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RESPONSES OF WHEAT GENOTYPES TO DISTINCT SEEDING DENSITIES

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ABSTRACT:
Optimizing seeding density is a fundamental strategy for maximizing wheat (*Triticum aestivum* L.) yield, yet establishing a universal recommendation is a persistent challenge in agronomy. The ideal plant population is highly dependent on complex interactions between genotype, management practices, and environmental conditions, often leading to contrasting results across studies. This variability makes generalized recommendations unreliable and highlights the critical need to understand cultivar-specific responses to guide precision management. The objective of this work was to test, using the model identity test, whether a single common regression model could adequately describe the cultivar responses or if distinct, genotype-specific models were required. A field experiment was conducted during summer and winter, in a randomized complete block design, and quadratic polynomial regression models were fitted for plant height, grain yield, hectoliter weight, and days to heading. The analysis of variance for the model identity test revealed significant differences ($P < 0.05$) between the complete (genotype-specific) and reduced (common) models for all traits in both seasons. This result led to the rejection of the null hypothesis of model equality, confirming that each cultivar exhibited a unique response pattern to the variation in seeding density. Similar genotype-specific and season-dependent responses were observed for all traits. The findings underscore strong genotypes × densities × environments interaction and demonstrate that a "one-size-fits-all" approach is inadequate for density recommendations. The identity test confirmed the need for distinct models, highlighting the importance of genotype-specific analysis in studies involving plant population density.

Keywords: Biometry, genotypes × environments interaction, model identity, plant population, regression analysis.

RESPOSTAS DE GENÓTIPOS DE TRIGO A DISTINTAS DENSIDADES DE SEMEADURA

RESUMO:
A otimização da densidade de semeadura é uma estratégia fundamental para maximizar a produtividade do trigo (*Triticum aestivum* L.), porém estabelecer uma recomendação universal continua sendo um desafio persistente na agronomia. A população ideal de plantas depende fortemente de interações complexas entre genótipo, práticas de manejo e condições ambientais, o que frequentemente leva a resultados contrastantes entre estudos. Essa variabilidade torna as recomendações generalizadas pouco confiáveis e evidencia a necessidade crítica de compreender as respostas específicas de cada cultivar para orientar o manejo de precisão. O objetivo deste trabalho foi testar, utilizando o teste de identidade de modelos, se um único modelo de regressão comum poderia descrever adequadamente as respostas das cultivares ou se seriam necessários modelos distintos, específicos por genótipo. O experimento de campo foi conduzido nas estações de verão e inverno, em delineamento em blocos ao acaso, e modelos de regressão polinomial quadrática foram ajustados

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para altura de plantas, produtividade de grãos, peso do hectolitro e dias para o espigamento. A análise de variância para o teste de identidade de modelos revelou diferenças significativas (P < 0,05) entre o modelo completo (específico por genótipo) e o reduzido (comum) para todas as características em ambas as estações. Esse resultado levou à rejeição da hipótese nula de igualdade de modelos, confirmando que cada cultivar apresentou um padrão único de resposta à variação na densidade de semeadura. Respostas semelhantes, específicas por genótipo e dependentes da estação, foram observadas para todas as características. Os achados evidenciam uma forte interação genótipos × densidades × ambientes e demonstram que uma abordagem "tamanho único" é inadequada para recomendações de densidade de plantio. O teste de identidade confirmou a necessidade de modelos distintos, ressaltando a importância da análise específica por genótipo em estudos envolvendo densidade populacional de plantas.

Palavras-chave: Biometria, interação, genótipos × ambientes, identidade de modelos, população de plantas, análise de regressão.

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INTRODUCTION

Wheat (*Triticum aestivum* L.) plays a vital role in Brazilian agriculture, with domestic production increasing from 4,6 million to 7,8 million metric tons between 2012 and 2022 (FAO, 2024). However, the country still struggles to meet internal demand, reinforcing the need for strategies that enhance productivity and improve crop adaptation (Conab, 2023). Among agronomic practices, seeding density is a key factor influencing growth, phenology, and yield components (Baloch et al., 2010).

