Bulgarian Journal of Agricultural Science, 30 (No 2) 2024, 323–332

Agronomic performance associated with the incidence of frost on wheat cultivars in Brazil

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Abstract

Follmann, D. N., Vendrame, M., da Rosa, G. B., dos Santos, E. D. & Pereira, A. P. (2024). Agronomic performance associated with the incidence of frost on wheat cultivars in Brazil. *Bulg. J. Agric. Sci., 30*(2), 323–332

The subtropical environments, are the regions with the largest area of wheat cultivation in Brazil, however, events, such as frost formation in the period of flowering and grain filling negatively influence the production, due to direct loss in grain formation. Identifying cultivars, which have a higher genetic resistance to frost damage, can provide strategies for maintaining the productive potential in commercial crops in subtropical region in Brazil. The study aimed to evaluate the linear relationships among characters and the agronomic performance of wheat cultivars of different cycles, under the influence of frost stress in a subtropical low altitude region. The experiment was conducted in a subtropical climate triticultural region in the South of Brazil (Santa Maria, RS). A randomized block design with seven cultivars and four repetitions was used, totaling 28 experimental units. The cultivar cycle from the emergence stage to physiological maturity was recorded, as was the recording of the phenological stage on the day of frost formation. The characters evaluated were: plant height, number of fertile tillers, number of spikelets per plant, number of grains per plant, whole grains in the main stem, damaged grains in the main stem, whole grains in the tillers, damaged grains in the tillers, thousand-grain mass, hectoliter weight, grain yield, harvest index, and number of spikes per m². Analysis of variance, test for comparison of means between treatments with significant effect, Pearson linear correlation analysis, and trail analysis were performed. The results show that the cultivars and phenological stages of the plants have different degrees of sensitivity to frost damage, with the early anthesis stage being less sensitive to frost damage than the late milky grain stage. Therefore, the linear relationships indicate that the characters plant height, number of fertile tillers, number of grains per plant, whole grains and hectoliter weight, have positive relationship with grain yield. There is a genetic effect for tolerance to frost damage. The use of cultivars with similar cycle behavior are not indicated, as they increase the risk of frost losses when sowing in only one growing season.

Keywords: wheat cultivation; subtropical environment; trail analysis; Pearson correlation; cold damage in grasses

Introduction

Wheat (*Triticum aestivum* L.) is a species of annual cycle belonging to the Poaceae family, it is the second most produced cereal in the world and represents the largest cultivation area in the subtropical region of Brazil in the winter period. Worldwide, the country ranks 20th in wheat production, behind countries such as China, India, and the USA (FAOSTAT, 2022). According to FAO, in the year 2021 the area cultivated with the crop in the country was 2.7 million hectares with a production of 7.8 million tons.

Wheat cultivation is important in the composition of sustainable agricultural production systems as an alternative to winter crop rotation in production systems, contributing to the integrated management of pests, diseases, weeds, soil structuring and coverage, and nutrient cycling, in addition to profitability for the producer (Barro et al., 2017). The crop has great importance in the diet due to its quality and quantity of protein, accounting for 21% of protein requirements and 19% of daily calories in the human diet (Tadesse et al., 2019). In Brazil, annual consumption is approximately 12 million tons, requiring the importation of grain from other countries to supply the internal demand (Amis, 2020).

The areas cultivated with wheat in Brazil are concentrated in the South, Southeast, and Center-West regions. The states of Paraná and Rio Grande do Sul, subtropical region, together account for 80% of national grain production (CONAB, 2020). This vast area of cereal production houses a diversity of soils and climate conditions for each growing region.

Meteorological variables interfere directly in the annual variation of agricultural crops. The effects of low temperatures, such as frost formation, on crop development and wheat yield vary depending on the cultivar and stage of plant development. When plants are exposed to frost, the growth of extracellular ice causes water to move from the protoplast into the extracellular space, which dehydrates the cell (Xin & Browse, 2001). The more concentrated the solution, the lower the water potential and freezing temperature operation (Silva et al., 2008).

Some plant characters are more affected than others by adverse environmental conditions, so grain yield is the result of the response of different components to these conditions (Parent et al., 2017). The grain yield of wheat is the result of estimating three components: number of spikes per m², number of grains per spike, and thousand-grain mass. However other plant characters influence productivity indirectly through direct influence on the components, such as the number of plants and fertile tillers per m² (Gelalcha & Hanchinal, 2013; Mecha et al., 2017).

