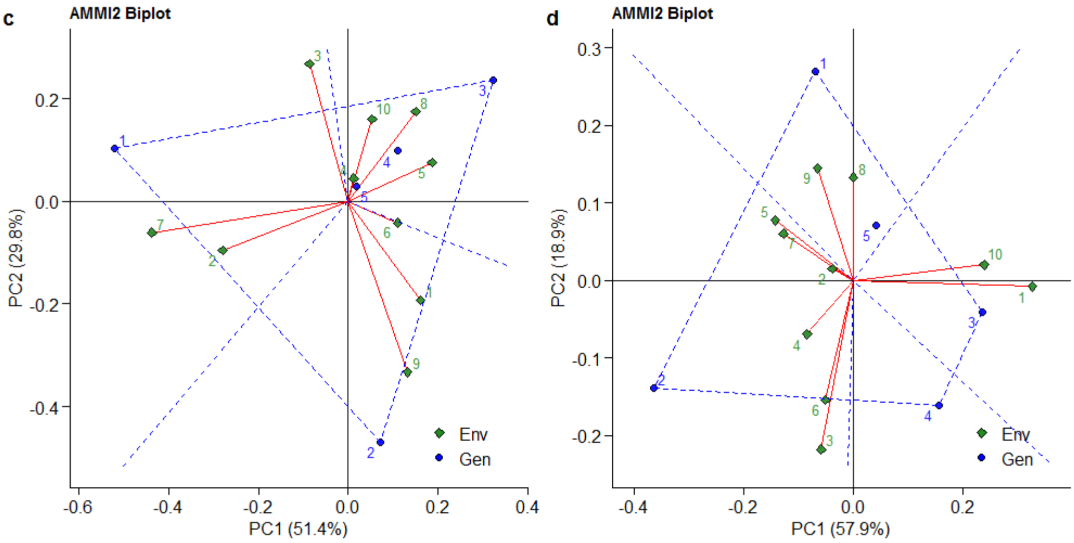

Figure 4. Additive main effects and multiplicative interaction (AMMI) analysis for crude fiber (c) and mineral matter (d) contents in five wheat genotypes grown in five different environments based on two different sowing times. PC1 = principal component 1; PC2 = principal component 2; Environment (Env) in green, based on sowing on May 15 (1: Cachoeira do Sul; 2: Cruz Alta; 3: Santo Augusto; 4: São Gabriel; and 5: Vacaria) and June 15 (6: Cachoeira do Sul; 7: Cruz Alta; 8: Santo Augusto; 9: São Gabriel; and 10: Vacaria). Genotype (Gen) in blue: (1) BRS Parrudo, (2) LG ORO, (3) Mirante, (4) ORS 1403, and (5) TBIO Sinuelo.

The non-structural carbohydrate content (Figure 5) accounted for 72.7% of the total variance explained by PC1. LG ORO (G2) showed better adaptation to the mega-environment comprising Cachoeira do Sul with sowing in May (1) and Vacaria, regardless of the sowing time (5 and 10). BRS Parrudo (G1) and TBIO Sinuelo (G5) exhibited superior performance with sowing in June at Cachoeira do Sul (6), Cruz Alta (7), and São Gabriel (9).

According to Cotrim et al. (2019), mega-environments are formed based on the geographic proximity of these regions and edaphoclimatic interrelations, which affect plant responses to environmental stimuli.

