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ARTICLE

Performance of potential parents for a rainfed tropical wheat breeding program

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Abstract: *The aim of this study was to evaluate the genetic variability and performance of the agronomic traits of wheat cultivars in the southern region of Minas Gerais for the purpose of choosing parents for a rainfed wheat breeding program. We evaluated 78 wheat cultivars in two locations in Minas Gerais regarding different agronomic traits. The statistical analyses were carried out using Henderson's mixed-model approach. The genetic values of the cultivars were predicted, and the heritabilities and accuracies were estimated for selection of cultivars. The cultivar × location interaction was decomposed into its simple and complex fractions. The genetic and environmental correlations between the traits were estimated, and selection was made for multiple traits using the sum of the standardized variables (Z-index). The genetic variance was significant for all the traits, and the cultivar × location interaction was significant. By the Z-index, 15 wheat cultivars more adapted were identified.*

Keywords: Triticum aestivum *L., genotype by environment interaction, genetic variability, index selection*

INTRODUCTION

Brazil is currently one of the main importers of wheat worldwide, despite its enormous potential for growth in production of this cereal crop. However, the cultivation area of this grain crop has increased through occupation of regions in central Brazil (Fioreze et al. 2020). Wheat production in this region progresses together with the creation and implementation of technologies for profitable yields that ensure the growth of tropical wheat growing. Through recommendation for wheat growing in the states of MG, SP, GO, MS, BA, MT, and the Distrito Federal, the region has a potential area of 2.7 million hectares in the *Cerrado*, with a notable opportunity for cultivation in a rainfed system. This cultivation is beneficial for the production system as it does not compete with crops that are dependent on an irrigation structure (Chagas et al. 2021).

In the state of Minas Gerais, the greatest increase in wheat growing occurred as of 2013, due to good market prices. That can be explained by the state holding some advantages in relation to wheat growing: the climate is quite favorable, the low relative humidity during a large part of the cycle favors reduction in pest attack, and harvest during the dry period provides a product with excellent

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hectoliter weight and flour quality, thus achieving good yields. The possibility of harvest in the off-season of the South region of Brazil and of Argentina, along with proximity to the main consumer centers, also increases the competitiveness of the product from Minas Gerais (CONAB 2017).

The southern region of the state of Minas Gerais, specially formed by the Central West and South mesoregions, is responsible for 31.25% of grain production in the state (SEAPA 2023); in addition, it has climate conditions that distinguish it from other regions of the *Cerrado* biome, such as marked occurrence of dew in the growing period defined for wheat in the region in high-altitude areas. Thus, it becomes necessary to develop a wheat-breeding program specifically for this region.

The expansion of wheat growing toward Central Brazil passes through better definition of suitable environments and the development of adapted cultivars. It is essential that plant breeding obtains cultivars with high yield potential, an early cycle, greater resistance to lodging and to diseases, and technological quality of grain appropriate for the final product. It must also allow better use of the genotype × environment (G×E) interaction in this new agricultural frontier, optimizing the use of resources and maximizing yields (Pasinato et al. 2018). Various studies have reported the existence of the G×E interaction in wheat, such as those carried out by Coelho et al. (2010), Condé et al. (2010), and Marinho et al. (2022) in Brazil, which makes cultivar selection complex, especially because genotypic performance changes across the environments. That reduces the magnitude of association between the phenotypic and genotypic values, limiting genetic gain from selection (Bornhofen et al. 2017). Thus, multi-environment experiments in locations that represent the growing environments must be carried out to evaluate the adaptability of the wheat cultivars, whether they are introduced from other countries or developed in Brazilian breeding programs, exploiting the agronomic traits of interest. As this type of information is introduced in breeding programs, the development of cultivars adapted to Brazilian conditions is accelerated (Pereira et al. 2019).