Numerous studies have reported contrasting findings regarding the optimal plant density for wheat, often depending on genotype and environmental conditions (Gao et al., 2021, Ma et al., 2018). This complexity underscores the importance of evaluating the genotype × density × environment interaction to guide genotype-specific recommendations. Despite this, many studies still rely on analysis of variance (ANOVA), often treating seeding density as a categorical variable. This approach may obscure underlying trends when the factor is inherently quantitative.

In such contexts, regression models provide a more suitable framework by modeling the continuous relationship between plant density and traits of interest (Regazzi, 1999). However, when multiple genotypes are involved, it becomes essential to determine whether these responses follow a shared functional form or if each genotype requires a distinct model. This raises a fundamental statistical question: Can the behavior of all genotypes be represented by a single regression equation, or do the genotypes exhibit statistically different patterns of response?

To address this question, the model identity theory (Regazzi, 1993; Regazzi and Silva, 2010) offers a solution. Through the comparison of complete (individual models per genotype) and reduced (a common model for all genotypes) models, this method uses analysis of variance on nonlinear regression fits to test the equality of model parameters across groups.

Therefore, this study aimed to assess the phenotypic responses of five wheat genotypes to increasing seeding densities under both winter and summer conditions. Specifically, we tested whether a common regression model could adequately describe the cultivar responses or whether distinct models were required.

MATERIALS AND METHODS

The experiments were conducted at the experimental station of the Federal University of Viçosa (UFV), located in Viçosa, Minas Gerais, Brazil (20°46' 4.95"S, 42°52'12.05"W, 658m a.s.l.). The trials were arranged in a randomized complete block design in a 5 × 4 × 2 factorial arrangement with three replications. This design involved five wheat cultivars, four planting densities (200, 300, 400, and 500 seeds per square meter), and two growing seasons (winter and summer). The climate was Aw (Alvares et al., 2013), according to the Köppen system, with hot and humid summers, while winters are cold and dry. The commercial cultivars used in this study were ORS Senna, ORS Guardião, ORS 1403, ORS Feroz, and ORS Absoluto (OR Sementes, Passo Fundo, RS, Brazil). These cultivars were selected for their high grain yield, and recommendation for the state of Minas Gerais. In each of the growing seasons, the experiment included 60 experimental plots. Each plot consisted of five rows that were 5.0 m long and spaced 0.20 m apart, resulting in a total area of five square meters. The experimental plots were uniformly distributed to ensure consistent row-to-row spacing. All five rows within each plot were considered useful areas for trait assessment.

The soil is classified as Ferrasol (IUSS Working Group WRB, 2022) and underwent preparation through plowing and harrowing. Planting was carried out in February and June 2021, with seeds sown manually in furrows at a depth of 2-3 cm. These periods were chosen to align with the region's agricultural cycle, in which silage corn is the main annual crop. In this region, silage corn is typically planted in September, October, or November and harvested in January, February, or March. After that, farmers commonly grow beans or start another corn cycle. Introducing wheat within these planting periods enables an evaluation of its performance and adaptation to local conditions, positioning it as a potential option for second and third-season cropping. After seedling emergence, thinning was performed to ensure the intended planting density levels. Fertilization was conducted based on the interpretation of soil chemical analysis. Urea (45% N) was used for the top-dressing nitrogen fertilization in order to achieve 90 kg of N per hectare. Half of the nitrogen dose used for top-dressing fertilization was applied when 50% of the plants in the plots had reached the tillering stage, whereas the remaining dose was applied at the stem elongation stage (Kuhnem et al., 2020).

