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Sowing density associated with the agronomic performance and linear relationships between the morphological traits of sunflower

Abstract – The objective of this work was to evaluate the effect of sowing density on sunflower morphological traits and on the linear relationships between these traits under second-crop conditions, in addition to identifying the traits that can assist in the indirect selection of sunflower hybrids. The experimental design was in randomized complete blocks, with four replicates and six treatments (sunflower sowing densities: 20, 30, 40, 50, 60, and 70 thousand plants per hectare). The sowing density of 51.45 thousand plants per hectare provides the maximum yield per area under second-crop conditions. Sowing density negatively influences the magnitude of the linear associations between the traits number of achenes and individual yield per plant and between plant height and thousand-achene mass. In addition, under a high sowing density, the association between plant height and thousand-achene mass becomes negative. The traits number of achenes per capitulum and capitulum diameter show the highest magnitudes of linear association with individual yield per plant and, therefore, can be used for the indirect selection of sunflower hybrids.

Index terms: *Helianthus annuus*, Pearson's correlation, plant population.

Densidade de semeadura associada ao desempenho agrônomo e às relações lineares entre caracteres morfológicos do girassol

Resumo – O objetivo deste trabalho foi avaliar o efeito da densidade de semeadura sobre caracteres morfológicos do girassol e sobre as relações lineares entre esses caracteres em condições de segunda safra, além de identificar os caracteres que auxiliem na seleção indireta de híbridos de girassol. O delineamento experimental foi em blocos ao acaso, com quatro repetições e seis tratamentos (densidades de semeadura do girassol: 20, 30, 40, 50, 60 e 70 mil plantas por hectare). A densidade de semeadura de 51,45 mil plantas por hectare proporciona a máxima produtividade por área em condições de segunda safra. A densidade de semeadura influencia negativamente a magnitude das associações lineares entre os caracteres número de aquênios e produtividade individual por planta e entre altura de planta e massa de mil aquênios. Além disso, em condições de alta densidade de semeadura, a associação entre altura de planta e massa de mil aquênios passa a ser negativa. O número de aquênios por capítulo e o diâmetro do capítulo apresentam as maiores magnitudes de associação linear com a produtividade individual por planta, e, portanto, podem ser utilizados para seleção indireta de híbridos de girassol.

Termos para indexação: *Helianthus annuus*, correlação de Pearson, população de plantas.

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Introduction

Sunflower (*Helianthus annuus* L.) stands out worldwide as the third oilseed crop in raw material production, ranking only behind the soybean [*Glycine max* (L.) Merr.] and canola (*Brassica napus* L.) crops (Qadir et al., 2020). In the 2022/2023 growing season, the area grown with sunflower covered 28.02 million hectares, with a production of 52.39 million tons and a mean yield of 1,870 kg ha⁻¹, being projected to reach 28.38 million hectares in 2023/2024, with an expected production of 56.80 million tons and a mean yield of 2,000 kg ha⁻¹ (USDA, 2024).

In Brazil, the area estimated for sunflower cultivation was 55.4 thousand hectares in the 2023/2024 growing season, mainly in the Midwest, the main sunflower-producing region in the country (CONAB, 2023). The mean yield of the crop was 1,520 kg ha⁻¹ in the 2022/2023 growing season (CONAB, 2023), which can be considered low compared with those of other sunflower-producing countries (Soares et al., 2019). According to Castro & Leite (2018), the main reasons for the low yield in Brazil are: the low technological level used in sunflower production, generally treated as a secondary crop; the weak transfer of technology and technical information to producers; and the limited investment in research on sunflower cultivation compared with that on other crops, such as soybean and corn (*Zea mays* L.).

Other factors that influence sunflower grain yield include climate conditions and phytosanitary and cultural management (Hiolanda et al., 2018). For an increased yield, the development of cultivars and improved hybrids, as well as cultural management, are the main factors to be considered (Gordeyeva et al., 2023).

