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CROP PRODUCTION

Wheat genotypes selection via multi-trait for abiotic stresses

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ABSTRACT: Abiotic stresses, such as heat, drought and salinity, affect the development of wheat crop and hinder its expansion to the central region of Brazil. The identification of genotypes tolerant to these conditions is important for improving yield performance. The present research evaluated the impact of different abiotic stresses on germination and seedling development and selected wheat genotypes tolerant to these stresses, using multi-trait analysis. Heat, drought and salinity stresses were induced in seeds of 23 wheat genotypes. Seed germination, seedling length and dry mass were evaluated. An adaptability and stability model and a multi-trait selection index were applied to the data. Drought and salinity negatively affected the development of seedlings of the 23 evaluated genotypes. However, the VI 14055, ORS Madre Pérola and BRS 404 genotypes conferred the best adaptability and stability results and were selected by the MGIDI, which revealed that great performance can be achieved in regions with potential for abiotic stress, in the early stages of development.
Key words: adaptability and stability, drought stress, heat stress, salinity stress, *Triticum aestivum L.*

Seleção de genótipos de trigo via multi-trait para estresses abióticos

RESUMO: Estresses abióticos como calor, seca e salinidade afetam o desenvolvimento da cultura do trigo e dificulta a sua expansão para a região central do Brasil. A identificação de genótipos tolerantes a estas condições são importantes para o melhoramento genético da cultura. Logo, objetivou-se avaliar o impacto de diferentes estresses abióticos sobre parâmetros de germinação e do desenvolvimento de plântulas de trigo via análise multi-trait. Estresses térmico por calor, seca e salinidade foram induzidos em sementes de 23 genótipos de trigo. Foram avaliados a germinação das sementes, comprimento e massa seca da plântula. Foram aplicados sobre os dados, modelo de adaptabilidade e estabilidade e índice de seleção multi-trait. Os ambientes de estresse abiótico por seca e salinidade afetaram negativamente o desenvolvimento das plântulas dos 23 genótipos avaliados. Contudo, os genótipos VI 14055, ORS Madre Pérola e BRS 404 combinam os melhores resultados de adaptabilidade e estabilidade e foram selecionados pelo MGIDI. Por meio disso, estes genótipos são potencias para serem recomendados às regiões em que se ocorre estes tipos de estresses abióticos.
Palavras-chave: adaptabilidade e estabilidade, estresse por seca, estresse por calor, estresse por salinidade, *Triticum aestivum* L.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the second most cultivated cereal in the world (FAOSTAT, 2020) and accounts for 20% of all calories consumed worldwide (POUR-ABOUGHADAREH et al., 2021a). Global wheat production for the 2021/22 crop season is estimated at 780.2 million tons, which means a 0.56% increase, compared to 2020/21 (CONAB, 2021).

The global demand for wheat is expected to increase by around 60% in 2050 to feed 9.7 billion people in the world (YADAV et al. 2020). However, forecasts for 2050 point to an increased average global temperature (+ 2 °C) and reduced precipitation (drought) (see details in REYNOLDS et al. 2021). Drought and high temperature cause great losses in wheat productivity. Besides, stress due to salinity, heavy metal toxicity and frost can also reduce wheat productivity in several regions of the world (MONDAL et al., 2021). Research centers, such as CIMMYT (International Maize and Wheat Improvement Center), carry out breeding programs aimed to select genotypes less sensitive to abiotic stresses (MONDAL et al., 2021; REYNOLDS et al., 2021).

Brazil is a major importer of wheat and, to become self-sufficient, in using Southern and Midwestern regions, especially in the Cerrado biome (tropical climate - hot and dry), which reach approximately new 2.7 million hectares (PASINATO et al., 2018; MELLERS et al., 2020). In these regions, the main abiotic stresses are heat, drought, aluminum (MELLERS et al., 2020) and salinity (OLIVEIRA et al., 2021), which may limit the yield potential of the crop (MELLERS et al., 2020). Drought and heat can reduce production by 40-60%, mainly affecting fertilization, grain number and grain filling (MAHROOKASHANI

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et al., 2017). Salinity, similarly, to the others, reduces production, due to reduced germination, and affects physiological and metabolic processes (AL-TABBAL & AL-ZBOON, 2021).

The expansion of wheat cultivation to new frontiers in Brazil requires the selection of genotypes tolerant to abiotic stresses. Therefore, the evaluation and selection for tolerance in the germination and seedling development phases are important, since, at these stages, abiotic stresses can directly affect the final stand of plants and the development of the culture, which negatively impacts grain yield (DADSHANI et al., 2019; MOHAMMED et al., 2021).

In view of the above, the present research evaluated the impact of abiotic stresses on parameters of germination and seedling development, seeking to select tolerant wheat genotypes, using multi-trait analysis.

MATERIALS AND METHODS

Plant material

In this study, 23 genotypes (13 cultivars and 10 lines) of wheat (*Triticum aestivum* L.) were evaluated. The pedigree of the genotypes in the present study are shown in table 1. Seed moisture content, germination percentage and seed vigor were previously evaluated, according to the Rules of Seed Testing (BRASIL, 2009) and methodologies for vigor tests (KRZYZANOWSKI et al., 2020).