In summer, irrigation was conducted until the tillering stage. In winter, sprinkler irrigation was applied according to the crop water requirements from sowing until the seed physiological maturity. Weed control was achieved through the application of a commercial product containing Clodinafope-propargyl and Metsulfuron-methyl. Pest and disease management involved the use of Chlorpyrifos and Tebuconazole-based products. The management of irrigation and the control of pests, diseases, and weeds followed the recommendations proposed by Kuhnem et al. (2020).

The following agronomic traits were evaluated in this study: Plant height (PH), which represents the average height, in centimeters, of five random plants within the plot. Data collection was performed after the beginning of the reproductive period. Grain yield (GY), measured in grams, converted to kilograms per hectare, adjusted for 13% moisture content. Hectoliter weight (HW), expressed in kilograms per 100 liters. At the end of the crop cycle, plants were manually harvested and threshed to obtain the grains. This process was repeated three times, and the means were calculated to ensure data reliability. Days to heading (DH), registered as the number of days from seedling emergence to the appearance of spikes in 50% of the plants within the plot.

To evaluate the response of agronomic traits to the increase in seeding density, a quantitative factor, the data were fitted to a quadratic polynomial regression model for each cultivar in each growing season. The model fitted for each cultivar is expressed by the following equation (Eq. 1):

$$y_{ij} = \beta_{0i} + \beta_{1i}x_{ij} + \beta_{2i}{x_{ij}}^2 + \varepsilon_{ij} \qquad \text{(Eq. 1)}$$

Where:
- y_{ij} is the observed value of the trait in the j-th experimental unit of the i-th cultivar;
- x_{ij} is the seeding density level;
- β_{0i}, β_{1i}, and β_{2i} are the regression coefficients (intercept, linear, and quadratic, respectively) for the i-th cultivar;
- ε_{ij} is the associated random error, assumed as $\varepsilon_{ij} \sim NID(0, \sigma^2)$.

To determine whether the response curves of the cultivars were statistically identical, the model identity test (Regazzi, 1993; Regazzi and Silva, 2010) was employed. This procedure compares a complete model, where a distinct quadratic equation is fitted for each cultivar, with a reduced model, where a single common equation is fitted for the set of all cultivars. The null hypothesis of total model identity (coincident models) was tested as follows:

H_0: $\beta_{0i} = \beta_0$; $\beta_{1i} = \beta_1$; $\beta_{2i} = \beta_2$ for all i
H_a: At least one of the equalities is not true.

The comparison between the complete and reduced models was performed through an analysis of variance on the regression sums of squares, using the F statistic (Bates and Watts, 1988) to test the significance of the model reduction (Table 1). The rejection of the null hypothesis indicates that the cultivars respond differently to the variation in seeding density, requiring specific equations to describe their behavior. Statistical analyses were conducted using the Genes software (Cruz, 2016).

Table 1. Analysis of variance for non-linear model identity test.

Source of variation	Degrees of Freedom	Sum of Squares (SS)	Mean Squares (MS)	F_0
Complete model (β)	Hp	$SS_1 = \beta' X' Y$		
Reduced model (θ)	p	$SS_2 = \theta' Z' Y$		
Reduction Effect (H_0)	$(H-1)p$	$SS_3 = SS_1 - SS_2$	$MS_1 = \frac{SS_3}{(H-1)p}$	$\frac{MS_1}{MS_2} \sim (F_\alpha)\big((H-1)\big)p; (N-Hp)$
Error	$N-Hp$	$SS_4 = SS_5 - SS_1$	$MS_2 = \frac{SS_4}{N-Hp}$	
Total	N	$SS_5 = Y'Y$		

H: number of groups; p: number of parameters; N: total number of observations; SS: sum of squares; MS: mean squares; β: vector of the estimated parameters of the complete model; θ: Vector of the estimated parameters of the reduced model; Y: vector of the observed values of the dependente variable; X: the matrix of the independent variable; F_α: tabulated F statistic value at a significance level α.

