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Seed physiological quality of wheat cultivars in response to phosphate fertilization

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ABSTRACT: Mineral nutrients play an important role in the composition of seeds, influencing the germination rate and the production of vigorous seedlings, which is fundamental for the establishment of the plant stand and crop yield. This work aimed to evaluate the effect of phosphate fertilization on phosphorus (P) content and the physiological quality of seeds of wheat cultivars. A 2 × 16 split plot design was used, with two rates of P (0 and 140 kg.ha^{-1}) and 16 wheat genotypes (cultivars BR 18, BR 23, BRS 208, BRS 254, BRS 264, BRS 404, BRS Graúna, BRS Pardela, BRS Sabiá, WT 15025, CD 118, IPR Catuara, Ocepar 14, Supera, TBIO Bandeirante and TBIO Iguaçu). The evaluation includes: first count, germination, accelerated aging, seedling emergence and length, electrical conductivity, emergence speed index, P content in seeds, and thousand-seed weight. The data of P rates and wheat genotypes were subject to analysis of variance and to the comparison of means by the F-test and Scott-Knott test, respectively. The seeds of BR 18 and Ocepar 14 showed higher physiological quality, whereas the seeds of TBIO Iguaçu, CD 118, and BRS Sabiá showed lower vigor. Phosphate fertilization provides the production of wheat seeds with higher P content and physiological quality, but it does not influence the thousand-seed weight of most wheat cultivars.

Index terms: *Triticum aestivum* L., phosphorus, macronutrient, germination, vigor.

RESUMO: Os nutrientes minerais desempenham importante papel na composição das sementes, influenciando a taxa de germinação e a produção de plântulas vigorosas, o que é fundamental para o estabelecimento do estande de plantas e produtividade da cultura. O objetivo deste trabalho foi avaliar o efeito da adubação fosfatada sobre o teor de fósforo (P) e a qualidade fisiológica de sementes de cultivares de trigo. Foi utilizado delineamento em parcelas subdivididas 2 × 16, sendo duas doses de P (0 e 140 kg.ha^{-1}) e 16 genótipos de trigo (cultivares BR 18, BR 23, BRS 208, BRS 254, BRS 264, BRS 404, BRS Graúna, BRS Pardela, BRS Sabiá, WT 15025, CD 118, IPR Catuara, Ocepar 14, Supera, TBIO Bandeirante e TBIO Iguaçu). Foram avaliados: primeira contagem, germinação, envelhecimento acelerado, emergência e comprimento de plântulas, condutividade elétrica, índice de velocidade de emergência, teor de P nas sementes e massa de mil sementes. Os dados de doses de P e genótipos de trigo foram submetidos à análise de variância e à comparação de médias pelo teste F e teste de Scott-Knott, respectivamente. As sementes da BR 18 e Ocepar 14 apresentaram maior qualidade fisiológica, enquanto as sementes da TBIO Iguaçu, CD 118 e BRS Sabiá apresentaram menor vigor. A adubação fosfatada proporciona a produção de sementes de trigo com maior teor de P e qualidade fisiológica, mas não influência a massa de mil sementes da maioria das cultivares de trigo.

Termos para indexação: *Triticum aestivum* L., fósforo, macronutriente, germinação, vigor.

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INTRODUCTION

The domestic production of wheat (*Triticum aestivum* L.) is enough to meet only half of the Brazilian demand (CONAB, 2020). Thus, it is necessary to improve crop productivity by means of new cultivation technologies. In this context, it is important to develop new agricultural management techniques — appropriate for each genetic material — so as to enable the highest physiological quality of the seeds, favoring the initial establishment of the seedlings, the plant development, and the grain yield of the crops. Accordingly, some attempts have been made, such as treating wheat seeds with symbiont microorganisms or plant growth-promoting hormonal substances (Hungria et al., 2010; Yu et al., 2016; Silva and Pires, 2017; Silva and Martins, 2020).

The seed physiological quality and the potential for producing vigorous plants are defined, mainly, by the genetic composition of each genotype and the management practices used in crops. Genetic characteristics strongly influence the chemical composition of seeds, since genotypes differ in terms of the development cycle, tillering capacity, susceptibility to pests and diseases, and nutritional requirements, which directly influence the quality of the seeds produced (Marcos-Filho, 2015).

Genetic materials more stable and adapted to local environmental conditions contribute to the production of wheat seeds with higher physiological quality (Szareski et al., 2018). In this sense, it is imperative to identify cultivars with lower nutritional requirements, considering that Brazilian soils – mostly weathered and acidic – have low availability of the main nutrients required by the crop, such as phosphorus (P) (Santos et al., 2008).