To improve the agronomic performance of crops, understanding the relationships between characters of agronomic interest is fundamental. Linear correlation techniques, such as Pearson, interpret the strength of the linear association between a pair of variables. However, when a variable presents high association with more than one variable it is desirable to determine a dependent (of interest) and verify the direct and indirect effects via other independent variables on the variable under study, for this, one option is the use of the trail analysis technique. Study by Gelalcha & Hanchinal (2013) verified the significant linear correlation between agronomic characters such as number of tillers and thousand-grain mass with wheat grain yield. They also observed that these traits influenced grain yield indirectly, mainly via biomass production that had a direct influence on grain yield. Therefore, improving attributes that directly impact biomass will indirectly improve grain yield.

In this context, the study aimed to evaluate the linear relationships among characters and the agronomic performance of wheat cultivars of different cycles, under the influence of frost stress in a subtropical low altitude region.

Material and Methods

The experiment was conducted in the 2020 crop year in an experimental area with suitability for wheat cultivation in Santa Maria (29° 41′ 23.10″ S and 53° 47′ 33.13″ W), altitude of 90 m, in the state of Rio Grande do Sul (RS), Brazil. The climate of the region according to the Köppen classification is humid subtropical, with hot summers and no defined dry season (Cfa) (Alvares et al., 2013) and the soil of the experimental area is classified as Paleudalf (Classification according to Soil Taxonomy: USDA, 2010). The meteorological data for site characterization were obtained from an automatic weather station located 500 m from the experiment.

The summer crop that preceded wheat was corn (*Zea mays* L.). The experimental design used was randomized block design, with seven treatments (cultivars) and four repetitions, totaling 28 experimental units. The treatments consisted of the cultivars: TBIO Astro, TBIO Audaz, TBIO Capricho CL, TBIO Duque, TBIO Sinuelo, TBIO Sonic, and TBIO Toruk. The cultivars were chosen based on the representativeness of the cultivated area in the state, different cycles, and some with little time on the market (new releases). The experimental units were composed of 9 rows, with spacing of 0.20 m between rows and 5 m long, totaling an area of 9 m^2.

Sowing of the experiments was performed on May 14, 2020, at the opening of the sowing period indicated by the Agricultural Risk Zoning (Zoneamento Agrícola de Risco – ZARC) (MAPA, 2021), with the aid of a plot seeder, with a density adjusted to 300 plants m^{-2}. Before sowing, soil sampling of the area was performed, followed by fertilization for the expectation of 4 t ha^{-1} of grain, according to the Fertilization and Liming Manual (CQFS, 2016). During the sowing process, mineral fertilization was performed in the sowing furrow. Subsequently, nitrogen fertilization was applied in the form of top dressing urea when the plants reached the V3 (beginning of tillering) and V5 (full tillering of the crop) stages. The other cultural treatments carried out to control weeds, pests, and diseases in the crop followed the technical recommendations for the wheat crop (EMBRAPA, 2019). During the course of the experiment, the date of flowering and physiological maturity was recorded, and the phenological stage of each treatment on the day frost formation occurred was also noted (Table 1).

Table 1. Cycle of wheat cultivars from emergence to anthesis, and from emergence to physiological maturity. Santa Maria, RS, Brazil, 2023

Cultivar	EIA, days	EMF, days
TBIO Astro	77	138
TBIO Audaz	84	141
TBIO Capricho CL	95	147
TBIO Duque	82	141
TBIO Sinuelo	102	147
TBIO Sonic	77	138
TBIO Toruk	84	141

Days elapsed from emergence to the beginning of anthesis, when 50% of the plants were at stage 6.1 on the scale proposed by Zadoks 1974 (EIA), and days elapsed from emergence to physiological maturity, when 90% of the spikes were at stage 9.0, according to the scale proposed by Zadoks 1974 (EMF)

When the plants reached physiological maturity and were ready to be harvested, 40 plants per plot were collected for frost damage assessment. Frost damage was assessed individually on the 40 plants collected, measuring the variables: whole grains in the main stem (WGMS) and damaged grains in the main stem (DGMS). When the plant contained fertile tillers, the same assessments were made on the main plant for each of the fertile tillers.

Ten of the 40 plants collected were selected to measure the following variables: plant height from the neck to the end of the spike (PH, cm), number of fertile tillers, that is, tillers that contained spikelets with grain formation (NFT), number of spikelets per plant (NSP), and number of grains per plant (NGP). Subsequently, the 10 plants were taken to an oven for 72 hours at 105°C and the dry mass was measured on a precision scale, and the harvest index (HI) was determined using the formula:

$$\left[\frac{\text{DM grain}}{\text{DM grain} + \text{DM straw}}\right]$$

where: DM grain – grain dry mass; and, DM straw – straw dry mass.