Characterization of abiotic stresses

Seeds of all wheat genotypes were sown on paper towel sheets, moistened with different solutions (varying according to the stress to be applied), in an amount equivalent to 2.5 times the mass of the dry paper. The stress conditions were control (1), thermal by heat (2), dry (3) and saline (4). For the conditions, four replicates of 50 seeds were used. The control solution was distilled water. Heat stress was induced in a germination chamber, BOD type, at alternating temperatures of 30 °C (8 hours - day) and 20 °C (16 hours - night), by sowing the seeds in paper towel rolls moistened with distilled water.

For the induction of drought and salt stress, the seeds were sowed in paper towel moistened with polyethylene glycol (PEG-6000) solution at -0.30 MPa or sodium chloride (NaCl), at -0.30 MPa, respectively. The amount of PEG-6000 was determined by the equation given by (MICHEL & KAUFMANN, 1973).

Table 1 - The pedigree of 23 wheat genotypes used in the study.

Genotypes	---------------------Cross---------------------	----------Obtentor--------	---------------Year---------------
ORS 1403 (G1)	Inia Tijereta/Alcover//Abalone	OR Sementes	2016
ORS Madre Pérola (G2)	Marfim/Quartzo	OR Sementes	2017
ORS Destak (G3)	ORS 1405/3/Marfim/Quartzo//Marfim	OR Sementes	2020
TBIO Sintonia (G4)	Marfim/Quartzo//Marfim	Biotrigo	2013
BRS 264 (G5)	Buck Buck/Chiroca//Tui	Embrapa	2005
MGS 1 Aliança (G6)	PF858/OCEPAR11	Epamig	1999
CD 150 (G7)	CD 104/CD 108	Coodetec	2009
CD 151 (G8)	BRS 120/ORL 95282	Coodetec	2012
CD 1303 (G9)	CD 150/BRS 177	Coodetec	2016
CD 1705 (G10)	CD 0536/CD 0562	Coodetec	2016
TBIO Duque (G11)	Toruk#3/Celebra//Noble	Biotrigo	2017
BRS 404 (G12)	MGS 1 Aliança/WT 99172	Embrapa	2015
BRS 394 (G13)	Embrapa 22 e CM 106793 (Roek/3/CMH75A66/CMH76217//PVN"S")	Embrapa	2015
VI 14022 (G14)	BRS254/Aliança	UFV*	2014
VI 14026 (G15)	BRS254/Aliança	UFV*	2014
VI 14050 (G16)	IAC364/BRS207	UFV*	2014
VI 14055 (G17)	IAC364/BRS207	UFV*	2014
VI 14088 (G18)	IAC364/BRS207	UFV*	2014
VI 14426 (G19)	BRS264/BRS207	UFV*	2014
VI 14194 (G20)	BRS264/VI98053	UFV*	2014
VI 14001 (G21)	Embrapa 42/ Pioneiro	UFV*	2014
VI 14208 (G22)	BRS264/VI98053	UFV*	2014
VI 14197 (G23)	BRS264/VI98053	UFV*	2014

*Wheat Improvement Program of the Federal University of Viçosa.

$$\Psi_s = \frac{[-(1.18x10^{-2})C - (1.18x10^{-4})C^2 + (2.67x10^{-4})CxT + (8.39x10^{-7})C^2xT]}{10}$$

Where: Ψ_s: osmotic potential (MPa); C: concentration (g L^{-1} PEG-6000); and T: temperature (°C).

The amount of NaCl used in the saline solution was calculated using the Van't Hoff equation (HILLEL, 1971):

$$\Psi_s = -RxTxCxi$$

Where: R: universal gas constant (0.008314 MPa mol K^{-1}); T: absolute temperature (273.15 + °C); C: molar concentration of solute (mol L^{-1}); i: van't hoff factor, considering the ratio between the number of particles in the solution and the amount of dissolved ions.

The tests were conducted in a completely randomized design, with four replications. The treatments were 23 wheat genotypes submitted to thermal (heat), drought, saline and control conditions.

Evaluations

The evaluations were performed on the fourth and eighth day after sowing (BRASIL, 2009), and the results were expressed as percentage of normal seedlings, which were defined as those exhibiting well-developed shoot and root structures.

On the fifth day after sowing, 10 normal seedlings from each repetition were randomly selected to measure shoot length (SL, in mm), root length (RL, in mm) and total length (TL, in mm). The length was obtained with the aid of a ruler graduated in millimeters.

The total dry matter of seedling (DM, in mg) was also measured in these 10 seedlings, which were previously removed with the aid of a stiletto, later added in paper bags, taken to the forced air circulation oven and kept at 65 °C, for 72 hours. The material was weighed on a precision analytical balance (0.001 g), and the results were expressed in mg $seedling^{-1}$.

Statistical analysis

The experiment was carried out in a 4×23 double factorial design, with the control and three stress environments (thermal by heat, water deficit and saline) and 23 genotypes in a completely randomized design, with four replications. The joint analysis of variance was performed according to the statistical model:

$$Y_{ijk} = \mu + G_i + E_j + GxE_{ij} + e_{ijk}$$

Where: Y_{ijk} is the observation evaluated in the i-th genotype and j-th environment; μ is the general average of the tests; G_i is the effect of the i-th genotype considered fixed; E_j is the effect of the j-th environment considered random; $G \times E_{ij}$ is the random effect of the interaction between genotype i and environment j; e_{ijk} is the random error associated with the observation Y_{ijk}.