Among the nutrients required for the proper growth and development of wheat plants, P stands out because it plays a key role in the synthesis of proteins, nucleotides, and enzymes, as well as being fundamental in photosynthesis and other plant physiological and biochemical processes (Zhu et al., 2012). In addition, P can be found in seeds as phytic acid (responsible for P availability during the germination process), in phosphatides, nucleic acids, and inorganic P components that are essential for the initial seedling development (Agostini and Ida, 2006; Marin et al., 2015).

Although P is one of the macronutrients required in smaller quantities by crops, large amounts of P are used in Brazilian agriculture, because soils are highly weathered and deficient in this nutrient, besides having a high capacity to fix P to mineral particles, reducing its availability to plants (Novais and Smyth, 1999).

The differential response of each wheat genotype to P availability in the soil (Abichequer et al., 2003) suggests that the selection of cultivars with high P utilization and/or uptake efficiency, besides favoring the production of high quality seeds, also enables the optimal use of this nutrient, avoiding unnecessary expenses with increased rates of P fertilizer.

Marin et al. (2015), using increasing P rates in soybean [*Glycine max* (L.) Merr.] crops, found that P fertilization resulted in the production of more vigorous seeds with higher nutritional content. In addition, these authors found that seeds with higher P contents contributed to improved grain yields in soybean crops. On the other hand, Salum et al. (2008) and Fidelis et al. (2013) working on bean (*Phaseolus vulgaris* L.) and rainfed rice (*Oryza sativa* L.) plants, respectively, found low effects of P fertilization on physiological quality characteristics of the seeds produced. However, scientific papers studying the effect of P fertilization on P content in wheat seeds, and its consequences on the physiological quality of these seeds produced are scarce, especially considering a large number of genetic materials evaluated. Thus, the hypothesis of this work considers the existence of genetic variability in the capacity of wheat cultivars to uptake P and to remobilize it to the seeds, with distinct influences on seed germination and seedling development.

Therefore, this work aimed to evaluate the effect of P fertilization on P content and the physiological quality of seeds produced by 16 wheat cultivars.

MATERIAL AND METHODS

The experiment was set up at the experimental farm of *Embrapa Soja*, located in Londrina-PR (23°11’37 “S 51°11’03 “W; altitude 628 m). The landscape is slightly undulated, and the soil of the experimental area is a clayey Rhodic Oxisol

(838 g.dm^{-3} clay); the regional climate, according to the Köppen classification, is humid subtropical (Cfa), with warm and rainy summers, and average annual temperature and rainfall of 21.2 °C and 1392 mm, respectively, infrequent frosts, and no defined dry season. Average daily rainfall, relative humidity, and mean temperature data, recorded at a weather station located 500 m from the experiment, are shown in Figure 1, along with the irrigations applied throughout the growing season.

Soil samples were collected in the experimental area in the 0-20 cm layer of the soil profile, passed through a 2 mm sieve, air dried, homogenized, and sent to the laboratory for chemical characterization (Embrapa, 1997). Results are shown in Table 1.

A 2 × 16 split plot design was used, consisting of two P rates (low P = 0 kg.ha^{-1}; and high P = 140 kg.ha^{-1}) in the plot, applied in the sowing furrow, and 16 wheat genotypes (cultivars BR 18, BR 23, BRS 208, BRS 254, BRS 264, BRS 404, BRS Graúna, BRS Pardela, BRS Sabiá, WT 15025, CD 118, IPR Catuara, Ocepar 14, Supera, TBIO Bandeirante and TBIO Iguaçu) allocated in the subplots, distributed in four randomized blocks. Each experimental unit was composed of five sowing lines, 2.5 m long, spaced 0.2 m apart, totaling an area of 2.5 m^2.

Wheat sowing was performed over the brachiaria stubble established in 2018, with a sowing density of 250 viable seeds.m^{-2} (measured in the laboratory by germination test performed prior to sowing), without thinning after seedling emergence. The base P fertilization of the high P rate treatments was done with monoammonium phosphate [$(NH_4)H_2PO_4$; 47.5% P_2O_5 and 9% N] in the sowing furrow. Nitrogen (N) fertilization was applied when the seedlings had two fully developed leaves, using ammonium nitrate (NH_4NO_3; 27% N) at a rate of 60 kg.ha^{-1} N. Nitrogen amount was balanced across all treatments, as a function of the N applied to the high P rate treatments at the time of base P fertilization with monoammonium phosphate.

The phytosanitary management and other wheat agronomic practices were based on the recommendations of the Brazilian Wheat and Triticale Research Commission (Silva et al., 2017).