Optimizing crop nutrition, sowing density, and sowing time is key for the cultural management of sunflower (Gordeyeva et al., 2023). Sowing density, for example, is one of the main agronomic practices that interfere with sunflower grain yield (Farweez et al., 2020), underscoring the need of determining the appropriate number of seeds per unit of area for yield improvement (Dong et al., 2023). However, information is still scarce regarding the recommendation of the ideal sowing density to be used for sunflower cultivation as a second crop, despite its agronomic and economic benefits for agricultural production systems (Santos et al., 2023).

The development of sunflower genotypes with a higher production potential is another important factor. However, the genotype-selection stage is one of the most difficult in the improvement process due to the complex traits related to grain yield (Carvalho et al., 2015), considered a quantitative trait with a low heritability. For this reason, genetic improvement frequently uses correlations to identify associations between traits, mainly for the indirect selection of cultivars (Riaz et al., 2019). The presence or absence of relationships between traits can contribute to improving the efficiency of the criteria for the selection of sunflower varieties (Radić et al., 2021). In this context, the knowledge of the relationships between traits is essential for studies aiming the improvement of sunflower cultivation (Nobre et al., 2018). However, there are no known reports in the literature quantifying the effect of sowing density on the correlations between sunflower morphological and production traits, which can lead to dubious and erroneous results, as well as to misleading comparisons between these traits' associations.

The objective of this work was to evaluate the effect sowing density on sunflower morphological traits and on the linear relationships between these traits under second-crop conditions, in addition to identifying the traits that can assist in the indirect selection of sunflower hybrids.

Materials and Methods

The experiment was conducted in 2022 in an experimental area located in the municipality of Santa Maria, in the central region of the state of Rio Grande do Sul, Brazil (29°71'S, 53°70'W, at an altitude of 90 m).

According to Köppen-Geiger's classification, the predominant climate in the region is Cfa, i.e., humid subtropical, with hot summers and no-defined dry season. The soil in the experimental area is managed under a no-tillage system and classified as an Argissolo, according to Brazilian Soil Classification System (Santos et al., 2018), equivalent to an Ultisol (Soil Survey Staff, 2022).

The experimental design was in randomized complete blocks, with four replicates and six treatments consisting of different sunflower sowing densities (20, 30, 40, 50, 60, and 70 thousand plants per hectare).

Twenty-four experimental units were composed of four sowing rows with a length of 5.0 m and spacing of 0.50 m, totaling an area of 10 m². The usable area of each plot was 4.0 m², after excluding the borders. Sowing was conducted manually on 1/19/2022, with emergence on 1/26/2022. The ADV 5504 commercial hybrid was used.

Eight plants were marked in the usable area of each experimental plot during the phenological development of the crop. When the crop was at the R6 stage, the height (in meters) of these plants was measured using a measuring tape (Castiglioni et al., 1994), and, at harvest point, their capitula were collected. The total 192 plants were evaluated in the laboratory of the research group on annual-crop ecophysiology and management of Universidade Federal de Santa Maria. The measured traits were: capitulum diameter (in centimeters), thousand-achene mass (in grams), and individual production per plant (in grams). Yield per area (in kg ha⁻¹) was determined by harvesting the usable area of each plot. Thousand-achene mass, individual production per plant, and yield per area were corrected to 13% moisture. The number of achenes per capitulum (NAC) was estimated using the following equation: $NAC = (\text{individual production per plant} \times 1,000) / \text{thousand-achene mass}$.

The data were initially analyzed for adherence of residuals, as well as for normal distribution and homogeneity of variances by the Shapiro-Wilk and Bartlett tests, respectively, both at 5% probability, identifying compliance with statistical assumptions. The experimental data were subjected to the analysis of variance, and, when a significant effect was obtained, a polynomial regression was used to verify the effect of sowing densities on the evaluated variables.

To determine Pearson's correlation coefficients, the observations of the experiment were arranged into three distinct groups regarding sowing density, namely: low density, 20 and 30 thousand plants per hectare; medium density, 40 and 50 thousand plants per hectare, which was the reference for cultivation in the main cropping season; and high density, 60 and 70 thousand plants per hectare.