After collecting the plants for individual evaluations, the number of spikes per square meter (SPI) was counted and the useful area of the plot (3 m², being 3 linear meters and 5 rows of plants spaced at 0.20 m between rows) was harvested, where the following variables were subsequently determined: grain yield (YIE, kg ha^{-1}), thousand-grain mass (TGM, g), and hectoliter weight (HW, kg hl^{-1}).

All the evaluated variables were submitted to variance analysis and the means of the treatments were compared using the Scott-Knott test at 5% error probability. The variables with significant treatment factor in the variance analysis were subjected to Pearson linear correlation test at 5% error probability. Subsequently, the diagnosis of multicollinearity of the correlations was performed as a requirement for conducting the trail analysis by means of the condition number (CN) and variance inflation factor (VIF) test (Montgomery et al., 2021). For multicollinearity to be regarded as weak (absence of VIF >10 and CN < 100) only the variables PH, NSP, NGP, TGM, PH, WGMS, WGT2, DGT1, and YIE were retained for the trail analysis.

The analyses were performed with the aid of R software and the Microsoft Office Excel® program.

Results and Discussion

During the entire experimental period, the water balance of the crop (Figure 1) verified the occurrence of moments of excess and water deficit that represent 388.15 and 60.61 mm, respectively, distributed during the experimental period. The month of August, a period in which the cultivars considered precocious had already started their reproductive period, was marked by the occurrence of severe frost on August 21, when there was a minimum temperature of -0.9°C (Figure 2). According to the Zadoks scale (Zadoks, 2016) the cultivars TBIO Astro and TBIO Sonic were at the soft mass stage (scale number 8.5), and they entered anthesis on the date of July 29; TBIO Audaz and TBIO Toruk final milky grain stage (7.7), showing anthesis on August 5. TBIO Duque milky grain stage (7.5), which entered anthesis on August 3, andTBIO Capricho CL and TBIO Sinuelo at anthesis onset stage (6.0), which presented at anthesis on August 16 and 23, respectively. A frost caused damage to the cultivars under study, through analysis of variance there was a significant effect of the treatment factor for the evaluated characters in response to damage from frost, with the exception of the SPI variable. In general, a higher coefficient of variation is observed for the qualitative variables of the grains, such as WGMS (81.51%), WGT1 (126.99%), and WGT2 (279.56%). For the TGM, HW, and PH variables, the variation was lower, values of 3.00, 3.49, and 8.61%, respectively (Table 2).

At the time of frost formation, the treatments TBIO Sinuelo and TBIO Capricho CL, cultivars considered late-cycle, were in the stage (6.0) and showed the highest grain yields with 3461 and 2735 kg ha^{-1}, respectively. The lowest grain yields were in the treatments TBIO Duque with 986 kg ha^{-1} and TBIO Toruk with 695 kg ha^{-1} with frost formation at stages (7.5) and (7.7), respectively (Table 3). Whaley et al. (2004), Liu et al. (2020), and Wu et al. (2022) also observed significant losses in wheat grain

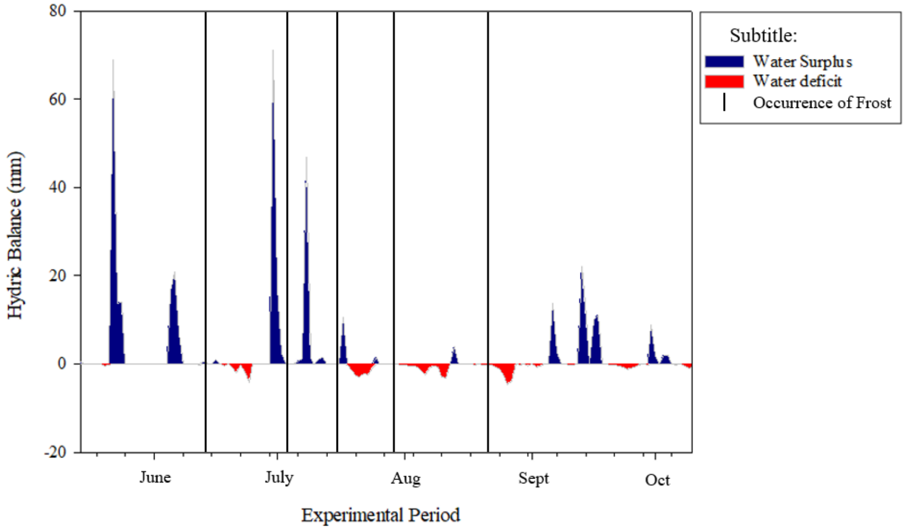

Fig. 1. Crop water balance and frost occurrence periods during the 2020 growing season, Santa Maria, RS, Brazil, 2023