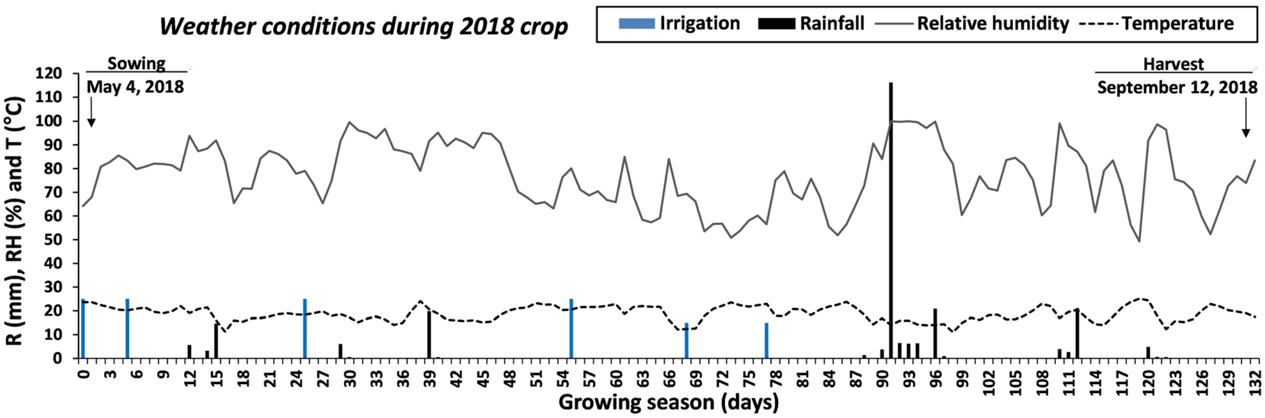

Figure 1. Irrigation and rainfall (R), relative humidity (RH), and average temperature (T) in the 2018 wheat growing season in Londrina (May 04 to September 12, 2018 = 132 days).

Table 1. Chemical characterization of the soil (0-20 cm layer) of the experimental area.

pH[(1)]	SOC[(2)] g.dm^{-3}	P[(3)] mg.dm^{-3}	K[(3)]	Al[(4)]	Ca[(4)]	Mg[(4)]	H+Al[(5)]	CEC[(6)]	V[(7)] %
			----------	----------	cmol$_c$.dm^{-3}	----------	----------	----------	
5.6	19.3	2.4	0.76	0.20	4.73	1.13	3.80	10.42	63.5

[(1)]pH in water (soil:water ratio = 1:2.5). [(2)]Soil organic carbon (wet combustion – Walkley-Black). [(3)]Available phosphorus and exchangeable potassium (Mehlich-1 extractant). [(4)]Exchangeable aluminum, calcium, and magnesium (KCl 1 mol.L^{-1} extractant). [(5)]Potential acidity (based on the SMP index). [(6)]Cation exchange capacity. [(7)]Base saturation. Note: Results correspond to the average of six replications.

Wheat harvest (three center rows × 2.5 m long) was conducted with a self-propelled harvester developed for agricultural experimentation. Seed samples were then taken from each experimental unit and stored in cold chamber to perform seed physiological analyses, which included the following tests:

First count and germination: performed with eight subsamples of 50 seeds per treatment, distributed on germination paper moistened with distilled water at 2.5 times the dry weight of the substrate. The paper rolls with the seeds were kept in a germinator at a temperature of 20 °C. The evaluation consisted of two counts, the first at four days (first count) and the second at eight days after sowing, counting the percentage of normal seedlings (Brasil, 2009).

Accelerated aging test: performed with four replications of 240 seeds per treatment. A metal screen was placed in plastic gerboxes containing 40 mL of water inside, on which the seeds were distributed uniformly, with no direct contact with the water. Boxes were kept in an accelerated aging chamber at 42 °C for 48 hours (h) (Lima et al., 2006). After this period, the germination test was carried out at a temperature of 20 °C. The number of normal seedlings was counted five days after installation, with results expressed in percentage (Brasil, 2009).

Seedling length: obtained by sowing four replications of 20 seeds per treatment on the upper third of the germination paper, moistened with distilled water at 2.5 times the weight of the dry substrate. The paper rolls were placed in a germinator for five days at 20 °C in the dark. At the end of this period, normal seedlings were measured, separated in shoot and root parts, with the help of a graduated ruler, and the results were expressed in $cm.seedling^{-1}$.

Electrical conductivity: performed with four replications of 50 seeds, by the mass method. The replications of seeds had their respective masses determined and were subsequently placed in a container with 75 mL of distilled water for a period of 24 h at 25 °C. After this period, readings were taken in a constant electrode conductivity meter equal to 1.0, and the results were expressed in $\mu S.cm^{-1}.g^{-1}$.

Seedling emergence: performed using four replications of 50 seeds, which were sown in boxes containing sand, approximately at 4 cm deep. Fifteen days after sowing, the number of emerged seedlings was counted, and result was expressed as a percentage.