Statistical analyses were performed using the package metan (OLIVOTO & LÚCIO, 2020) of the R software 4.1.2 (R CORE TEAM, 2021).

For each variable, the adaptability and stability were evaluated by the method of LIN & BINNS (1988), and the estimates of P_i were obtained using the Genes software system (CRUZ, 2016).

The principal component analysis (PCA) was realized with the factoextra (KASSAMBARA & MUNDT, 2020) and FactoMineR (HUSSON et al., 2020) packages. The ggplot2 package was used for the analysis and building of the box-plot figures (WICKHAM, 2016).

RESULTS

Seed quality

The results of seed moisture content, germination and vigor of the 23 genotypes are presented in table 2. The seeds showed average humidity of 11.86% with germination and vigor above 80%, showing seed good quality.

Descriptive statistics

The box plots of the six variables studied in the three abiotic stress environments are presented in figure 1. The means of shoot length (SL), total seedling length (TL) and first count of germination (FCG) in the control and under heat stress conditions did not differ, which means that heat stress has no effect on these variables (Figure 1). Conversely, dry matter (DM) production seems to have been favored by the application of heat stress, which is shown by its mean slightly higher than that of the control (Figure 1).

Environments of drought and saline stresses reduced seedling development, mainly affecting shoot growth, total length and dry matter weight of seedlings (Figure 1). In addition to these characters, the said environments presented reduced speed of seed germination, according to the FGC (Figure 1). For RL, only the saline stress environment resulted in significant reduction (Figure 1).

Germination (GE) presented no variation regarding the type of studied environment (Figure 1). Therefore, it is observed that the stress levels applied to the seeds of the 23 wheat genotypes did not affect the ability of the seeds to form a normal seedling. Seedling vigor and germination speed were affected though (Figure 1).

For the PEG drought stress environment, it is worth noting that the SL values were lower and that no difference was found in the RL for the control and heat stress environments, which indicates that seedlings with lower water availability invested in root growth to

Table 2 - Water content, germination and vigor seeds the wheat genotypes used in the study.

Genotypes	Water content (%)	--Germination (%)--	------------------------Vigor------------------------	
			FGC (%)	CT (%)
ORS 1403 (G1)	11.42	95	89	93
ORS Madre Pérola (G2)	13.16	88	82	89
ORS Destak (G3)	14.12	98	83	95
TBIO Sintonia (G4)	12.25	83	78	90
BRS 264 (G5)	15.38	90	88	91
MGS 1 Aliança (G6)	11.55	95	88	95
CD 150 (G7)	11.10	84	70	87
CD 151 (G8)	12.55	80	80	86
CD 1303 (G9)	11.53	94	87	97
CD 1705 (G10)	12.02	94	92	98
TBIO Duque (G11)	12.58	85	75	90
BRS 404 (G12)	11.54	83	76	89
BRS 394 (G13)	10.96	95	87	94
VI 14022 (G14)	11.02	87	86	87
VI 14026 (G15)	10.79	82	75	83
VI 14050 (G16)	11.21	88	88	93
VI 14055 (G17)	11.71	85	73	86
VI 14088 (G18)	12.10	89	71	86
VI 14426 (G19)	10.79	85	85	86
VI 14194 (G20)	10.34	89	87	90
VI 14001 (G21)	11.32	92	71	92
VI 14208 (G22)	11.18	89	85	96
VI 14197 (G23)	12.10	89	80	84
Average	11.86	88	82	90

FGC: First Germination Count; CT: cold test.

improve water acquisition (Figure 1). Besides, when the seeds are subjected to saline stress, lower values of SL, RL, TL and DM are observed, which reveals the toxicity caused by the salts (Figure 1).

Through the likelihood ratio test (LRT) deviance (Table 3), it was possible to observe significant differences ($P \leq 0.05$) for all the variables studied. However, in the interaction analysis (LRT_{ge}), the GE variable was not significant. For broad-sense heritability (h^2), we observed low values (< 0.30) for the variables SL, FGC and GE, whereas intermediate values (0.30 – 0.60) were observed for the variables RL, TL and DM (Table 3). The heritability based on the genotypic mean (h^2_{mg}) of the studied variables presented from moderate (h^2_{mg} of 0.67 and 0.52 for SL and FGC, respectively) to high values (h^2_{mg} of 0.86, 0.87, 0.89 and 0.77 for RL, TL, DM and GE, respectively). The genotype-environment correlation (r_{ge}), presented values between 0.01 (GE) and 0.21 (FGC). This result observed for GE indicated the non-existence of complex G×E interaction, as observed in LRT_{ge}. The genotypic variation coefficient (CVg) ranged from 3.80% to 11.03% for GE and DM, respectively, which indicates the occurrence of genetic variation for the variables studied. For CVr, the greatest stability among the variables was obtained by FGC, and the highest value (14.98) could conduce to effective gains.