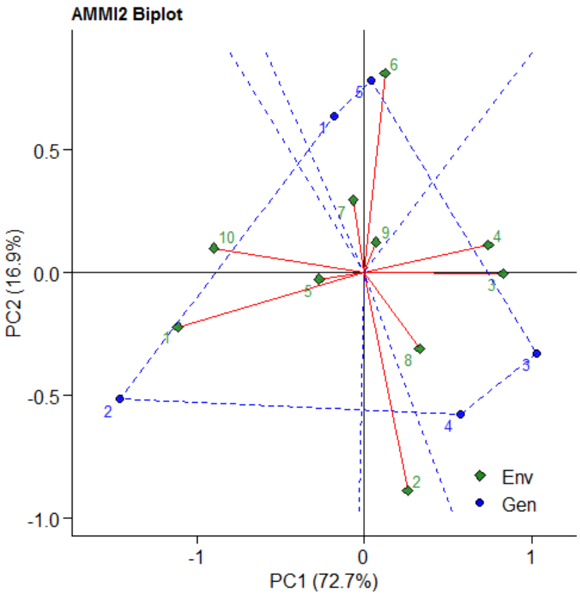

Figure 5. Additive main effects and multiplicative interaction (AMMI) analysis for non-structural carbohydrate contents in five wheat genotypes grown in five different environments based on two different sowing times. PC1 = principal component 1; PC2 = principal component 2; Environment (Env) in green, based on sowing on May 15 (1: Cachoeira do Sul; 2: Cruz Alta; 3: Santo Augusto; 4: São Gabriel; and 5: Vacaria) and June 15 (6: Cachoeira do Sul; 7: Cruz Alta; 8: Santo Augusto; 9: São Gabriel; and 10: Vacaria). Genotype (Gen) in blue: (1) BRS Parrudo, (2) LG ORO, (3) Mirante, (4) ORS 1403, and (5) TBIO Sinuelo.

Genotype selection depends on understanding G × E interactions and cultural practices, a process facilitated by statistical methodologies that combine various trends and interrelationships (Jat et al., 2017). The Multi-Trait Stability Index (MTSI) (Figure 6) is a useful tool for integrating multiple variables and guiding the selection the best genotype based on the stability ideotype. Therefore, LG ORO (G2) was selected based on this index (MTSI = 0.5), indicating that it has the superior traits of the wheat stability ideotype, including high contents of crude proteins, lipids, and non-structural carbohydrates, as well as reduced contents of mineral material and crude fiber in grains. A linear correlation analysis was conducted to better understand the meteorological and qualitative trends in wheat grains (Figure 7).

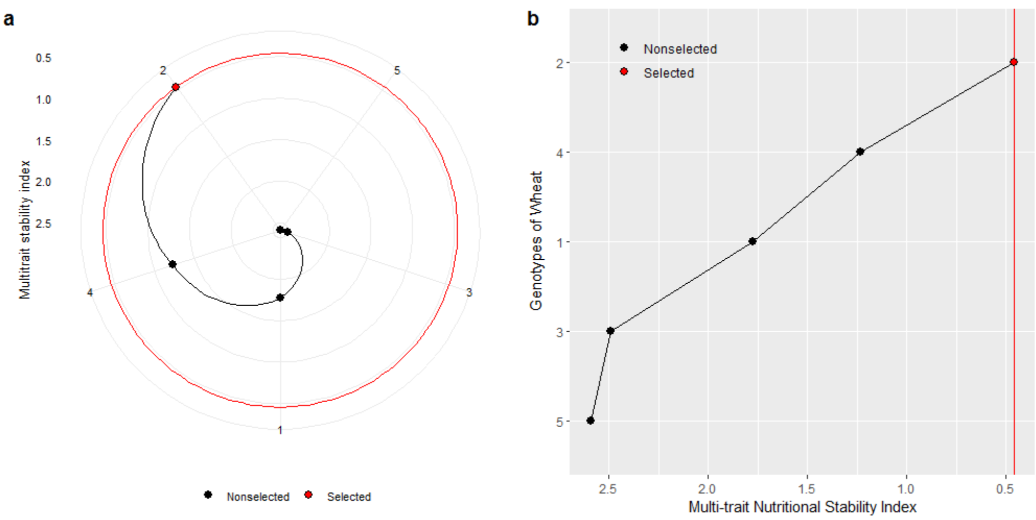

Figure 6. Multi-Trait Stability Index (MTSI) of five wheat genotypes (BRS Parrudo, G1; LG ORO, G2; Mirante, G3; ORS 1403, G4; and TBIO Sinuelo, G5) grown in five different environments based on two sowing times (May 15 and June 15). Rio Grande do Sul, Brazil.