The matrix of Pearson's linear correlation coefficients (r) between the traits plant height, capitulum diameter, thousand-achene mass, NAC, and individual production per plant was estimated.

The significance of the coefficients was verified using Student's t-test.

Statistical analyses were conducted with the Microsoft Office Excel application and the R, version 4.0.4, software (R Development Core Team, 2021) through the *Agricolae*, *Dplyr*, and *Corrplot* packages, adopting a 5% significance level in all analyses. The *Sigma Plot*, version 14.5, software (Grafiti LLC, Palo Alto, CA, USA) was used to represent graphically the regressions.

Results and Discussion

The analysis of variance showed no significant effect of the density factor on the traits plant height and thousand-achene mass (Table 1). Similarly, Fonseca et al. (2020) found no increase in plant height with an increase in plant population up to a density of 80 thousand plants per hectare. Souza et al. (2014) also did not observe any significant effect of sowing density on the traits plant height and thousand-achene mass.

The behavior of capitulum diameter, number of achenes per capitulum, production per plant, and yield per area in response to the different experimental densities is shown in Figure 1. The increase in sowing density led to a decrease in capitulum diameter (Figure 1 A), number of achenes per capitulum (Figure 1 B), and individual production per plant (Figure 1 C). This finding is likely due to an increase, under a high density, in the intraspecific competition between plants for environmental resources, such as nutrients, water, and solar radiation, which reduces plant growth and limits individual production per plant (Li et al., 2019). Ferreira et al. (2023) observed a similar behavior for these traits. Likewise, Li et al. (2019) described a significant decrease in capitulum diameter with an increasing sowing density.

Yield per area increased with an increasing density until the sowing density of 51.45 thousand plants per hectare (Figure 1 D), when the point of maximum technical efficiency was obtained, corresponding to a yield of 2,021.52 kg ha⁻¹. According to Kandil et al. (2017), sunflower yield increases with an increase in plant population to a certain level. In this line, Dong et al. (2023) added that sunflower yield is proportional to sowing density up to a critical density, beyond which there is no increase in yield. Therefore, it is

fundamental to determine the optimal sowing density for the sunflower crop, which can maximize light interception, for example, contributing to a high yield (Li et al., 2019). However, the adequate density depends on the sunflower genotype to be used (Gordeyeva et al., 2023), as well as on the growing environment (Pinkovskyi & Tanchyk, 2021).

In Brazil, the recommended density for sunflower cultivation is generally in the range of 40 to 45 thousand plants per hectare (Castro & Leite, 2018). However, considering that the maximum technical efficiency was obtained with a sowing density of 51.45 thousand plants per hectare in the present study, the increase in plant population may be a potential strategy to mitigate the effects of restricted crop growth due to high summer temperatures. In this line, Pereira & Hall (2019) suggested that the potential sunflower yield might be increased by increasing the plant population above what is currently considered appropriate.

In the literature, Partal (2022), working with different sunflower sowing densities, obtained the highest mean yield of 2,226 kg ha⁻¹ with a population of 50 thousand plants per hectare. In contrast, Stasiak et al. (2018), in a similar study, found a higher mean yield of 1,460.4 kg ha⁻¹ when using a lower sunflower population of 47,150 thousand plants per hectare.

Pearson's correlations were obtained between the traits of the sunflower plants grown at low (Figure 2 A), medium (Figure 2 B), and high (Figure 2 C) sowing densities. Under low sowing densities, the r between these traits ranged from $-0.28 \leq r \leq 0.84$ (Figure 2 A). The NAC x production per plant correlation showed a positive linear association of high magnitude ($r = 0.84$), whereas the correlations capitulum diameter

x production per plant ($r = 0.65$), NAC x capitulum diameter ($r = 0.44$), and plant height x thousand-achene mass (0.42) were positive, with a moderate to weak degree of association. In addition, the NAC x thousand-achene mass correlation was negative, with a weak linear association ($r = -0.28$).