Emergence speed index: conducted together with the test for seedling emergence in the sand, counting the emerged seedlings daily, without discarding them, and obtaining a cumulative value. The results were calculated according to Maguire (1962).

Thousand-seed weight: obtained by counting and weighing eight replications of 100 seeds per treatment. The average was multiplied by 10 to obtain the value of thousand-seed weight (Brasil, 2009).

Samples of the seeds collected from the experimental plots were dried in an oven with forced air circulation at 65 °C for 48 h. Then they were ground in a stainless-steel Wiley mill, passed through a 0.1 mm sieve, for subsequent determination of the P content by spectrometry (Silva, 2009). Phosphorus determination procedure started by nitro-perchloric digestion [solution of HNO_3 + $HClO_4$ (3:1)] of the ground seeds, where 500 mg of each sample were mixed with 8 mL of the acid mixture in an Erlenmeyer flask, and then heated slowly in a digester block up to 200 °C for 3 to 4 h (until $HClO_4$ white steam ceased to be released). After cooling until room temperature, H_2O was added to make up the volume of the mixture to 25 mL. Phosphorus content in the digestion extract was determined by the spectrometric method with molybdenum blue, where 2 mL of extract was mixed with 8 mL of working reagent (solution 725 + ascorbic acid + H_2O) in a test tube, and the mixture was homogenized in a Vortex test tube mixer, followed by resting for 30 min. Then the absorbance was read in a spectrometer at 725 nm, obtaining the P content in the solution based on the P calibration curve previously performed. Phosphorus content in the seeds was calculated considering the dilution factors applied during the analytical procedure.

The data obtained were subjected to normality (Shapiro-Wilk) and homogeneity of variance (Bartlett) tests. Subsequently, analysis of variance (ANOVA) was performed, and the means of the ‘P rates’ treatments were compared by the ANOVA conclusive F-test and the means of the ‘genotypes’ were compared using the Scott-Knott test. In addition, Pearson’s correlation between P content in the seeds and each seed physiological quality trait was calculated, considering all experimental plots (n = 128 observations).

RESULTS AND DISCUSSION

A significant effect of the interaction between wheat genotypes and P rates was found for the first germination count, accelerated aging, shoot length, and thousand-seed weight variables (Table 2). For seed germination, root length, electrical conductivity and P content in seeds, isolated effects of the ‘genotype’ and ‘P rate’ factors were found. However, for seedling emergence and emergence speed index, only the ‘genotype’ factor showed an isolated effect.

For the variables in which the isolated effect of P rate was found, plants that received 140 $kg.ha^{-1}$ P produced seeds with better physiological characteristics (Figures 2A-2F). Among these variables, there was a positive Pearson’s correlation between P content in seeds and their germination (r = 0.259***), and a negative correlation between P content and seed electrical conductivity (r = -0.202*). According to Guerra et al. (2006), higher P content in the soil can provide the production of seeds with higher P content, improving the formation of the embryo and cotyledons and the availability of energy (for example, in the form of adenosine triphosphate – ATP) for the metabolic activities of the seedlings.

Table 2. Summary of the analysis of variance (ANOVA) of the values of first germination count (FGC), germination (G), accelerated aging (AA), seedling shoot length (SSL), seedling root length (SRL), electrical conductivity in seeds (ECS), emergence of seedlings in the sand (ESS), emergence speed index of seedlings (ESIS), thousand-seed weight (TSW), and phosphorus content in the seeds (PCS) of sixteen wheat genotypes as a function of two P rates.

Source of variation	Df	Mean square				
		FGC	G	AA	SSL	SRL
Block	3	10.4	4.15	16.6	0.33	1.27
P rate (P)	1	2032***	732***	42.8*	0.27^{ns}	11.6°
Error for P	3	4.11	2.93	1.62	0.17	1.26
Genotype (G)	15	77.7***	60.9***	165***	2.40***	2.56*
P x G	15	31.6*	18.8^{ns}	75.4***	0.39*	2.13^{ns}
Error for G	90	17.0	10.9	15.0	0.20	1.35
CV (P) (%)		2.32	1.85	1.42	8.36	12.4
CV (G) (%)		4.73	3.57	4.34	9.17	12.8
Source of variation	Df	Mean square				
		ECS	ESS	ESIS	TSW	PCS
Block	3	18.7	36.8	1.46	10.9	0.10
P rate (P)	1	1069*	732^{ns}	18.0^{ns}	5.78^{ns}	1.73°
Error for P	3	84.0	139	5.61	3.74	0.27
Genotype (G)	15	142***	92.7*	3.29***	49.9***	0.14***
P x G	15	22.2^{ns}	42.3^{ns}	0.52^{ns}	8.25**	0.05^{ns}
Error for G	90	18.7	42.8	1.11	3.61	0.04
CV (P) (%)		19.6	12.9	21.9	5.41	23.4
CV (G) (%)		9.27	7.15	9.73	5.32	8.64