Adaptability and stability

Table 4 presents the adaptability and stability estimates, for the 5 best genotypes, obtained through the LIN & BINNS, (1988) method, for all the variables studied. For SL, the genotypes VI 14055, BRS 394, BRS 264, MGS 1 Aliança and CD 151 stood out, as they presented lower *Pi* values. For RL, the same was observed for genotypes VI 14194, VI 14055, TBIO Sintonia, VI 14001 and ORS Madre Pérola. For TL, genotypes VI 14055, ORS Madre Pérola, BRS 404, BRS 394 and TBIO Sintonia. For DM, genotypes ORS Madre Pérola, VI 14055, MGS 1 Aliança, BRS 404 and VI 14001. For FGC, genotypes ORS Madre Pérola, ORS Destak, BRS 264, VI 14050 and BRS 404. Genotype VI 14055 was always included among the those selected for the variables SL, RL, TL and DM.

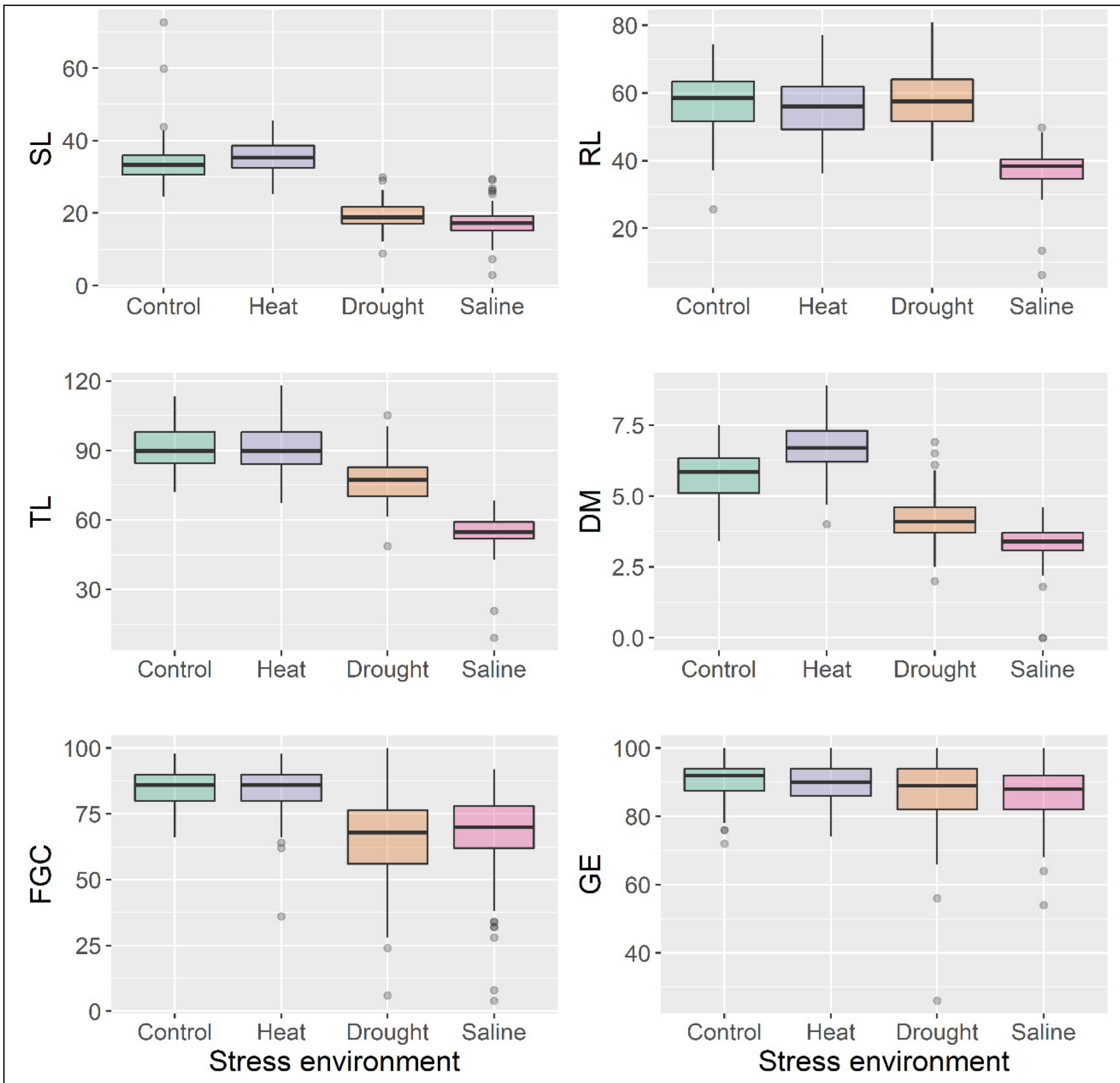

Figure 1 - Box plot of the variables shoot length (SL), root (RL) and total (TL) of seedlings, seedling dry matter (DM), first germination count (FGC) and germination (GE) evaluated in 23 wheat genotypes subjected to three abiotic stress environments.

Principal component analysis

The principal component analysis (PCA) (Figure 2) explained 91.7% of the total variation in the first two components (PC1 and PC2). The GE was not added, since it presented no variation in the environments studied (Figure 1).

As observed in figure 1 for the control environments and heat stress is observed in figure 2, so that the genotypes were associated, when evaluated in these environments. In addition, they tended to cluster in the positive PC1 score (Figure 2).