RESULTS AND DISCUSSION

The analysis of variance applied to the identity test (Table 2) revealed significant differences between the complete and reduced models for all evaluated traits in both growing seasons. This result indicates that the hypothesis of model equality, that is, whether a single equation is adequate to represent the response of all genotypes to increasing seeding densities, must be rejected. Therefore, the response behavior must be modeled separately for each cultivar.

Table 2. Analysis of variance for regression (the complete and reduced) models for wheat genotypes in winter and summer.

Source of variation	Degrees of freedom	Plant height	Grain yield	Hectoliter weigth	Days to heading
		cm	kg/ha	kg/100L	Days
		Mean squares			
		Winter			
Complete model	15	9853.16	15051410.29	6864.39	5659.03
Reduced model	3	48900.14	73700767.44	34311.22	28198.66
Reduction effect	12	91.42*	389071*	2.68*	24.12*
Error	5	2.75	25672.65	0.68	0.24
		Summer			
Complete model	15	8728.51	3369063.17	6185.40	3777.29
Reduced model	3	43358.71	16653863.14	30902.08	18715.56
Reduction effect	12	70.96*	47863.18*	6.23*	42.72*
Error	5	21.92	14819.45	7.27	0.48

*Significant by the F statistic at the 95% confidence level.

The necessity for genotype-specific modeling is further supported by the parameter estimates presented in Table 3, which show marked variation in the values of the intercept (β_0) and slope (β_1) among all cultivars. This variation reflects not only different baseline trait values across genotypes, but also distinct directions and magnitudes of response as seeding density increases. In practical terms, it implies that the underlying biological mechanisms influencing the response to plant density are not homogeneous across genotypes, and this heterogeneity is statistically identifiable.

Table 3. Parameter estimates for five genotypes in the complete and reduced models in the winter and summer (G1: Feroz; G2: Guardião; G3: Senna; G4: Absoluto; G5: 1403)

Gen	**Plant height**				**Grain yield**				**Hectoliter weight**				**Days to Heading**			
	β_0	β_1	β_2	Sr	β_0	β_1	β_2	Sr	β_0	β_1	β_2	Sr	β_0	β_1	β_2	Sr
Winter																
Complete model																
G1	56	0.1	0	8	5016	-9	0.1	683	81.6	-0.06	0.00	2.1	59	0.0	0	1
G2	119	-0.2	0	6	1425	12	-0.2	960	72.6	0.00	0.00	1.8	69	-0.1	0	1
G3	121	-0.2	0	6	2432	4	0.0	777	67.03	0.03	0.00	1.7	75	-0.1	0	3
G4	98	-0.0	0	5	575	-21	0.3	522	62.6	0.05	0.00	1.9	71	-0.1	0	1
G5	110	-0.1	0	5	1870	26	-0.4	947	88.2	-0.11	0.00	1.8	72	0.0	0	3
Reduced model																
CE	101	0.1	0	9	2716	2	0.0	863	74.39	-0.02	2.32	2.1	69	-0.1	0	4
Summer																
Complete model																
G1	73	0.1	-0.1	4	2927	-5	0.1	326	65.9	0.05	0.00	2.2	48	0.0	0	1
G2	21	0.3	-0.1	4	2359	-6	0.1	205	47.2	0.14	0.00	2.2	50	0.0	0	3
G3	75	0.0	0	6	2091	-3	0.0	396	66.6	0.00	0.00	3.5	43	0.0	0	2
G4	-2	0.5	-0.1	5	702	5	-0.1	363	53.1	0.07	0.00	3.6	45	0.0	0	2
G5	98	-0.1	0	6	1416	-0.4	0.0	177	82.9	-0.08	0.00	3.4	59	0.0	0	0
Reduced model																
CE	3	0.2	0	8	1899	-1.98	0.0	323	63.1	0.04	0.00	3.4	49	0.0	0	5

Sr: standard errors; β_0: intercept; β_1: linear coefficient for seeding density; β_2: quadratic coefficient for seeding density; CE: Commom Equation.