Under medium sowing densities, the r between sunflower traits ranged from $-0.32 \leq r \leq 0.69$ (Figure 2 B). The NAC x production per plant correlation showed a positive linear association of high magnitude ($r = 0.69$), while the correlations capitulum diameter x production per plant ($r = 0.66$), plant height x thousand-achene mass ($r = 0.61$), and plant height x capitulum diameter ($r = 0.50$) were positive, with a moderate to weak degree of association. Moreover, the NAC x thousand-achene mass correlation was negative, with a weak linear association ($r = -0.32$).

Under high sowing densities, the r between sunflower traits ranged from $-0.60 \leq r \leq 0.91$ (Figure 2 C). The NAC x production per plant correlation showed a positive linear association of high magnitude ($r = 0.91$), whereas the correlations capitulum diameter x production per plant ($r = 0.49$), NAC x capitulum diameter ($r = 0.45$), and plant height x NAC ($r = 0.39$) were positive, with a moderate to weak degree of association. The NAC x thousand-achene mass ($r = -0.55$) and plant height x thousand-achene mass ($r = -0.60$) correlations were negative, with moderate magnitudes of linear association.

Ghaffari et al. (2019) also observed significant correlations ($r = 0.85$ and $r = 0.75$, respectively) between number of achenes per capitulum and achene production per plant and between capitulum diameter and achene production per plant. Likewise, Reavanth et al. (2022) found that achene production per plant

Table 1. Mean squares of the analysis of variance of the sunflower (*Helianthus annuus*) traits evaluated in 2024 in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil⁽¹⁾.

Source of variation	DF	PH	CAPD	TAM	NAC	PROD	YLD
Blocks	3	743.4 ^{ns}	16.66*	491.6 ^{ns}	441,102.0 ^{ns}	216.3 ^{ns}	15,078.6 ^{ns}
Density	5	376.0 ^{ns}	98.31*	661.9 ^{ns}	2,010,551.0*	6,605.2*	422,379.0*
Experimental error	15	301.4	3.98	235.9	138,411.7	256.9	53,284.0
Sampling error	168	30.0	1.75	15.2	47,782.9	94.7	254.0
Average	-	143.44	17.20	43.12	1,018.99	44.28	708.13
CV (%)	-	5.74	4.34	17.81	14.77	14.38	16.30

⁽¹⁾DF, degrees of freedom; PH, plant height; CAPD, capitulum diameter; TAM, thousand-achene mass; NAC, number of achenes per capitulum; PROD, individual production per plant; and YLD, yield per area. *Significant by the F-test, at 5% probability. ^{ns}Nonsignificant by the F-test.

showed a positive linear correlation with capitulum diameter ($r = 0.83$). Amorim et al. (2008) obtained positive correlations between grain yield and capitulum diameter ($r = 0.63$), while Radić et al. (2021) reported a significant correlation ($r = 0.75$) between the number of achenes per capitulum and achene production per plant. Similarly, Abro et al. (2020) described a positive linear correlation ($r = 0.83$) between capitulum diameter and number of achenes per capitulum.

Pearson's correlations between traits in the groups with a low (Figure 2 A), medium (Figure 2 B), and high (Figure 2 C) density showed a trend of a higher correlation between NAC x production per plant regardless of sowing density, indicating that an increase

in the number of achenes per capitulum resulted in the maximization of individual sunflower yield. However, the magnitude of the NAC x production per plant correlation was higher in the groups with a low ($r = 0.84$) and high ($r = 0.91$) density than in the one with a medium density ($r = 0.69$).