The success of a breeding program involves choosing parents that allow obtaining segregating populations that give rise to lines superior to those already in existence (Ramalho et al. 2012). There are various methodologies in the literature to choose parents in plant breeding (Hallauer et al. 2010). One practical manner is based on evaluation of per se performance of genotypes in the breeding target-environment. Therefore, evaluating a panel of wheat cultivars developed by different breeders is favorable in the sense of capitalizing on the beneficial effects of the selection already made.

With these considerations, the aim of this study was to evaluate the genetic variability and performance of the agronomic traits of wheat cultivars from different breeding programs for growing in the southern region of Minas Gerais so as to identify potential parents for a rainfed wheat breeding program directed toward the region.

MATERIAL AND METHODS

Description of the locations

The experiments were set up in the following locations in the state of Minas Gerais, Brazil: 1) the Crop and Livestock Scientific and Technological Development Center of the Universidade Federal de Lavras (Muquém Farm; lat 21º 14' S, long 45º 00' W, alt 918 m asl), in the municipality of Lavras, MG, in the Campo das Vertentes mesoregion. The mean annual temperature is approximately 19.4 °C and the mean annual rainfall is 1461.8 mm. The climate is classified on the Köppen scale as highland tropical (Cwa). The soil type is red-yellow latosol. 2) 3W Farm (lat 21° 42' S, long 44° 70' W, alt 1023 m asl), in the municipality of Itutinga, MG, Campo das Vertentes mesoregion. The mean annual temperature is 19.3 °C and the mean annual rainfall is 1433.3 mm. The climate is classified on the Köppen scale as highland tropical (Cwa). The soil type is red-yellow latosol.

The experiments were carried out in the 2021 crop season, and the wheat was sown on March 11, 2021, in Lavras and May 3, 2021, in Itutinga. The climate data in the periods in which the experiments were carried out, with information on rainfall from the weather station of INMET in the municipality of Lavras and from rain gauge instruments set up on the 3W Farm, are shown in Figure 1. The temperature data were obtained based on data from the NASA POWER project.

Planning and implementation of the experiments

A total of 78 wheat cultivars coming from different breeding programs were evaluated (Table 1), with 68 cultivars evaluated in Lavras and Itutinga, 2 only in Lavras (‘Valente’ and ‘Supera’), and 8 only in Itutinga (‘BRS 208’, ‘BRS 210, ‘BRS 296’, ‘CD 108’, ‘Embrapa 22’, ‘Fundacep Campo Real’, ‘IPR 130’, and ‘TBIO Sinuelo’). The experiments were set up in an alpha-lattice experimental design, with three replications. Plots consisted of five 5.0-m rows, with between-row spacing of 0.20 m and sowing density of 50 seeds per linear meter.

Traits evaluated

The following traits were evaluated: Heading date (HD, days) – number of days from sowing up to the point at which 50% of the plants of the plot showed head emergence. This trait was evaluated only in Lavras. Plant height (HGT, cm)