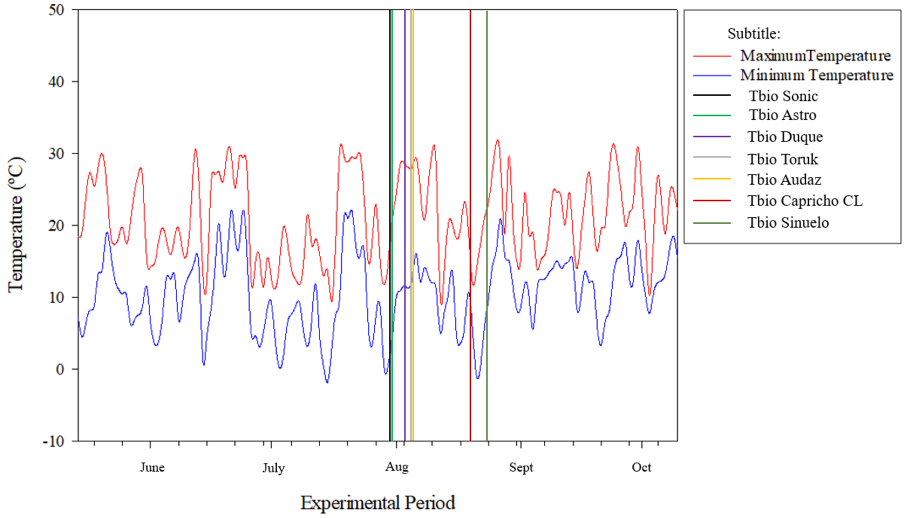

Fig. 2. Maximum and minimum temperature, anthesis starting date of wheat cultivars in the 2020 crop year. Santa Maria, RS, Brazil, 2023

yield as a result of frost. Reznick et al. (2021) in a study conducted in Ponta Grossa, state of Paraná, Brazil, with different nitrogen doses, the cultivars TBIO Sinuelo and TBIO Toruk did not differ statistically for grain yield with 2532 and 2607 kg ha^{-1}, respectively. In the present study, the difference in YIE between the two cultivars was 2766 kg ha^{-1}, showing the effects suffered by the cultivars as a result of frost formation in different phenological stages, highlighting the genetic influence and the vegetative stages for frost damage, as observed for the cultivar TBIO Audaz, which had a similar cycle to the cultivar TBIO Toruk, but with higher average YIE.

In addition to higher YIE, the two treatments, TBIO Sinuelo and TBIO Capricho CL, had the highest HI and HW values, differing statistically from the other treatments. The HI that corresponds to the percentage of grain to total plant dry matter is usually influenced by environmental adversities (Koppensteiner et al., 2022). The HI values were higher than 55% for the two treatments, while the other treatments had HI lower than 32% and did not differ between them. Mecha et al. (2017) corroborate with the results, as, they observed direct and positive effect of harvest index on wheat grain yield. Already the HW, defined as the weight of a known volume of grain that reflects grain density, is influenced by genetics, management, and environment (Nuttall et al., 2017). The treatments TBIO Sinuelo and TBIO Capricho CL had HW higher than 78, being characterized as Type 1 wheat. Obtaining a high HW value means larger and better quality grains (Nuttall et al., 2017), being an indicator of the good development of cultivars under field conditions, where

Table 2. Mean squares of the analysis of variance (ANOVA) of the variables analyzed as a function of the occurrence of severe frosts in the reproductive stages of the wheat crop. Santa Maria, RS, Brazil, 2023

SV	DF	PH	NFT	NSP	NGP	WGMS	DGMS	WGT1
Blocks	3	340.19*	1.52ns	447.59**	845.11ns	1347.93*	503.68*	878.46*
Treatments	6	1397.10*	3.27*	442.76*	11359.03*	17519.29*	12492.97*	4838.01*
Residue	1110	40.57	0.66	130.63	476.12	91.78	58.13	91.80
Mean	–	74.02	1.04	25.71	38.43	11.75	25.71	7.54
CV (%)	–	8.61	78.06	44.45	56.78	81.51	44.45	126.99
SV	DGT1	WGT2	DGT2	TGM	HW	YIE	HI	SPI
Blocks	28.92ns	93.13ns	5.80ns	1.36ns	3.56ns	141596.43*	24.59ns	25199.18ns
Treatments	223.13*	577.40*	14.21*	76.79*	120.55*	4060789.11*	1042.44*	30817.41ns
Residue	28.01	40.98	6.03	1.01	6.34	36738.66	127.19	17242.48
Mean	2.53	2.29	0.57	33.61	72.29	1698.85	36.64	321.62
CV, %	208.74	279.56	428.58	3.00	3.49	11.28	30.78	40.83

SV: Sources of variation; DF: Degrees of freedom; CV: Experimental coefficient of variation (%); PH: plant height from the neck to the end of the spike (cm); NFT: number of fertile tillers; NSP: number of spikelets per plant; NGP: number of grains per plant; WGMS: whole grains of the main stem; DGMS: damaged grains in the main stem; WGT1: whole grains of tillers 1; DGT1: damaged grains of tillers 1; WGT2: whole grains of tillers 2; DGT2: damaged grains of tillers 2; TGM: thousand-grain mass (g); HW: hectolitre weight (kg hl^{-1}); YIE: grain yield (kg ha^{-1}); HI: harvest index; SPI: number of spikes per m^2. * Significant at 5% probability of error by the F test. ns – not significant by the F test.