Df = degrees of freedom; CV = coefficient of variation. ns, °, *, **, and *** = not significant, and significant at the $p \leq 0.1$, $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively, by the F-test. Note: when the main effects (‘P rate’ or ‘genotype’) were significant and had no interaction with each other, comparisons between treatment means are shown in Figure 2. On the other hand, when there was significant interaction between the main effects, comparisons between treatment means of one effect were unfolded individually within each level of the other main effect, which results are shown in Figure 3.

De Marco (1990), when assessing the physiological performance of wheat seeds with different P contents, which were sown in soils with different P levels, found that in soils with low P availability, seeds with higher P content produced seedlings with better development. Likewise, Zhu and Smith (2001), when studying the influence of seed P content on wheat plant growth and development, found that increasing the P reserve in the seed improved plant growth. Furthermore, they pointed out that plants grown from seeds with high P reserves usually uptake higher amount of P from the soil, which was mainly attributed to the enhanced development of the root system, corroborating the results obtained in this work for root length, which was significantly higher in the treatments with P fertilization (Figure 2B).

The results obtained also corroborate Marin et al. (2015), who reported that P fertilization provided higher soybean seed vigor, and increased the content of other nutrients, such as iron and zinc, in the seeds produced. On the other hand, Salum et al. (2008), working with beans, found that the physiological quality of the seeds was rarely