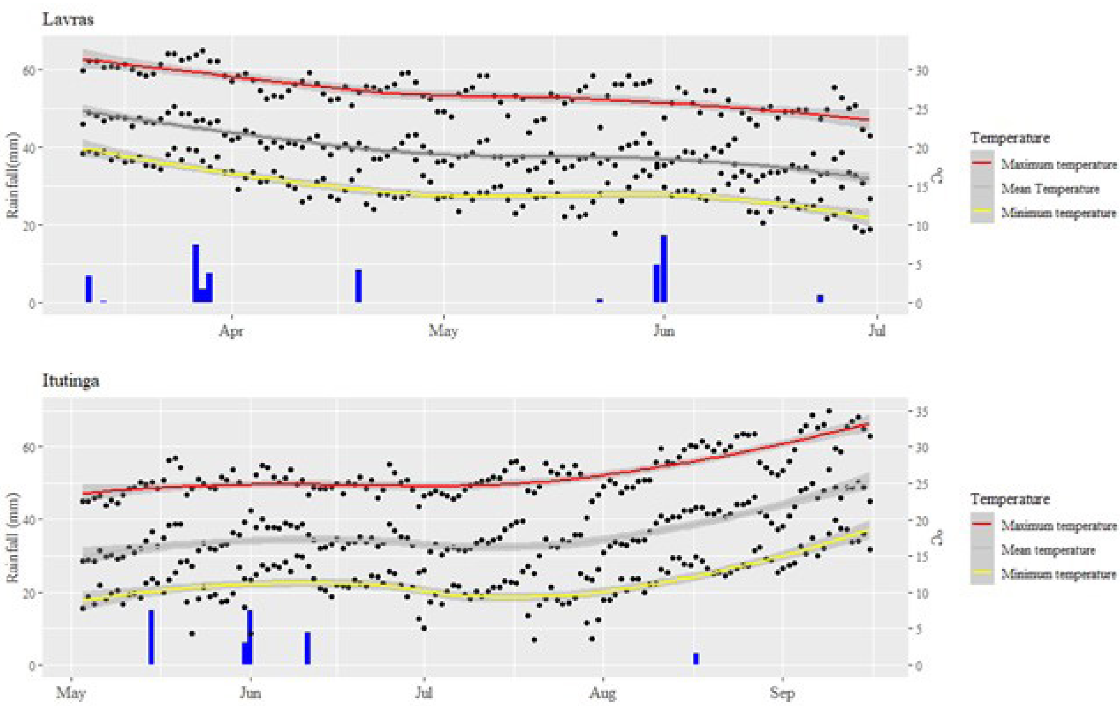

Figure 1. Maximum, mean, and minimum temperatures (°C) and rainfall (mm) throughout the period of conducting the experiments in the municipalities of Lavras and Itutinga, MG, Brazil.

Table 1. Breeding programs and respective cultivars evaluated in the experiments

Breeding Program	Cultivars
Biotrigo	FPS Nitron, TBIO Alvorada, TBIO Aton, TBIO Audaz, TBIO Duque, TBIO Iguaçu, TBIO Itaipu, TBIO Mestre, TBIO Sintonia, TBIO Seleto, TBIO Sinuelo, TBIO Sonic, TBIO Sossego, TBIO Tibagi
Coodetec	CD 105, CD 108, CD 1104, CD 111, CD 116, CD 118, CD 122, CD 124, CD 1252, CD 1303, CD 1440, CD 151, CD 1595
Embrapa	BR 18, BRS 208, BRS 210, BRS 220, BRS 229, BRS 264, BRS 296, BRS 331, BRS 394, BRS 404, BRS Angico, BRS Gaivota BRS Gralha Azul, BRS Louro, BRS Pardela, BRS Reponte, BRS Sanhaço, BRS Tangará, Embrapa 22, Embrapa 42
Epamig	Aliança
Fundacep	Fundacep Campo Real, Fundacep Cristalino, Fundacep Horizonte, Fundacep Raízes
IAC	IAC 24, IAC 385 Mojave, IAC 388 Arpoador, IAC 389 Atacama
IAPAR	IAPAR 78, IPR 128, IPR 130, IPR 136, IPR 144, IPR Catuara, IPR Potyporã
OR Sementes	Ametista, Jadeíte 11, ORS 1403, ORS Citrino, ORS DESTAK, ORSFEROZ, ORS GUARDIÃO, ORS Madrepérola, ORSSENNA, Topázio, Valente
OR Sementes/Biotrigo	Mirante, Marfim, Supera
UFV	UFVT 1 Pioneiro

– measured from the soil surface to the upper part of the spike using a ruler at two points in the plot after heading of all the plants of the plot. Moisture (M, %) – measured using the moisture and impurity analyzer Gehaka® G650 based on a grain sample from each plot after harvest. Thousand-seed weight (W1000, g) – measured using an electronic seed counter ESC 2011 Comp. Sanik®, based on the weight of 1000 seeds without husk. Hectoliter weight (HW, kg hL^{-1}) – measured using the moisture and impurity analyzer Gehaka® G650, based on grain weight without husk at moisture content of around 13%. Grain yield (YLD, kg ha^{-1}) – measured from the weight of grain without husk, in grams, using a benchtop balance at moisture corrected to 13% and converted to kilograms per hectare.