Table 3. Comparison test of means among cultivars for different characters of agronomic interest. Santa Maria, RS, Brazil, 2023

Cultivar	PH	NFT	NSP	NGP	TGM	HW	YIE	HI
TBIO Astro	67.57 e	1. 25 a	28.35 a	37.55 b	26.18 d	66.00 c	1301 c	27.75 b
TBIO Audaz	74.05 c	0.72 b	22.92 b	25.37 c	36.31 b	73.98 b	1314 c	26.55 b
TBIO Capricho CL	79.80 b	1.35 a	25.90 b	57.62 a	31.81 c	78.13 a	2735 b	57.78 a
TBIO Duque	75.55 c	0.90 b	22.75 b	26.82 c	35.12 b	72.96 b	986 d	29.16 b
TBIO Sinuelo	82.82 a	1.40 a	31.45 a	65.27 a	35.87 b	79.71 a	3461 a	61.94 a
TBIO Sonic	67.20 e	0.97 b	26.05 b	35.22 b	30.62 c	66.00 c	1400 c	31.10 b
TBIO Toruk	71.15 d	0.72 b	22.57 b	21.15 c	39.37 a	69.27 c	695 e	22.18 b
Mean	74.02	1.04	25.71	38.43	33.61	72.29	1698.85	36.64
CV, %	8.61	78.06	44.45	56.78	3.00	3.49	11.28	30.78

CV: Experimental coefficient of variation (%); PH: plant height from the neck to the end of the spike (cm); NFT: number of fertile tillers; NSP: number of spikelets per plant; NGP: number of grains per plant; TGM: thousand-grain mass (g); HW: hectolitre weight (kg hl^{-1}); YIE: grain yield (kg ha^{-1}); HI: harvest index. * Means followed by the same letter in the column do not differ by the Scott-Knott test at 5% probability of error.

high HW has a direct relationship with maintaining potential quality in flour production (Manley et al., 2009).

The fractionation of nitrogen fertilization applications is a promising strategy to increase the YIE and quality of wheat grains (Tedone et al., 2018), adding the fact that the stage of treatments at the time of frost occurrence is at the beginning of anthesis, resulted in high HW content. Thus, it is evident that the use of cultivars with different cycles is effective for production safety due to the occurrence of bad weather in critical sub-periods of the crop. The negative highlights were the treatments TBIO Sonic and TBIO Astro that presented a HW value of 66.00, being commercially typified as Type 3 wheat. Wheat that fits into the Type 3 category can still be used in the milling industry, but is sold at much lower prices than Type 1, because it is through the HW measurement that the Brazilian market purchases and pays for the wheat grains.

YIE is simply dependent on three components: number of spikes per area, number of grains per spike, and the weight of grain. The SPI did not differ between treatments evidencing good plant establishment. NFT was higher in three treatments, TBIO Sinuelo, TBIO Capricho CL, and TBIO Astro, however the three treatments responded differently for NSP and NGP. TBIO Astro was among the highest for NFT and NSP, however differed from the highest for NGP, as a result of spikelets abortion, resulting in few grains per spike. Whaley et al. (2004) reported the death of spikelets as a symptom of frost damage, Wu et al. (2022) stated that frost reduces the number of grains per spike, and Barlow et al. (2015) concluded that the greatest impacts are associated with sterility to abortion of formed grains.

For the cultivar TBIO Capricho CL showed the highest values for NFT and NGP, differing from the highest for NSP, the result infers that by having a lower NSP and higher NGP the abortion of spikelets was lower. Liu et al. (2020) and Ji et al. (2017) observed that the reduction in YIE was mainly attributed to the decrease in NSP and NGP. However, Wu et al. (2022) state that frost reduces NSP to a lesser degree compared to NGP and YIE, corroborating this, Liu et al. (2020) and Ji et al. (2017) state that improving NGP can decrease grain yield variation and also increase it. The cultivar TBIO Sinuelo showed the highest values for NFT, NSP, and NGP, showing the best agronomic performance of the cultivar, much as a result of the frost occurring when the plants were still in the stage (6.0), allowing the cultivar to perform better agronomically in comparison to the other treatments.