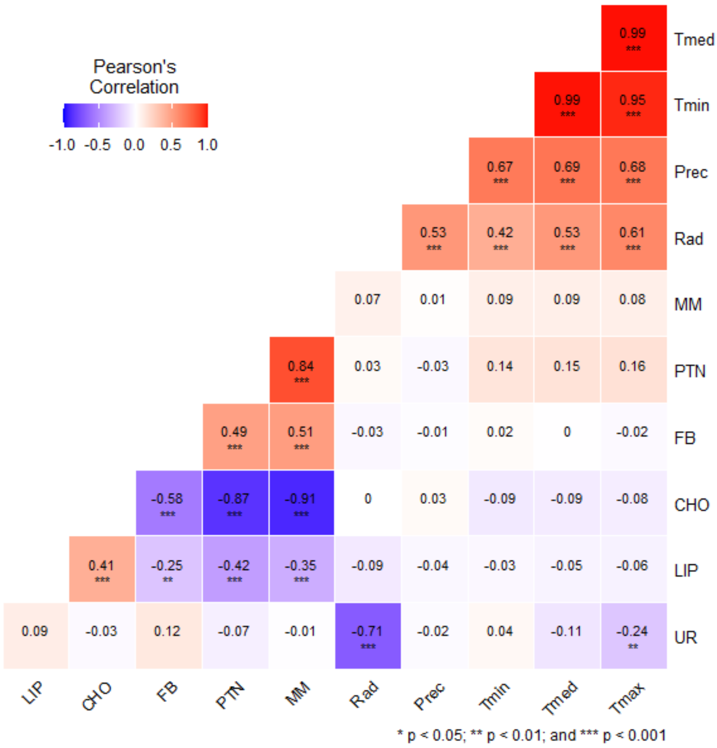

Figure 7. Pearson correlation analysis between wheat grain nutritional quality parameters and climate variables. Tmax = maximum air temperature; Tmean = mean air temperature; Tmin = minimum air temperature; Prec = rainfall; Rad = radiation; RAH = relative air humidity; TPN = crude protein; LIP = lipids; CF = crude fiber; MM = mineral matter; CHO = non-structural carbohydrates.

Carvalho et al. (2016) characterized the magnitudes of correlation coefficients as null (r = 0), weak (r = 0.01 to 0.30), medium (r = 0.31 to 0.60), strong (r = 0.61 to 0.90), and high (r > 0.91). A strong and positive correlation was observed for maximum, mean, and minimum air temperatures, which were moderately correlated with rainfall and total incident radiation.

The nutritional quality of wheat grains strongly correlates mineral matter with crude protein, as well as crude protein with crude fiber and lipids. Inverse trends were observed between crude protein and non-structural carbohydrates. Consequently, significant linear correlations with meteorological estimates were not feasible, which can be attributed to the low linearity of environmental parameters. The use of selection indexes provides a more efficient genotype selection based on multiple traits, resulting in time savings, increased effectiveness in breeding programs, improved cultivar positioning strategies, and reduced financial resource waste (Moura et al., 2022).

4. Conclusions

The environments of São Gabriel and Cruz Alta, Rio Grande do Sul, Brazil, with sowing on May 15 and June 15, respectively, were favorable for increasing crude protein and lipid contents in wheat grains. The environments of São Gabriel and Vacaria, at both sowing times, were favorable for increasing lipid and non-structural carbohydrate contents in wheat grains.

The wheat genotype LG ORO was identified as the agronomic and nutritional ideotype, demonstrating stability and superiority in crude proteins, lipids, and non-structural carbohydrates in grains.

Authors' Contribution

All authors contributed equally to this manuscript. Willyan Júnior Adorian Bandeira and Ivan Ricardo Carvalho performed data analysis, writing, and review. Murilo Vieira Loro, Leonardo Cesar Pradebon, and Jaqueline Piesanti Sangiovo conducted the textual review. Kassiana Kehl conducted the experiment and collected the data.

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