Statistical analyses

The data on each trait were analyzed using Henderson's linear mixed-model approach (Resende 2002). The variance components were estimated by the residual maximum likelihood method, and significance was checked by the likelihood ratio test at 5% probability. These analyses were carried out using the lme4 package (Bates et al. 2015) in the R software (R Core Team 2022).

The individual analyses per location were carried out considering the triple alpha-lattice design. The selective accuracy $r_{\tilde{g}'g'}$ (Resende and Duarte 2007) and the experimental coefficient of variation (CV_e) were estimated for each location using the following estimators:

$$r_{\tilde{g}'g'} = \sqrt{1 - \frac{\overline{PEV}}{\hat{\sigma}^2_{g'}}} \; ; \; CV_e = \frac{\sqrt{\hat{\sigma}^2_e}}{\overline{y}}$$

where PEV is the mean prediction error variance associated with the predicted genetic value of each cultivar via BLUP (best linear unbiased prediction); $\hat{\sigma}^2_{g'}$ is the genetic variance among cultivars; $\hat{\sigma}^2_e$ is the error variance; and $\overline{y}$ is the overall mean of each experiment.

Multi-location analysis was carried out according to the following statistical model:

$$y_{ijkl} = \mu + a_l + r_{j(l)} + b_{j(kl)} + g_i + ga_{il} + e_{ijkl}$$

where y_{ijkl} is the observation of the i-th cultivar in the j-th block within the k-th replication in the l-th location; μ is the constant associated with all the observations; a_l is the effect of the l-th location; $r_{j(l)}$ is the effect of the j-th replication in the l-th location; $b_{j(kl)}$ is the effect of the k-th block within the j-th replication in the l-th location, in which $b_{j(kl)} \sim N(0, \sigma^2_b)$; g_i is the effect of the i-th cultivar, in which $g_i \sim N(0, \sigma^2_g)$ and σ^2_g is the genetic variance of the cultivars, free of the effect of the cultivar × location interaction; ga_{il} is the effect of the interaction between the i-th cultivar and the l-th location, in which $ga_{il} \sim N(0, \sigma^2_{ga})$ and σ^2_{ga} is the variance of the cultivar × location interaction; e_{ijkl} is the error associated with the observation y_{ijkl}, in which $e_{j(kl)} \sim N(0, \overline{\sigma^2_e})$ and $\overline{\sigma^2_e}$ is the mean variance of the experimental error.

The homogeneity of the error variances in the two locations was checked by the likelihood ratio test at 5% probability. The generalized heritability (H^2) on cultivar-mean basis proposed by Cullis et al. (2006) was estimated from multi-location analysis, according to the following estimator:

$$H^2 = 1 - \left[\frac{v_{BLUP}}{2 \times \hat{\sigma}^2_g}\right]$$

where v_{BLUP} is the mean prediction error variance of the difference between BLUPs of two cultivars.

Considering the significance of the cultivar × location interaction, the estimate of the variance component $\hat{\sigma}^2_{ga}$ was decomposed into its simple and complex parts, according to the expression of Robertson (1959), given by:

$$\hat{\sigma}^2_{ga} = \frac{1}{2}(\hat{\sigma}_{g'l} - \hat{\sigma}_{g'l'})^2 + (1 - r_{gll'})\hat{\sigma}_{g'l}\hat{\sigma}_{g'l'}$$

where $\frac{1}{2}(\hat{\sigma}_{g'l} - \hat{\sigma}_{g'l'})^2$ is the simple part of the cultivar × location interaction; $(1 - r_{gll'})\hat{\sigma}_{g'l}\hat{\sigma}_{g'l'}$ is the complex part of the cultivar × location interaction; $\hat{\sigma}_{g'l}$ and $\hat{\sigma}_{g'l'}$ refer to the genetic standard deviations of cultivars in the locations l and l'; and $r_{gll'} = \frac{\sigma_{gll'}}{\hat{\sigma}_{g'_l} \times \hat{\sigma}_{g'_{l'}}} = \frac{\sigma^2_g}{\hat{\sigma}_{g'_l} \times \hat{\sigma}_{g'_{l'}}}$ is the genetic correlation between locations l and l'.