In general, treatments with higher NGP showed lower TGM, which may be associated with the spikes that suffered more frost damage, had fewer grains, and were able to better fill these grains. The TBIO Toruk treatment was in the group that had the highest average grain mass, with TGM of 39.37 g, while TBIO Audaz, TBIO Sinuelo, and TBIO Duque were in the second best group for this item. TBIO Astro was in the worst group, with TGM of 26.18 g. It is noticed that TGM did not have a direct relationship with YIE, this may be associated with the lower number of grains per spike, where plants that showed greater damage to frost, formed a low number of grains per spike, however in some situations, the plant managing to have a good translocation of photoassimilates to the grains and raising the TGM value. Griffiths et al. (2015) found a negative correlation between thousand-grain mass and number of grains per area, whereas Mecha et al. (2017) found a direct and positive effect of thousand-grain mass and number of grains per spike on wheat grain yield. This shows that there is no consensus in the literature on the relationship between the productive components, emphasizing the dependence of genetic factors, management, and environment on the relationship between the variables (Nuttall et al., 2017).

The results of the study show the need for a balance between SPI and TGM, because even though there are many spikes per area and, consequently, a greater number of grains, if they do not have a considerable mass, the amount of extra grains per area will not be able to compensate the low TGM and the yield ends up being low, taking as an example the performance of the TBIO Astro cultivar. If we observe the data of the cultivar TBIO Toruk, we can see that the opposite is also true, corroborating the observations of Sangoi et al. (2007), that grains with greater mass do not necessarily guarantee greater productivity per area to the culture of wheat, because this cultivar was in the group that showed higher TGM, but showed low value for the variable SPI and, consequently, was among the cultivars that showed lower grain yield.

Symptoms such as shorter between nodes and death of spikelets are reported by Whaley et al. (2004), reduced number of grains per spike, number of spikes, and thousand-grain mass by Wu et al. (2022) and YIE by Whaley et al. (2004), Liu et al. (2020), and Wu et al. (2022). Grain freezing as a result of frost results in poorly formed, shrunken, and wrinkled grain, and the final dry grain size depends on the grain filling stage when heat stress occurs (Frederiks et al., 2015). Harvesting malformed grains can lead to degradation of whole grains due to excessive sorting processes during grain processing (Frederiks et al., 2015).

Table 4 shows that for the WGMS, WGT1, and WGT2 variables, which indicate the grains with the best quality, in all cases the best treatments were TBIO Sinuelo and TBIO

Table 4. Comparison test of means among cultivars for different qualitative characters of wheat grains. Santa Maria, RS, Brazil, 2023

Cultivar	WGMS	DGMS	WGT1	DGT1	WGT2	DGT2
TBIO Astro	2.76 e*	23.94 a	2.44 d	4.96 a	0.74 b	1.04 a
TBIO Audaz	9.01 d	5.76 d	4.74 c	2.08 b	0.74 b	0.56 b
TBIO Capricho CL	24.18 b	1.90 e	14.26 a	1.48 b	4.94 a	0.26 b
TBIO Duque	11.68 c	6.21 d	9.33 b	2.08 b	3.37 a	0.60 b
TBIO Sinuelo	28.10 a	2.83 e	15.37 a	1.73 b	4.45 a	0.84 a
TBIO Sonic	2.11 e	21.00 b	2.23 d	3.07 b	0.82 b	0.49 b
TBIO Toruk	4.41 e	8.06 c	4.43 c	2.31 b	0.94 b	0.20 b
Mean	11.73	9.96	7.54	2.53	2.29	0.57
CV, %	81.51	76.54	126.99	208.74	279.56	428.58

CV: Experimental coefficient of variation (%); WGMS: whole grains of the main stem; DGMS: damaged grains in the main stem; WGT1: whole grains of tillers 1; DGT1: damaged grains of tillers 1; WGT2: whole grains of tillers 2; DGT2: damaged grains of tillers 2. * Means followed by the same letter in the column do not differ by the Scott-Knott test at 5% probability of error.

Capricho CL, which were in the phenological stage of anthesis at the time of the climatic storm that caused damage to the other cultivars evaluated. Only for the variable WGT2 the cultivar TBIO Duque did not differ from the cultivars TBIO Sinuelo and TBIO Capricho CL, which were superior to the others. In relation to the DGMS, DGT1, and DGT2 variables, which point to damaged grains, it is observed without exception the highlight for the cultivar TBIO Astro, which was in the soft grain stage. The cultivar TBIO Astro only did not differ from the cultivar TBIO Sinuelo for the DGT2 variable.