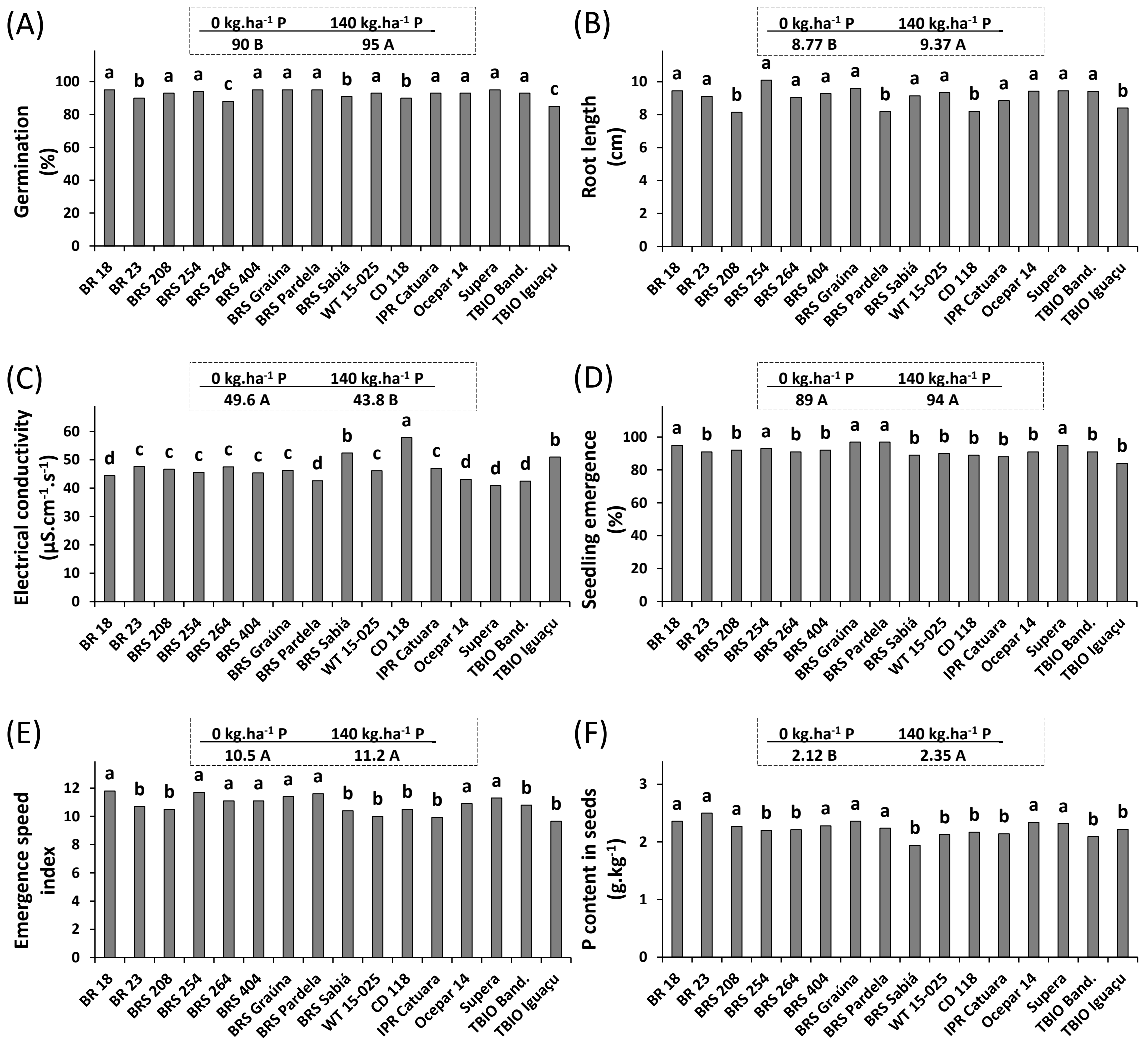

Figure 2. Comparisons between treatment means for germination (A), seedling root length (B), electrical conductivity in seeds (C), seedling emergence in the sand (D), emergence speed index of seedlings (E), and phosphorus content in seeds (F) of sixteen wheat genotypes as a function of two phosphorus rates (0 and 140 $kg.ha^{-1}$ P). Means of the 'genotypes' followed by different lowercase letters on the vertical bars differ from each other by the Scott-Knott test ($p \geq 0.05$). Means of 'phosphorus rates' followed by different capital letters within the text box (positioned on the graphs) differ from each other by the F-test (according to the analysis of variance – ANOVA).

affected by increasing P content in these seeds. In addition, Zucareli et al. (2011) found no effect of P fertilization on the seed physiological quality of beans. Finally, it is important to point out that excessive P content may decrease the quality of the seeds. For example, Krueger et al. (2013) found that the excess of P reduced soybean seed vigor, and a hypothesis was raised that the higher P content promoted increased pathogen colonization in the seeds during the germination process.

This divergence of results may be related to the distinct initial P content in the soil of each experiment, which, in some cases, may have been enough to promote a suitable crop P nutrition, not affecting the physiological quality of the seeds produced. This was not found in the current study, because the initial P availability in the soil (2.4 $mg.dm^{-3}$ P) is considered very low (Santos et al., 2008).

Concerning the isolated effect of 'genotype', it was found that, despite the differences, all cultivars showed seed germination above 80% (Figure 2A), which is the minimum value allowed for trading wheat seeds in the country (Brasil, 2013). The cultivars BRS 264 and TBIO Iguaçu had lower performance than others, as they showed seed germination below 90%. For seedling root length, most cultivars showed values between 9 and 10 cm, except BRS 208, BRS Pardela, CD 118 and TBIO Iguaçu that had slightly lower values, between 8 and 8.5 cm (Figure 2B).

The seeds of CD 118 showed the highest electrical conductivity (Figure 2C), negatively standing out from the other wheat cultivars. This may be assigned to damage or ruptures in the cell membranes, evidencing lower seed quality of this cultivar. TBIO Iguaçu and BRS Sabiá cultivars also showed high electrical conductivity in the seeds, although with lower values than CD 118. Other cultivars showed electrical conductivity of the seeds below 50 $\mu S.cm^{-1}.g^{-1}$, particularly BR 18, BRS Pardela, Ocepar 14, Supera, and TBIO Bandeirante, which had the lowest values for this physiological seed characteristic.

Wheat cultivars with better seedling emergence in the sand were BR 18, BRS 254, BRS Graúna, BRS Pardela, and Supera, which showed values higher than 93% (Figure 2D). These same cultivars, along with BRS 264, BRS 404, and Ocepar 14, also showed higher emergence speed index (Figure 2E). Moreover, six of these cultivars (except BRS 264 and BRS 254) showed the highest P contents in the seeds, along with BR 23 and BRS 208 cultivars (Figure 2F). However, there was no significant Pearson correlation ($r = 0.165^{ns}$) between these two variables (emergence speed index and P content in the seeds).

Concerning the first germination count, it was found that P fertilization of wheat crop favored this seed trait for most cultivars (except BRS 208, BRS Pardela, Ocepar 14, Supera, and TBIO Bandeirante) (Figure 3A). Furthermore, there was a positive Pearson's correlation (r = 0.238**) between seed P content and first germination count. Comparing all cultivars evaluated, individually within each P rate (0 or 140 $kg.ha^{-1}$), TBIO Iguaçu and BRS 264 showed the lowest values of first germination count of seeds harvested from the treatment with no P fertilization; and TBIO Iguaçu showed the lowest value of first germination count when its seeds were harvested in the treatment fertilized with 140 $kg.ha^{-1}$ P.