The genetic ($r_{g(t,t')}$) and residual ($r_{e(t,t')}$) correlations between the traits evaluated were estimated according to the following expressions (Falconer and MacKay 1996):

$$r_{g(t,t')} = \frac{\hat{\sigma}_{gtt'}}{\sqrt{\hat{\sigma}^2_{gt} \times \hat{\sigma}^2_{gt'}}};\ r_{e(t,t')} = \frac{\hat{\sigma}_{ett'}}{\sqrt{\hat{\sigma}^2_{et} \times \hat{\sigma}^2_{et'}}}$$

where $\hat{\sigma}_{gtt'}$ is the genetic covariance between the t and t' traits; $\hat{\sigma}^2_{gt}$ and $\hat{\sigma}^2_{gt'}$ are the genetic variances of cultivars for the t and t' traits; $\hat{\sigma}_{ett'}$ is the error covariance between the t and t' traits; and $\hat{\sigma}^2_{et}$ and $\hat{\sigma}^2_{et'}$ are the error variances for the t and t' traits.

For purposes of selection involving the multiple traits, the Z-index was used, based on the sum of the standardized BLUP means of each cultivar (Mendes et al. 2009), according to the following expression:

$$z_{it} = \frac{\bar{y}_{it} - \bar{y}_t}{s_t}$$

where z_{it} is the standardized BLUP mean value of cultivar i for trait t; $\bar{y}_{it}$ is the BLUP mean of cultivar i for trait t, in which $\bar{y}_{it} = \bar{y}_t + \tilde{g}_i$ and $\tilde{g}_i$ is the BLUP prediction of the genetic value of cultivar i; $\bar{y}_t$ is the mean value of the BLUP means of the cultivars for the trait t; s_t is the standard deviation of the BLUP means of the cultivars for the trait t. The standardized values of the traits for each cultivar were plotted on radar charts using the fsmb package (Nakazawa 2018). For the plant height trait, the value of the z-score obtained was inverted by multiplying it by (-1), aiming at selection of shorter plants. The 15 most promising cultivars were ranked based on the highest values of the Z-index, taking the following as the ideotype: plants of lower height and greater 1000-seed weight, higher yielding plants, and greater grain hectoliter weight.

RESULTS AND DISCUSSION

The genetic variance among the cultivars was significant ($P < 0.05$) for all the traits evaluated in both locations (Lavras and Itutinga) (Table 2). In general, the accuracy estimates signaled that the experiments had moderate to high accuracy ($r_{\tilde{g}'g'} > 0.70$) in both locations, ranging from 0.75 (plant height - HGT) to 0.96 (heading date - HD) in Lavras, and from 0.62 (grain yield - YLD) to 0.95 (thousand-seed weight – W1000) in Itutinga (Table 2). The YLD trait was most affected by environmental factors, as indicated by the higher values of the experimental coefficient of variation (CV_e). Bornhofen et al. (2018) evaluated the genetic gains achieved in a wheat breeding program maintained by Crop and Livestock Research Central Cooperative (Cooperativa Central de Pesquisa Agropecuária – COODETEC) in Brazil through annual evaluation of lines in multi-environment experiments and obtained CV_e values from 8.69 to 10.18 % for YLD. In general, the values of CV_e for the evaluated traits indicated high experimental accuracy based on the confidence intervals for this parameter in wheat trials presented by Nardino et al. (2023).