However, for the environments of drought stress and mainly saline, a greater concentration was observed for the grouping of the genotypes in the negative scores of PC1 (Figure 2). For the saline stress environment, it is still possible to observe that its grouping occurred in the opposite way to the SL and TL, which corroborates again the effect of the salt toxicity on the development of the seedlings of the 23 genotypes. Conversely, for the drought stress environment, the genotypes presented greater association with RL, which evidences the greater radicle growth also observed in figure 1.

Selection of genotypes tolerant to different environments

The multi-trait genotype-ideotype distance index (MGIDI) was used for the selection of genotypes tolerant to each environment (Table 3). Figure 3 exhibits the classification of the studied wheat

Table 3 - Variance components and estimated genetic parameters, for the traits shoot length (SL), root (RL) and total seedling (TL), seedling dry matter (DM), first germination count (FGC) and germination (GE) of 23 wheat genotypes submitted to three abiotic stress environments.

Parameters	------SL------	------RL-----	------TL-----	-----DM----	----FGC----	------GE-----
LRT_g	11.88*	38.14*	40.72*	5.01*	46.90*	21.36*
LRT_{ge}	14.09*	6.99*	10.99*	15.23*	13.68*	0.04^{ns}
PV	21.31	66.45	90.50	0.69	178.47	62.92
h^2	0.17	0.35	0.38	0.43	0.10	0.18
GEIr2	0.16	0.09	0.11	0.11	0.19	0.01
h^2_{mg}	0.67	0.86	0.87	0.89	0.52	0.77
Accuracy	0.82	0.93	0.93	0.94	0.72	0.88
r_{ge}	0.20	0.14	0.17	0.19	0.21	0.01
CVg	7.15	9.20	7.48	11.03	5.59	3.80
CVr	14.17	11.70	8.64	11.33	14.98	8.11
CV ratio	0.50	0.79	0.87	0.97	0.37	0.47
Mean	26.6	52.27	78.65	4.96	75.43	88.16

*Significant at 5% probability; ns, non-significant. LRT_g and LRT_{ge}, Likelihood ratio tests for genotype and genotype by environment interaction (G×E). PV: phenotypic variance; h^2: broad sense heritability; GEIr2: coefficient of determination of interaction effects; h^2_{mg}: heritability based on the mean; r_{ge}: genotype-environment correlation; CVg: genotypic variation coefficient; CVr: residual coefficient of variation.

genotypes, according to MGIDI. Five wheat genotypes were selected, using the selection percentual (~ 20%), namely, VI 14001 (G21), BRS 394 (G13), VI 14026 (G15), CD 150 (G7) and VI 14055 (G17), for the control environment (Figure 3a); VI 14026 (G15), TBIO Sintonia (G4), ORS Madre Pérola (G2), BRS 404 (G12) and VI 14055 (G17), for the heat stress environment (Figure 3b); ORS Madre Pérola (G2), BRS 404 (G12), BRS 394 (G13), VI 14194 (G20) and VI 14055 (G17), for the drought stress environment (Figure 3c); and VI 14055 (G17), ORS Madre Pérola (G2), BRS 404 (G12) and TBIO Sintonia (G4) and MGS 1 Aliança (G6), for the saline stress environment (Figure 3d).

Through the Vennplot (Figure 4), it is possible to identify the genotypes selected in one or more environments. We can visualize that the VI 14055 line was selected in all environments, which demonstrates great adaptive potential. We can highlight that, in each environment, genotypes such as VI 14001 and CD 150 could be selected for the control environment; VI 14194, for the drought stress environment; and MGS 1 Aliança, for the saline stress environment (Figure 4). Through Vennplot, it is still possible to analyze the genotypes selected in more than one environment, such as genotype VI 14026, selected for control environment and heat stress; BRS 394, for control environment and drought stress; TBIO Sintonia, for stress heat and saline stress; and ORS Madre Pérola and BRS 404 genotypes, selected for heat, drought and saline stress environments (Figure 4).

DISCUSSION

In the evaluation of seed quality tests, the degree of moisture needs to be uniform, in order to obtain consistent results. In this way, it prevents differences in metabolic activity and seed wetting speed from affecting the test results (MARCOS-FILHO, 2016). For germination and vigor, the seeds showed values above 80%, demonstrating satisfactory quality standards (BRASIL, 2013). The knowledge and standardization of genotypes for the same moisture and quality condition guarantees the expression of genetic differences.

Studies using germination tests are recommended for the evaluation of many genotypes, since they allow the identification of those most tolerant to stress in the early stages of seedling development (DADSHANI et al., 2019; MOHAMMED et al., 2021). Abiotic stresses affect seedling formation by, for example, decreasing dry matter accumulation and seedling length (PANTOLA et al., 2017). Therefore, it is important to measure these traits to enable the understanding of the adaptation and selection of tolerant wheat genotypes (STEINER et al., 2021).

Based on the results obtained in this study, we observed that drought and saline stress had greater impacts on the vigor of wheat seedlings. Therefore, it is possible to observe the occurrence of promising genotypes and the great genetic variability regarding tolerance to these environments.

The germination variable did not present significant G×E interaction nor was it affected among

Table 4 - Values of adaptability and stability (P_i), obtained by the method of LIN & BINNS (1988), for the traits shoot length (SL), root (RL) and total seedling (TL), seedling dry matter (DM), first germination count (FGC) and germination (GE) evaluated in 23 wheat genotypes submitted to three abiotic stress environments.