Seed vigor evaluated by the accelerated aging test was influenced by the interaction between 'genotype' and 'P rate' factors (Table 2). Thus, the seeds of BRS 208, BRS 404, BRS Graúna, BRS Pardela, and Supera cultivars produced in the crop fertilized with 140 $kg.ha^{-1}$ P showed higher vigor compared to the control treatment (0 $kg.ha^{-1}$ P) (Figure 3B). On the other hand, the opposite effect of P fertilization was seen in the seeds of BRS 264, BRS Sabiá, and TBIO Iguaçu cultivars. By comparing wheat cultivars within each P rate, we found that the seeds of BR 23, BRS 264, BRS Sabiá, CD 118, Supera, and TBIO Iguaçu showed lower vigor when they came from crops with no P fertilization. However, seeds of BRS 264 and BRS Sabiá cultivars had lower vigor when harvested in fields that received 140 $kg.ha^{-1}$ P, compared to the other cultivars. Nevertheless, it is important to note that, in this vigor test, most cultivars (except BRS 264 and BRS Sabiá at a P rate of 140 $kg.ha^{-1}$) had seed germination above the limit established for wheat seed trading (Brasil, 2013).

For shoot seedling length, only BR 23, BRS Pardela, and Supera cultivars showed a significant difference between treatments with 0 and 140 $kg.ha^{-1}$ P, where P fertilization promoted the formation of seeds that produced smaller seedlings (Figure 3C). When comparing cultivars within each P rate, we found that BR 23 seeds harvested from no P fertilized crop produced seedlings with higher shoot length. On the other hand, in the same situation, seeds of BRS Graúna, BRS Sabiá, WT 15-025, IPR Catuara, and TBIO Iguaçu cultivars produced the smallest seedlings. Finally, in the treatments fertilized with 140 kg.ha^{-1} P, a shorter shoot length was found for BRS Graúna, BRS Pardela, WT 15-025, CD 118, IPR Catuara, Supera, and TBIO Iguaçu cultivars. By analyzing these results, it is evident that the genetic factor prevails over the effects of P fertilization regarding the formation of seeds capable to produce higher seedlings.