Plant height varied among the genotypes and responded differently to changes in seeding density depending on the growing season (Figure 1). ORS Feroz, for instance, showed maximum height at intermediate densities (300–400 seeds m²) in summer, while ORS Guardião reached its maximum height at the highest density in winter and at the lowest densities in summer. ORS Senna also shifted its response depending on the season, with greater height at low density in winter and at intermediate density in summer.

These results indicate that plant height exhibited genotype-specific and season-dependent responses to seeding density. This variability reflects underlying differences in how genotypes regulate stem elongation in response to canopy closure and light competition (Farooq et al., 2016), or in their sensitivity to resource limitations at higher densities (Bastos et al., 2020). The results illustrate the complexity of density response patterns and support the importance of evaluating cultivar performance across multiple growing conditions.

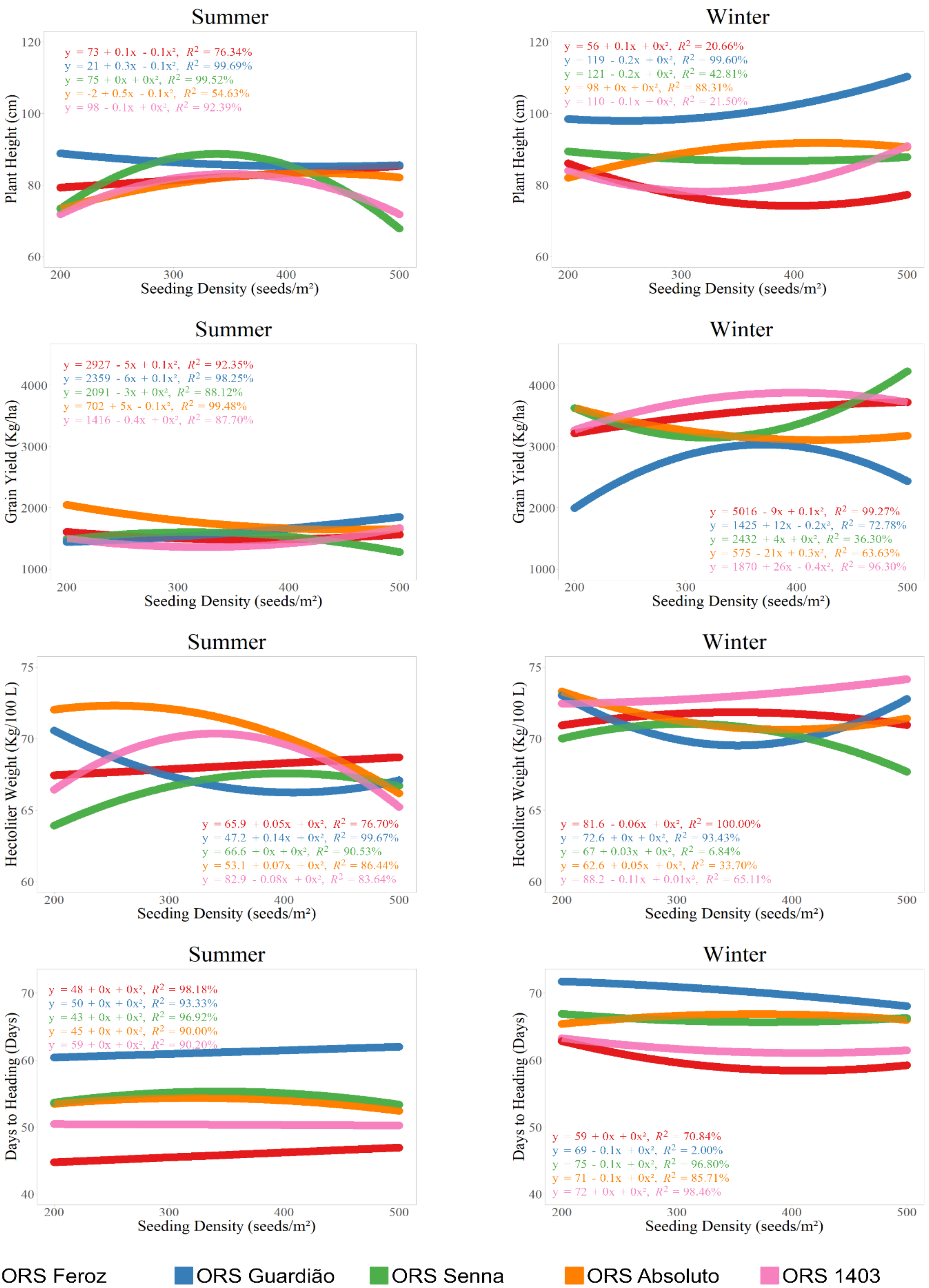

Figure 1. Performance of wheat genotypes in the summer and winter according to the seeding density (seeds per m²) for each evaluated trait.

Grain yield varied substantially among genotypes in response to seeding density, with distinct patterns observed in both growing seasons. ORS Feroz showed maximum yield at the lowest density (200 seeds m²) in summer, with slight reductions at higher densities and the highest yield at the maximum seeding density in winter. ORS Guardião exhibited the opposite behavior, reaching its highest grain yield at 400 seeds m² in winter and 500 seeds m² in summer. Other genotypes, such as ORS Senna and ORS Absoluto, displayed changes in the density–yield relationships across seasons, indicating that the density level associated with optimal productivity varies across genotypes or environments.

The yield variation observed reflects differences among genotypes in their capacity to balance light interception, interplant competition, and resource use efficiency. This interpretation is supported by Gao et al. (2021), who demonstrated that seeding density modifies population architecture in ways that influence yield differently across cultivars, particularly under varying environmental