Genotypes	-----SL-----	-----RL-----	-----TL-----	-----DM-----	----FGC----	-----GE-----
ORS 1403 (G1)	62.62	81.86	189.14	1.67	158.94	13.84
ORS Madre Pérola (G2)	21.99	19.43	21.13	0.10	7.16	11.12
ORS Destak (G3)	48.63	107.31	209.35	1.77	17.64	18.66
TBIO Sintonia (G4)	46.26	15.44	56.70	1.20	124.16	63.69
BRS 264 (G5)	17.41	209.69	214.54	0.34	27.56	10.37
MGS 1 Aliança (G6)	20.78	109.58	139.23	0.26	87.81	3.25
CD 150 (G7)	38.34	25.22	75.80	1.08	215.37	90.06
CD 151 (G8)	21.98	84.66	118.60	0.69	311.47	177.56
CD 1303 (G9)	56.17	81.60	181.72	1.32	219.34	7.65
CD 1705 (G10)	69.06	287.63	526.04	4.43	504.59	22.56
TBIO Duque (G11)	54.87	49.86	127.82	1.22	191.13	42.31
BRS 404 (G12)	25.62	23.99	46.73	0.28	34.91	29.03
BRS 394 (G13)	13.65	39.21	51.07	0.42	70.31	10.94
VI 14022 (G14)	34.07	78.43	125.81	0.94	73.53	37.03
VI 14026 (G15)	32.77	41.99	97.93	0.67	89.59	61.03
VI 14050 (G16)	24.32	112.64	159.58	0.68	28.44	23.44
VI 14055 (G17)	2.63	15.31	4.34	0.21	70.31	45.56
VI 14088 (G18)	27.61	55.36	103.74	0.42	204.69	78.31
VI 14426 (G19)	23.81	112.75	153.83	1.23	284.28	45.56
VI 14194 (G20)	31.35	5.72	101.47	0.43	134.09	58.62
VI 14001 (G21)	30.92	18.00	106.67	0.33	183.03	9.93
VI 14208 (G22)	40.80	163.40	251.08	0.73	89.31	10.16
VI 14197 (G23)	41.90	187.94	274.30	1.30	74.34	31.47

the environments. Seed germination is directly associated with their physiological quality (ZUFFO et al., 2020). For wheat, the minimum germination percentage for commercialization is 80% (BRASIL, 2013). Accordingly, the seeds of the different genotypes used in our study presented excellent quality in the different environments, since they obtained values above 80%.

In a study on the tolerance of black oat (*Avena strigosa* cv. Agro Planalto) and wheat (*T. aestivum* cv. Jadeite 11) to drought stress, using PEG, at different potentials (0, -0.2, -0.4 and -0.8 MPa), no reduction in the percentage of seed germination was observed in wheat, even at a potential of -0.8 MPa (STEINER et al., 2017). According to these authors, wheat presents greater tolerance to drought stress in the seed germination phase (STEINER et al., 2017). In barley (*Hordeum vulgare*), when 20% PEG was applied or not to the filter paper, a percentage of seed germination equal to 100% was observed in some of the genotypes (THABET et al., 2018).

The traits shoot length (SL), root (RL), total (TL) and dry matter (DM) of the seedling revealed great sensitivity to the drought, saline and heat stresses. A study with barley (THABET et al., 2018) observed a negative effect on the shoot and root development of the seedling caused by drought stress. These authors argued that the use of these variables are important to identify genotypes with better development under drought stress conditions (THABET et al., 2018). However, for the drought stress imposed by the PEG 6000 solution, the negative effect on seedling development was reported on seedling length (SL), rather than the root system (RL). The increased root development of seedlings is highlighted as one of the mechanisms of tolerance or resistance to water restriction (THABET et al., 2018). However, reduction was quite evident in the total length of the seedling. Studies with wheat report reduced length of the seedlings subjected to drought stress (by PEG 6000) (LIU et al., 2013). This results from the drought stress induced by PEG, which causes oxidative damage, including increased H_2O_2 and O^- (ROS), generation of malondialdehyde (MDA) and higher levels of proline and soluble sugar (GUO et al., 2017), which hinders the development of the seedling.

Regarding saline stress, the seedling traits (SL, RL, TL and DM) presented greater reductions

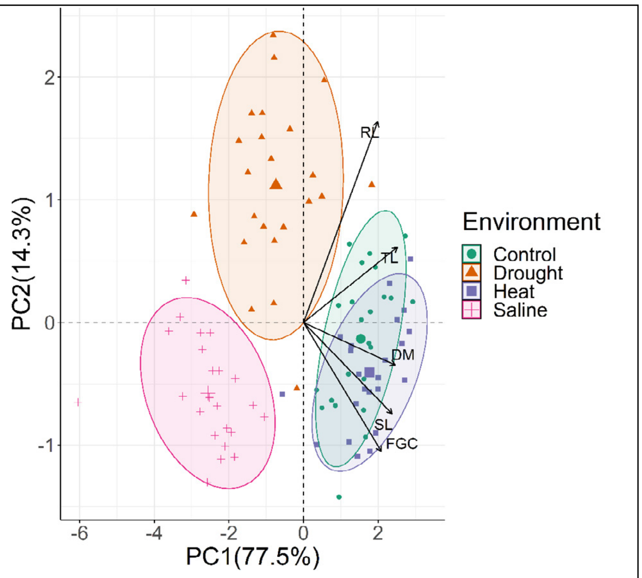

Figure 2 - Biplot of principal component analysis (PCA) obtained by the linear combination of variables related to seed germination and seedling development of 23 wheat genotypes, submitted to three abiotic stress environments. SL: shoot length; RL: root length; TL: total seedling length; DM: seedling dry matter; FGC: first germination count. PC1: principal component 1; PC2: principal component 2.