The DGMS variable was the only one to have a negative linear correlation with YIE, whereas WGMS had a positive correlation. The result reinforces the importance of physical grain quality on wheat grain yield due to the linear association. YIE correlated positively with PH, NFT, NGP, WGMS, WGT1, WGT2, HW, and HI (Figure 3). Mecha et al. (2017) and Gelalcha & Hanchinal (2013) reported positive correlation of YIE with NFT and HI. Mecha et al. (2017) further found positive correlation of HW with YIE, whereas Gelalcha & Hanchinal (2013) of YIE with NGP, results that corroborate with those of the present study. However, Mecha et al. (2017) and Gelalcha & Hanchinal (2013) observed positive correlation between YIE and TGM, diverging from the results found in the present study where TGM had no significant correlation with YIE.

The differences in the correlations between the characters studied, can be explained due to the fact that the associations between variables are influenced by morphological, physiological, and environmental traits through direct and indirect pathways (Ul-Allah et al., 2013; Al-Ashkar et al., 2021). In the trail analysis we observed the largest positive direct effects on YIE of the variables NGP and WGMS and indirectly of PH, WGMS, WGT2, NSP, and HW via NGP (Figure 4). For Gekakcha & Hanchinal (2013) most of the variables under study also indirectly influenced YIE, with biomass production being the main pathway.

Negative direct effects on YIE occurred by the variable NSP and indirectly by the variables NGP via NSP and DGT1 via WGMS, corroborating this, study by Ashfaq et al. (2014) observed negative direct effect of number of spikelets per plant on YIE. In a study by Vesohoski et al. (2011), the number of spikelets per spike and the number of grains per spike had a direct positive effect on YIE; however, the authors did not report the occurrence of adverse meteorological phenomena capable of causing spikelets abortion, such as frost. The results show that spikelet fertility is of utmost impor-

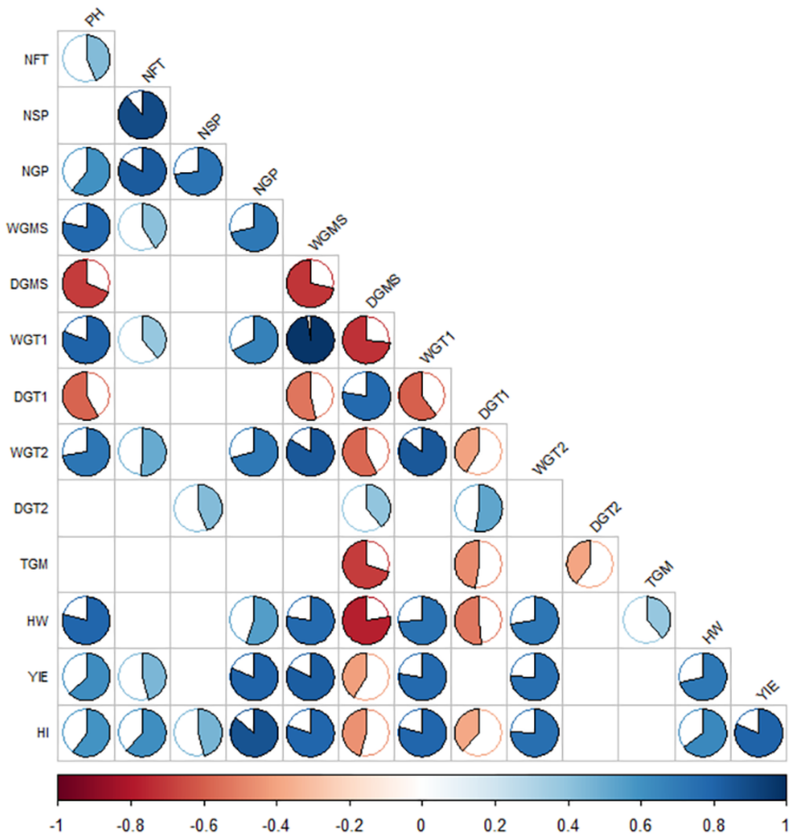

Fig. 3. Pearson linear correlation among wheat characters

PH: plant height from the neck to the end of the spike; NFT: number of fertile tillers; NSP: number of spikelets per plant; NGP: number of grains per plant; WGMS: whole grains from the main stem; DGMS: damaged grains of the main stem; WGT1: whole grains of tillers 1; DGT1: damaged grains of tillers 1; WGT2: whole grains of tillers 2; DGT2: damaged grains of tillers 2; TGM: thousand-grain mass; HW: hectolitre weight; YIE: grain yield; HI: harvest index. * Significant correlations were presented (positive in blue and negative in red) according to the t test ($p < 0.05$). Santa Maria, RS, Brazil, 2023