The variation between locations was significant (Tables 2 and 3). The means for all the traits were higher in the municipality of Itutinga than in Lavras. Such differences are associated with macroenvironmental factors, especially the technological management in Itutinga, with improvement in soil structure and fertility and a greater presence of straw, which helps maintain moisture (Thind et al. 2019)

Multi-location analysis (Table 3) showed that the genetic variance (σ^2_g) among cultivars, free of the cultivar × location interaction, was not null ($P < 0.05$) for HGT and W1000, and not significant for HW and YLD. As Ghaffar et al. (2018)

Table 2. Genetic and environment variance components (σ^2_g and σ^2_e), mean ($\bar{Y}$), accuracy ($r_{\tilde{g}g}$) in the cultivar mean values, and experimental coefficient of variation ($CV_{e\%}$) for agronomic traits in wheat cultivars evaluation experiments in Lavras and Itutinga, MG, Brazil, in the 2021 crop season

Trait	Location	σ^2_g	σ^2_e	$\bar{Y}$	$r_{\tilde{g}g}$	CV_e
Heading (days)	Lavras	16.22*	3.16	53	0.96	3%
Plant height (cm)	Itutinga	23.85*	7.02	87 a[1]	0.94	3%
	Lavras	7.99*	16.67	71 b	0.75	6%
Hectoliter weight (kg 100 L^{-1})	Itutinga	0.09*	0.23	79,6 a	0.72	1%
	Lavras	1.91*	1.58	78 b	0.87	2%
1000-seed weight (g)	Itutinga	10.30*	2.00	39 a	0.95	4%
	Lavras	8.52*	1.77	36 b	0.96	4%
Grain yield (kg ha^{-1})	Itutinga	49967.95*	183676.7	3739 a	0.62	12%
	Lavras	73924.46*	127708.7	1967 b	0.77	18%

* Significant by the likelihood ratio test at 5% probability (H_0: $\sigma^2_g = 0$). Mean values of the locations followed by different letters per trait differ by the F-Snedecor test at 5% probability.

Table 3. Estimates of the F-Snedecor (F_c) statistic for the effect of locations (H_0: $\bar{Y}$ *Lavras* = $\bar{Y}$ *Itutinga*), of the genetic variance of cultivars (σ^2_g) and of the genotype by environment interaction (σ^2_{ga}), and of cultivar mean-based heritability (H^2) for agronomic traits in wheat cultivar evaluation experiments in Lavras and Itutinga, MG, Brazil, in the 2021 crop season

Parameter estimates	**Plant height** (cm)	**Hectoliter weight** (kg 100 L^{-1})	**1000-seed weight** (g)	**Grain yield** (kg ha^{-1})
F_c	656.02$^+$	46.59$^+$	77.40$^+$	426.63$^+$
σ^2_g	10.65*	0.19	7.66*	25242.73
σ^2_{ga}	5.88*	0.77*	2.19*	39165.45*
H^2	66%	24%	83%	32%

$^+$ Significant by the F-Snedecor test at 5% probability; * Significant by the likelihood ratio test at 5% probability (H_0: $\sigma^2_i = 0$).

explain, the genetic variation observed for the traits under the same experimental conditions represents the high diversity in genetic composition of the wheat cultivars evaluated coming from different breeding programs.

The variance of the cultivar × location interaction (σ^2_{ga}) was significant for all the traits, which indicates that the wheat cultivars had differential relative performance in the two locations tested (Table 3). Munaro et al. (2014) investigated the G×E interaction on 63 wheat cultivars of the germplasm of COODETEC in 12 environments and also reported significant variance for the cultivar × location interaction.