conditions. Similarly, Ma et al. (2018) showed that seeding density alters shoot and root development, affecting the acquisition and utilization of resources in a genotype-dependent manner. These findings reinforce that, even under uniform management practices, genotypes differ in how they adjust physiologically and morphologically to changes in plant population.

Hectoliter weight responded differently to seeding density depending on genotype and season. ORS Senna showed higher values at intermediate densities, whereas ORS Feroz maintained more stable values across densities in both seasons. In contrast, ORS Absoluto exhibited a decline in hectoliter weight at higher densities in summer, while remaining relatively stable in winter. These patterns indicate that the relationship between seeding density and grain physical quality is not consistent across genotypes or growing conditions.

Variation in hectoliter weight among genotypes is associated with differences in their ability to sustain grain filling under varying levels of interplant competition. Denser stands can reduce light penetration and nutrient availability, which can lead to limited assimilation of grains allocation. Bastos et al. (2020) observed that the response of hectoliter weight to plant density depends on the tillering capacity of the genotype and the yield potential of the environment, highlighting how plant architecture influences grain development under crowding. Similarly, Lollato et al. (2020) reported an initial increase in the grain quality with higher seeding rates, followed by a decline at excessive densities, due to intensified competition and reduced source strength during grain filling. In the genotypes evaluated here, the observed patterns align with these findings, reinforcing that the effect of plant population on grain quality is both genotype- and context-dependent.

Days to heading varied among genotypes and were influenced by seeding density and growing season. In general, heading occurred earlier during summer across all genotypes, reflecting the combination of higher temperatures and shorter photoperiods typical of that period. Among cultivars, 1403 and ORS Feroz reached heading earlier, especially under high densities in summer, while ORS Guardião consistently exhibited later heading in both seasons.