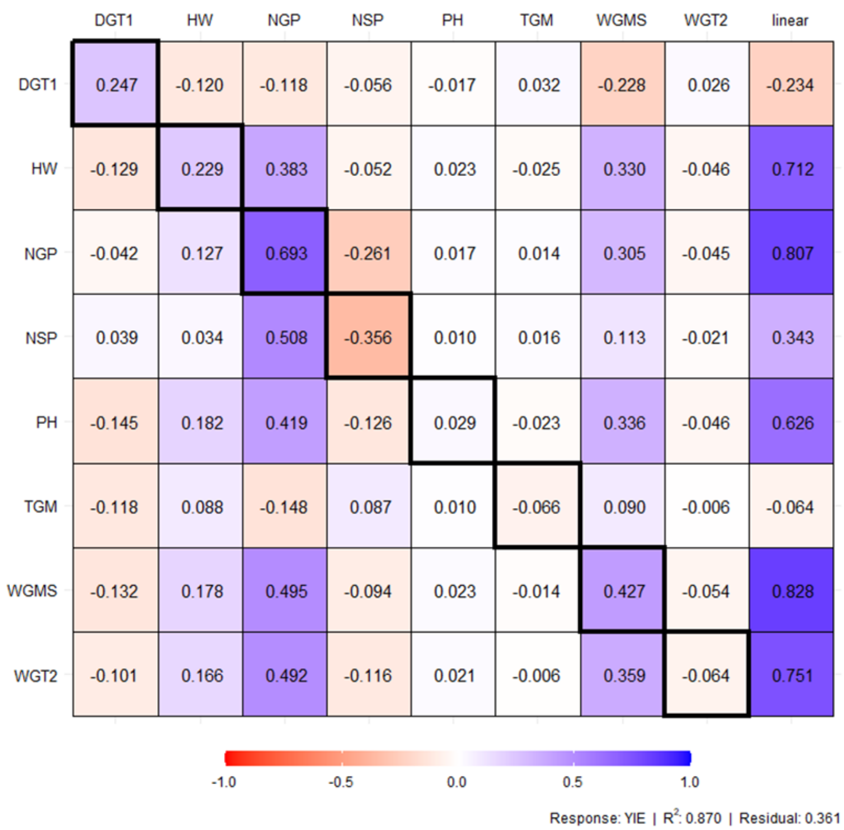

Fig. 4. Pearson linear correlation (vertical line), estimated direct effects (diagonal) and indirect effects (horizontal lines) of the characters
PH: plant height from the neck to the end of the spike; DGT1: damaged grains of tillers 1; WGT2: whole grains of tillers 2; WGMS: whole grains from the main stem; TGM: thousand-grain mass; NSP: number of spikelets per plant; NGP: number of grains per plant; HW: hectolitre weight; on the YIE: grain yield. Santa Maria, RS, Brazil, 2023

tance for evaluating the influence of the NSP trait on YIE. It is also observed that physical grain quality has a high impact on wheat YIE, due to the direct effects of WGMS and indirect effects of DGT1.

Thus, it is possible to infer that the occurrence of bad weather, such as severe frost in reproductive stages of soft grain mass, is detrimental to the quality of grains produced by wheat, since materials that were in reproductive period, but were in other stages also had damage to the quality of grains, but were not so high damage. In this way, it is also possible to observe the existence of cultivars that are more sensitive than others, because both the cultivar TBIO Astro and TBIO Sonic were at the same stage of development. However, in general, the occurrence of frost in the critical period of wheat crop conditioned losses to YIE and impacted morphological and yield variables in the wheat cultivars present in the study.

Conclusions

There are cultivars that are more sensitive than others to the incidence of severe frosts during the reproductive period of the wheat crop. The TBIO Capricho CL cultivar is more sensitive than the TBIO Sinuelo cultivar to frost occurrence at the beginning of anthesis.

The stage of development of the wheat crop influences frost damage. The late milky grain stage was more sensitive than cultivars that were present at the early anthesis stage.

The linear relationships, indicate that the characters plant height, number of fertile tillers, number of grains per plant, whole grains and HW have a positive relationship with grain yield.

The number of grains per plant and whole grains in the main stalk have the greatest direct effects on grain yield. Whereas plant height, whole grains in the main stem, number of spikelets per plant have the largest indirect effects on grain yield via number of grains per plant.

The use of cultivars with similar cycle behavior is not indicated, as they increase the risk of losses due to frost, when sowing is carried out in only one growing season.

Acknowledgments

To the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES and Conselho Nacional de Desenvolvimento Cientifico e Tecnológico – CNPq, for the financial support.

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Received: **April, 03, 2023**; *Approved*: **August, 20, 2023;** *Published:* **April, 2024**