in length and weight. The toxicity evidenced in saline stress demonstrated that, in addition to drought stress (RAHMAN et al., 2016; POUR-ABOUGHADAREH et al., 2021b), it causes ionic imbalance and production and accumulation of reactive oxygen species (ROS), which reduces cell division and elongation (RAHMAN et al., 2016; AL-TABBAL & AL-ZBOON, 2021; POUR-ABOUGHADAREH et al., 2021b). Researchers linked reduced shoot and root growth in wheat seedlings (*Triticum turgidum* var. sham 3) to reduced absorption of water by the seeds, due to salinity (AL-TABBAL & AL-ZBOON, 2021). In a study with barley, a highly significant effect of salinity stress on several growth and physiological traits was also observed, and the 20 genotypes were negatively affected by salinity (POUR-ABOUGHADAREH et al., 2021b).

Still on the salinity effect, we observed a negative effect of the salinity in the substrate on the germination rate (FGC). This corroborated other results obtained in wheat (cv. Caxton) (FULLER et al., 2012). The negative effect on seed germination speed can be explained by the toxicity of the salts, which affects cell division and differentiation, enzymatic activity and the uptake and distribution of nutrients during the germination process (RAHMAN et al., 2016).

Regarding heat stress, the recommended temperature for conducting germination tests for wheat is 20 °C (constant) (BRASIL, 2009). In our study, we sought to infer a degree of heat stress on seeds and seedlings, by assigning temperatures of 30 °C (8 hours – day) and 20 °C (16 hours – night) to the experiment. Studies infer that high temperatures (28 to 30 °C) impair the germination of wheat seeds (YAMAMOTO et al., 2008; AKTER & ISLAM, 2017), lower growth (YAMAMOTO et al., 2008) and reduce biomass production (AKTER & ISLAM, 2017). However, we observed that alternating temperatures of 30-20 °C favor the speed of germination, growth and accumulation of dry matter in the seedling. This can be explained by the fact that, at higher temperatures, the metabolic processes are accelerated, which increases cellular respiration in mitochondria and enzymatic activity (BEWLEY et al., 2013; MARCOS-FILHO, 2016). Studies using the wheat varieties Moomal-2000 and Meharan-89 presented higher germination, length and weight of fresh and dry seedlings, at temperatures of 20 or 30 °C (BURIRO et al., 2011).

For the variance components and genetic parameters studied, we observed low values for heritability (h^2) in all variables (< 0.5), which demonstrates low variability for these characteristics and hinders the work of wheat breeding. Thus, further studies with objectives similar to these are necessary in order to detect variability in seedling development under abiotic stress conditions. Regarding accuracy, it was