A joint inspection of the curves and the model parameters indicates a dynamic adjustment among the four measured attributes. When grain yield peaks at higher densities, as is the case for ORS Feroz in the winter (positive β_1), the hectoliter weight remains practically stable, suggesting that the increase in production is mainly due to a higher number of grains, rather than denser grains (Bastos et al., 2020). In contrast, for ORS Absoluto, the gain in hectoliter weight observed at lower densities coincides with the maximum point of grain yield at 200 seeds m², which reinforces that fuller grains depend on lower intraspecific competition (Lollato et al., 2020). On the other hand, ORS Senna shows a slight increase in hectoliter weight when shifted to intermediate densities (300–400 seeds m²), a range in which yield is still increasing, indicating a more neutral relationship between the two variables. Regarding phenological traits, the curves show that cultivars with a greater average height, such as Guardião and Senna, tend to have longer days to heading at low densities, and as the population increases, the slight shortening of days to heading suggests an acceleration of the cycle possibly induced by early canopy shading (Naveed et al., 2014; Bhatta et al., 2017). Conversely, Feroz and 1403, which are smaller, hardly change days to heading with density, reinforcing the idea that more compact genotypes make less use of phenological adjustments to cope with competition (Baloch et al., 2010). These patterns highlight a cultivar-specific trade-off between maximizing yield, preserving test weight, and adjusting the cycle, and reinforce the need for differentiated density recommendations by material.

The observed differences are consistent with reports that increased plant density can alter the canopy microenvironment and affect phenological development. According to Naveed et al. (2014), denser stands tend to promote earlier heading due to shading effects and greater competition, which modify light quality and temperature perception by the plants. Similarly, Bhatta (2017) attributed accelerated heading at higher densities to reduced light penetration and increased competition for resources, which can trigger early transition to reproductive stages in some genotypes.

The contrasting patterns observed across the tested genotypes and growing seasons confirm the complexity of the genotype × density × environment interaction. As previously discussed, wheat productivity in Brazil remains below domestic demand, and optimizing agronomic practices such as seeding density is a critical step toward improving crop performance and adaptability. However, our findings show that such optimization cannot be generalized, as each genotype expressed distinct phenotypic responses across plant populations and seasonal conditions. Traits linked to both morphology and grain quality exhibited patterns that were not consistent between cultivars, reinforcing the need for genotype-specific evaluations.

Applying the model identity methodology provides a more detailed understanding of how plant density influences key traits across genotypes, offering a statistically robust and biologically coherent framework for cultivar recommendation. Rather than seeking universal recommendations, the approach adopted here acknowledges the heterogeneity of plant responses as a fundamental feature of genotype evaluation. This perspective is particularly valuable in the context of modern breeding programs, where the ability to model cultivar-specific performance under variable management and environmental conditions is essential for effective selection and deployment.

This study highlights the importance of evaluating breeding lines across multiple seeding densities to avoid underestimating a genotype's potential. For instance, a breeding line that performs exceptionally well at low densities might not stand out in a denser plant population, and vice versa. In this context, the study provides a robust statistical framework for characterizing these distinct response patterns. This in-depth analysis enables breeding programs to more accurately select materials for different production systems by identifying both generalist genotypes, which exhibit stable performance across diverse populations, and specialist genotypes, which maximize yield under specific conditions.

For example, ORS Absoluto performed as a specialist under low-density systems across both seasons, achieving its maximum grain yield at just 200 seeds m^{-2}, a density that also favored higher hectoliter weight. In direct contrast, ORS Senna acted as a specialist for high-density systems in winter, reaching its peak productivity at 400 to 500 seeds m^{-2}. Meanwhile, other cultivars like ORS Feroz and 1403 exhibited a more generalized response, demonstrating that their grain yield remained stable for the different seeding densities within each season. This detailed characterization translates into direct benefits for farmers, serving as a basis for more refined decision-making. Seeding density can thus be treated as a strategic variable to optimize the balance between cost, productivity, and grain quality.

CONCLUSIONS

The results showed that genotype responses varied according to season and seeding density, indicating that a common regression model was not adequate to represent the responses of all genotypes. The identity test further confirmed the need for distinct models, emphasizing the importance of genotype-specific analysis in studies involving plant population density.

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