The existence of the G×E interaction has a negative impact on heritability (H^2), which is a relevant parameter for breeders because it is related to the proportion of the genetic variation in phenotypic manifestation of the traits (Ramalho et al. 2012). The values of the cultivar mean-based heritabilities were low for HW (24%) and YLD (32%), medium for HGT (66%), and high for W1000 (83%). Heritability is not an immutable parameter, and estimates may vary according to oscillations in genetic (e.g., genetic architecture of the trait, genotypes under testing) and environmental factors. Bornhofen et al. (2018) aimed at measuring genetic gains obtained in a wheat breeding program maintained by COODETEC in Brazil through annual evaluation of lines in multi-environment trials, and they observed a negative effect of the environmental component for the overall estimate of progress in grain weight. The authors furthermore highlight that the temporal stability of genotype performance over time is conditioned on the variability of the environmental factors from one crop season to another.

Knowledge of the predominance of the G×E interaction type, whether of the simple or complex type, assists in understanding its effects on selection and in decision making regarding strategies of mitigating its effect, as well as in improvement of assertiveness in recommendation of cultivars. Except for HW (51.31% of the interaction designated simple), the G×E interaction was mainly of a complex nature for all the traits, corresponding to 59.9% for HGT, 98.72% for W1000, and 96.80% for YLD. Similar results were obtained by Coelho et al. (2010).

According to the BLUP means in both locations, the cultivars BRS 404, TBIO Seleto, IAPAR 78, BRS Angico, and IPR 128 had the highest performances for HW. In relation to YLD, the cultivars TBIO Aton, ORS GUARDIÃO, ORS 1403, CD 105, and CD 1252 were the most productive.

In working with multi-trait selection, knowledge of the genetic correlation between traits assists in the definition of selection strategies to be adopted. Genetic correlation was positive among all the traits, but of low magnitude, ranging from 0.11 (HGT – W1000) to 0.34 (HGT – HW), corroborating that reported by Xhulaj and Koto (2022). The environmental correlations among all the traits were positive and of low magnitude, ranging from 0.06 (HW – W1000) to 0.28 (HGT - GY). To perform selection for multiple traits, breeders have a great predilection for use of a selection index, such as the sum of the standardized variables score (Mendes et al. 2009), due to the practicality of interpretation and decision making. The top-15 best-ranked cultivars in relation to the traits evaluated by the Z-index are highlighted in Figure 2, as well as the cultivars BRS 264 and TBIO Aton – those most grown in the region. The ordering of the cultivars showed that ORS GUARDIÃO, CD 105, Valente, BRS Angico, TBIO Aton, IPR 144, CD 1595, CD 1303, IPR 130, CD 1252, BRS Sanhaço, CD 122, BRS 404, TBIO Tibagi, CD 1104, and TBIO Audaz had the highest Z-index, as they had lower HGT and greater HW, W1000, and YLD. BLUP means for the best-ranked cultivars were 78 cm for HGT, 78.9 kg 100 L^{-1} for HW, 40 g for W1000, and 2,940 kg ha^{-1} for YLD. The GY obtained was lower than that reported by Soares Sobrinho et al. (2022), although the average HW was similar. The aim of wheat breeding is to develop new cultivars more adapted to the growing regions (CONAB 2017), with greater grain yield, HW, and W1000, with low HGT, and with resistance to lodging (Mori et al. 2016).