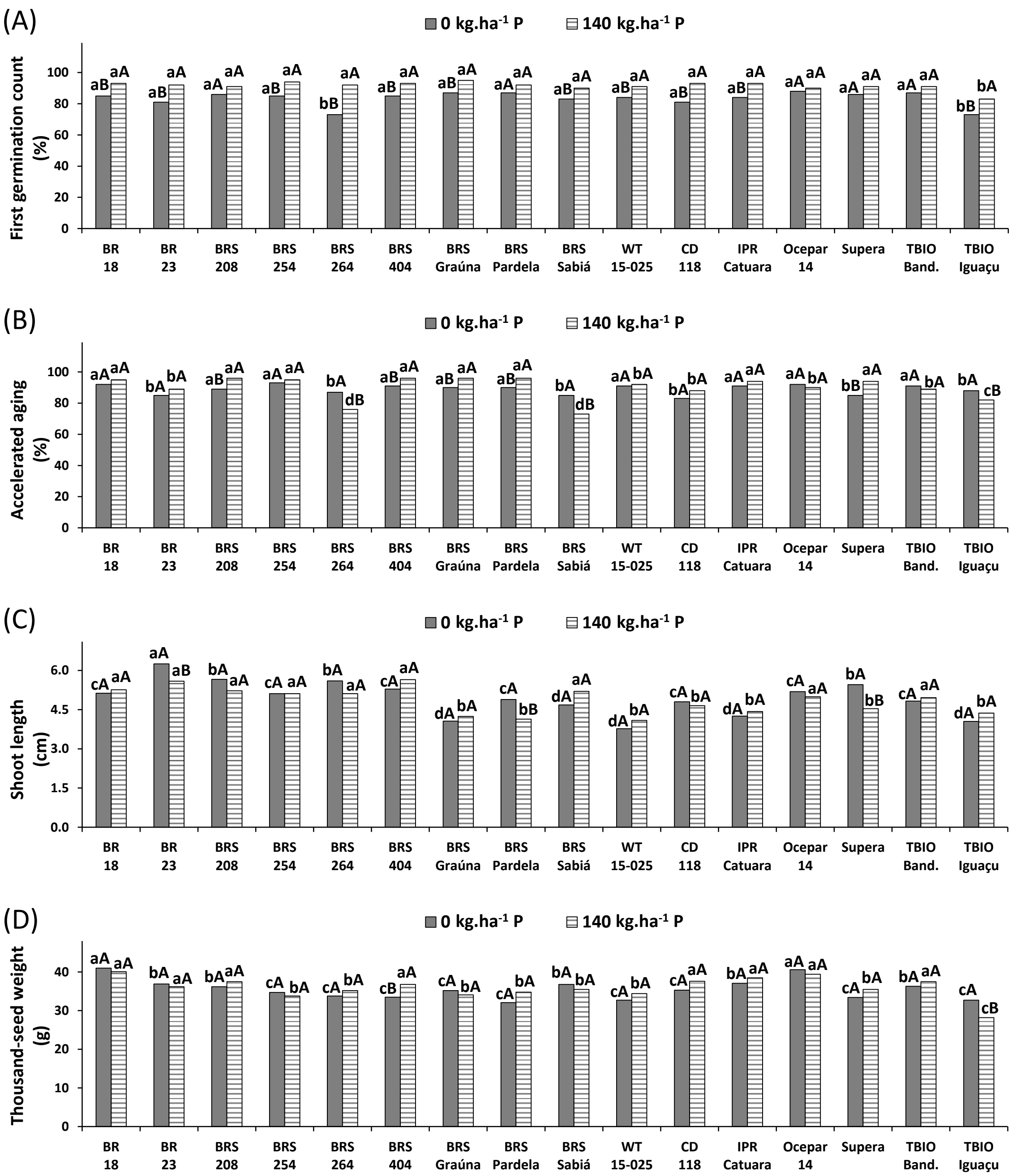

Figure 3. Unfolding of the significant interactions of the analysis of variance (ANOVA) for first germination count (A), accelerated aging (B), seedling shoot length (C) and thousand-seed weight (D) of sixteen wheat genotypes as a function of two phosphorus rates (0 and 140 kg.ha^{-1} P). Means of the 'genotypes' (individually for each phosphorus rate) followed by different lowercase letters on the vertical bars differ from each other by the Scott-Knott test ($p \geq 0.05$). Means of 'phosphorus rates' (individually for each genotype) followed by different capital letters differ from each other by the F-test (according to the ANOVA).

Phosphate fertilization in wheat crop did not influence the thousand-seed weight (Table 2), except for BRS 404 and TBIO Iguaçu cultivars, which is confirmed by the unfolding of the effects of ‘P rates’ within each ‘genotype’ (Figure 3D). On the other hand, when unfolding the effects of ‘genotype’ within each ‘P rate’, we found that the seeds of BR 18 and Ocepar 14 cultivars harvested in crops with no P fertilization showed higher values of thousand-seed weight. However, considering the treatments that received 140 $kg.ha^{-1}$ P, TBIO Iguaçu showed the lowest thousand-seed weight. It is evident the effect of P fertilization in changing the ranking order of wheat cultivars regarding thousand-seed weight, although P fertilization had a small direct influence on this seed trait, considering individually each cultivar.

The small effect of P fertilization on the thousand-seed weight of wheat cultivars might be explained by an argument from Grant et al. (2001), who reported that stress caused by P deficiency in the soil tends to decrease proportionally more the number of seeds produced than the mass and size of these seeds.

Through a global analysis of the results, we can consider that seeds of BR 18 and Ocepar 14 cultivars stood out with better physiological performance, even when coming from treatments with no P fertilization. This suggests a higher tolerance of these wheat cultivars to P deficiency in the soil, which can be explained by morphophysiological adaptations of the root system enabling the plant to access P in larger soil volume and/or deeper soil layers (Rotili et al., 2010), resulting in the production of seeds with higher P content and better physiological quality. On the other hand, seeds of TBIO Iguaçu, CD 118, and BRS Sabiá cultivars showed lower physiological performance, even when produced in plots fertilized with 140 $kg.ha^{-1}$ P, indicating that other factors (besides P availability) limited the physiological quality of the seeds produced under these environmental conditions.

Crusciol et al. (2013) found that some rice cultivars are more demanding for fertile soil. This can be extrapolated to wheat cultivars, which explains the significant effect of P fertilization only on some cultivars, considering the characteristics of first germination count, seed vigor (by accelerated aging test), seedling shoot length, and thousand-seed weight.

In addition, it is worth noting that the P rates can influence in different ways the physiological quality of the seeds produced in the crops. For example, the excess of P in the soil may impair the availability and uptake of other essential nutrients, particularly micronutrients such as zinc (Malavolta et al., 1997). Therefore, the definition of the most efficient and suitable P rate for each wheat cultivar is critical to the production of seeds with high physiological quality. In this sense, new studies are required to fill this knowledge gap.

CONCLUSIONS

Phosphate fertilization increases P content in the seeds produced. However, it has no effect on the thousand-seed weight of most wheat cultivars.

Phosphate fertilization improves the production of wheat seeds with higher physiological quality.

BR 18 and Ocepar 14 cultivars produce seeds with better physiological quality, irrespective of the P rate applied to the wheat crop.

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