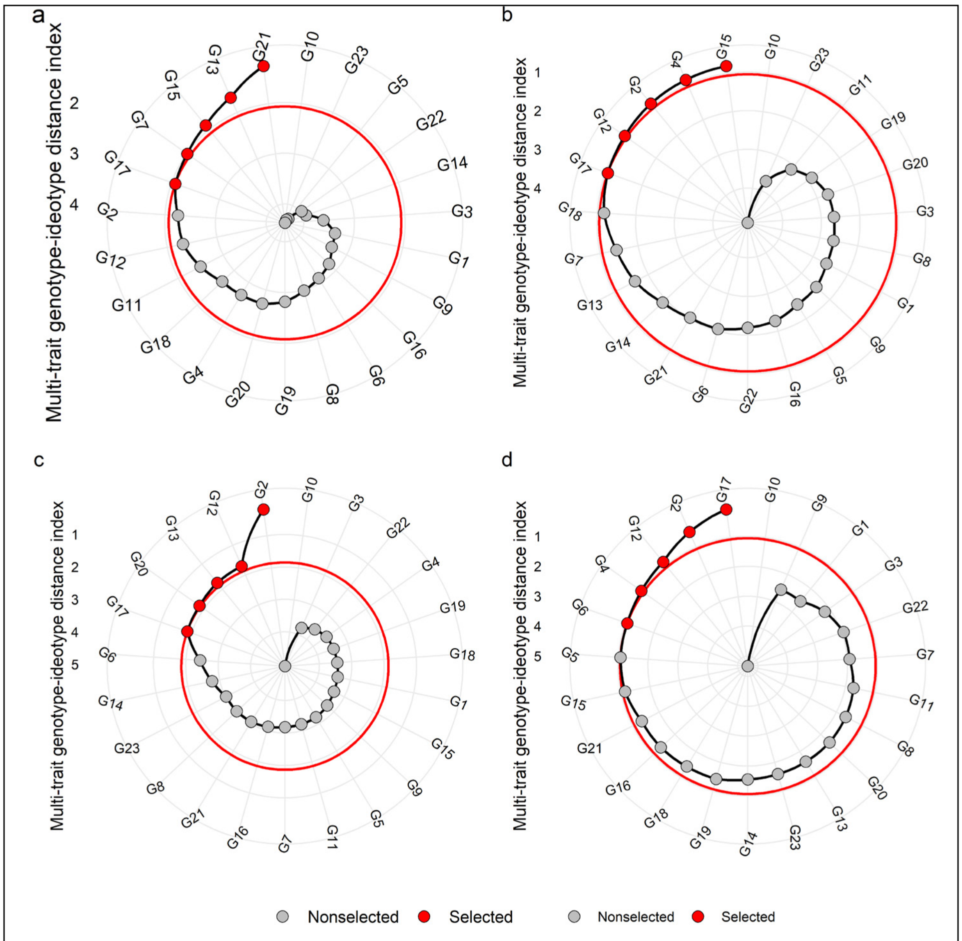

Figure 3 - Genotypes selected for each studied environment, based on the MGIDI index. Environments control (a), heat stress (b), drought stress (c) and saline stress (d).

possible to observe that the precision was greater than 0.7 for all analyzed variables, which demonstrated that the experimental design was effective in controlling the disturbance effects (RESENDE & DUARTE, 2007).

Through the study of adaptability and stability of genotypes to the stress environments studied, the five best genotypes were selected based on the lowest value of P_i (LIN & BINNS 1988), which indicated their good performance under the studied stress environments (ARJONA et al., 2020). The multivariate techniques employed are relevant when we seek to select wheat genotypes for a set of traits. Such observation is said to be common in plant breeding, which in turn makes it difficult to provide a generalized recommendation for multiple traits (STEINER et al., 2021).

Due to the large number of variables and genotypes studied, it is necessary to use multivariate analyses that reduce the dimensionality of the data and thus help to understand the data in a broad way. In our study, we applied PCA to group genotypes and environments, in order to analyze their associations with each variable studied. Hence, it was possible to verify that drought and saline stresses are very different, but negatively affected the genotypes. However, this method was not able to select the most tolerant genotypes, which was also observed in a study with barley (POUR-ABOUGHADAREH et al., 2021b).

Based on observation, it is necessary to employ other tools to select genotypes using the information of the multiple characteristics studied. Through MGIDI (OLIVOTO & NARDINO 2021), different wheat genotypes were classified based on this information for different environments. The MGIDI enabled the selection of four salt-tolerant barley genotypes (POUR-ABOUGHADAREH et al., 2021b) and three upland tolerant lentil genotypes in Southern Italy (SELLAMI et al., 2021).

Through Vennplot, it was possible to highlight the genotypes selected for each stress studied environment. An important highlight is

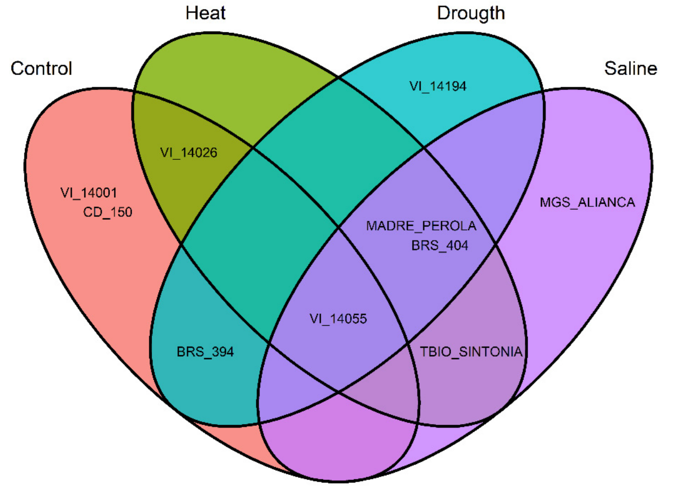

Figure 4 - Venn plot indicating the genotypes selected under different abiotic stress environments (Control, Heat, Drought and Saline), using the MGIDI index.

given to VI 14055, which is a line of the Wheat Breeding Program of the Universidade Federal de Viçosa, selected in the four environments studied and, therefore, promising for implementation in areas characterized by the particularities analyzed. In addition, it was possible to select other lines from the breeding program and commercial cultivars for one or more environments of abiotic stress. The use of Venn plot helped in the selection of wheat genotypes under conditions of control and drought stress, owing to the use of selection indexes (MGIDI, Smith-Hazel and factor analysis and ideotype-design - FAI) (POUR-ABOUGHADAREH & POCZAI, 2021).

CONCLUSION

The study of 23 wheat genotypes, under conditions of abiotic stresses by heat, drought and salinity, using an adaptability and stability model and multi-trait selection index allowed the identification of genotypes, such as VI 14055, ORS Madre Pérola and BRS 404, which conferred the best adaptability and stability results and were selected by the MGIDI. Thereby, these genotypes have the potential to be recommended to regions with the same types of abiotic stresses.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

AUTHORS' CONTRIBUTION

All the authors contributed equally for the conception and writing of the manuscript. All authors revised the manuscript and approved the final version.

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