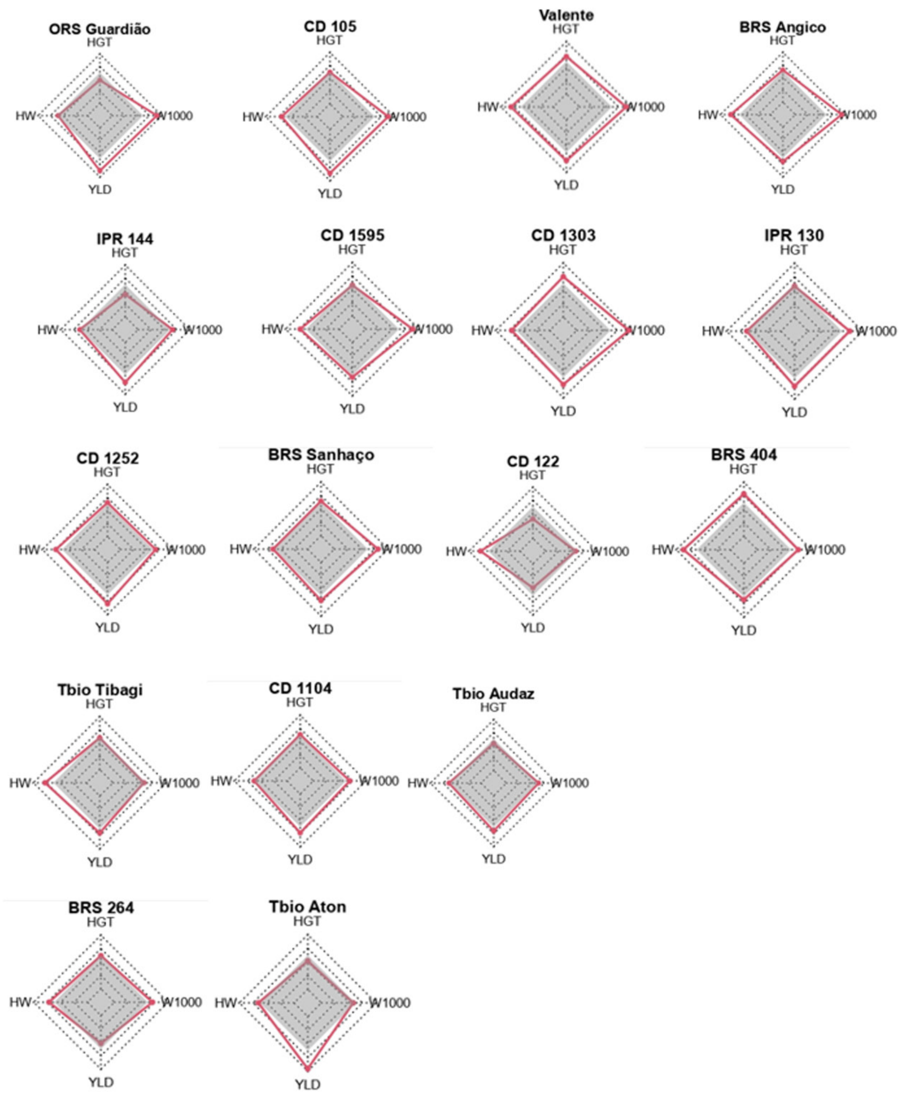

Figure 2. Radar chart based on the Z-index for the 15 best-ranked cultivars for the traits evaluated and for the cultivars BRS 264 and TBIO Aton. Gray area: mean of the experiment in relation to the traits evaluated; Red line: mean of the cultivar for the traits.

Mandarino (1993) suggests that high HW and W1000 show high wheat grain quality and high quality of the flour to be produced. In addition, Scheeren (2011) emphasizes that cultivars with shorter HGT have shown considerable reduction in lodging. Such cultivars match the ideotype of plants with lower height and better performance in relation to HW, W1000, and YLD. This result shows the possibility of using these cultivars in breeding programs. The results here contrasted with those found by Rüdell et al. (2021), who evaluated the performance of 12 wheat cultivars recommended for growing in the north of Rio Grande do Sul, including some of the cultivars evaluated in this study (Ametista, Jadeíte 11, Marfim, TBIO Iguaçu, TBIO Mestre, TBIO Sinuelo, and Topázio). They showed superior performance in the South region of Brazil. This indicates the need for developing cultivars for the Central region of Brazil.

The use of the Z-index led to the identification of 15 cultivars that are closest to the ideotype of wheat: low HGT and high W1000, HW, and YLD. In addition, it clearly shows that although the cultivar BRS 264 is most grown in the state currently, it was not among the 15 best ranked cultivars in relation to the traits evaluated. That shows the need to develop cultivars directed toward growing in the southern region of Minas Gerais.

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