The magnitude of the correlation between production per plant and capitulum diameter practically did not change in the groups with a low ($r = 0.65$) (Figure 2 A) and medium ($r = 0.66$) sowing density (Figure 2 B), only showing a slight reduction in the group with a high density ($r = 0.49$) (Figure 2 C). Moreover, the magnitude of the correlation between capitulum diameter and NAC did not undergo any significant

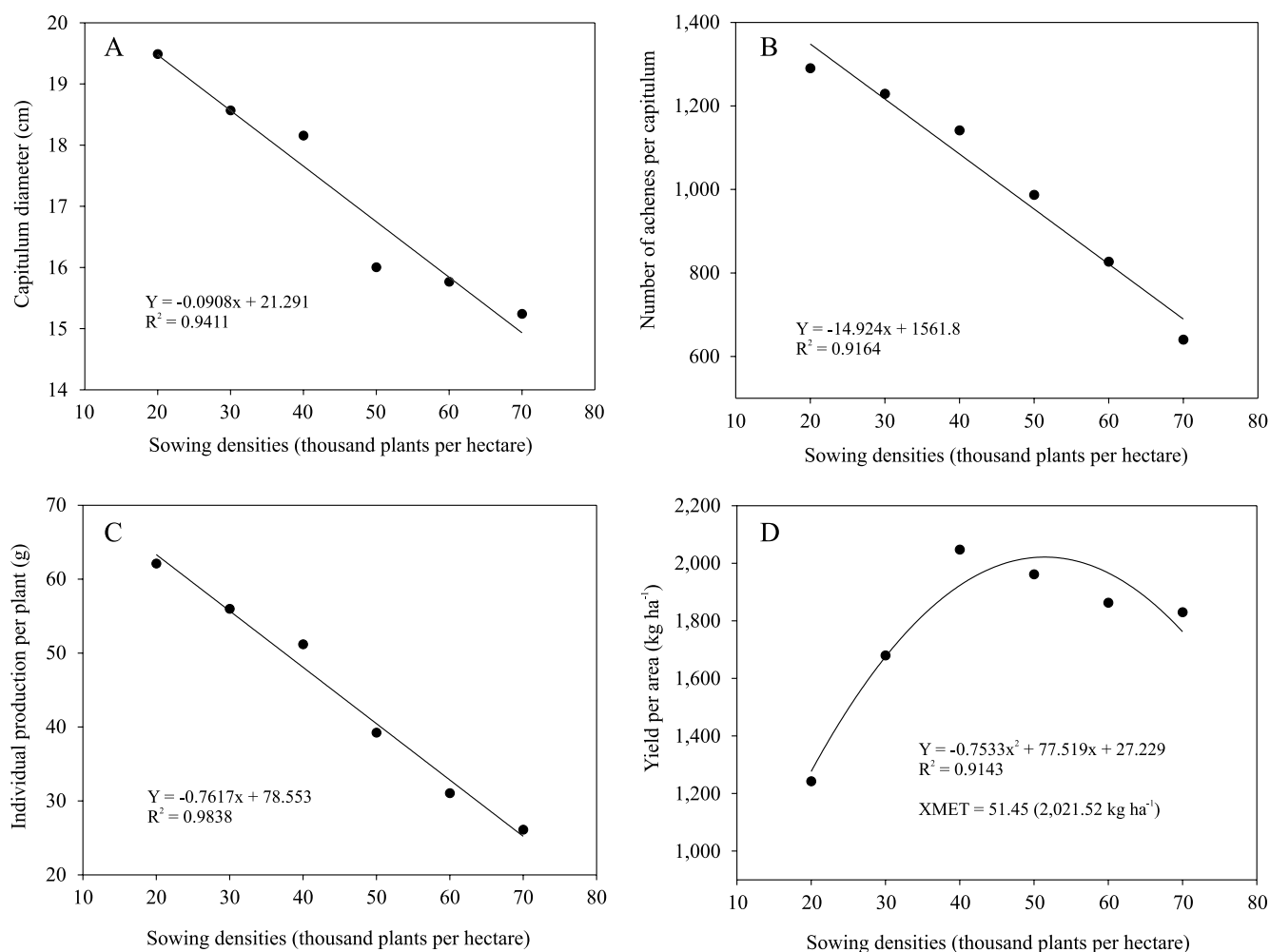


Figure 1. Behavior of the sunflower (*Helianthus annuus*) traits capitulum diameter (A), number of achenes per capitulum (B), individual production per plant (C), and yield per area (D), in 2024, in response to the experimental densities in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil.

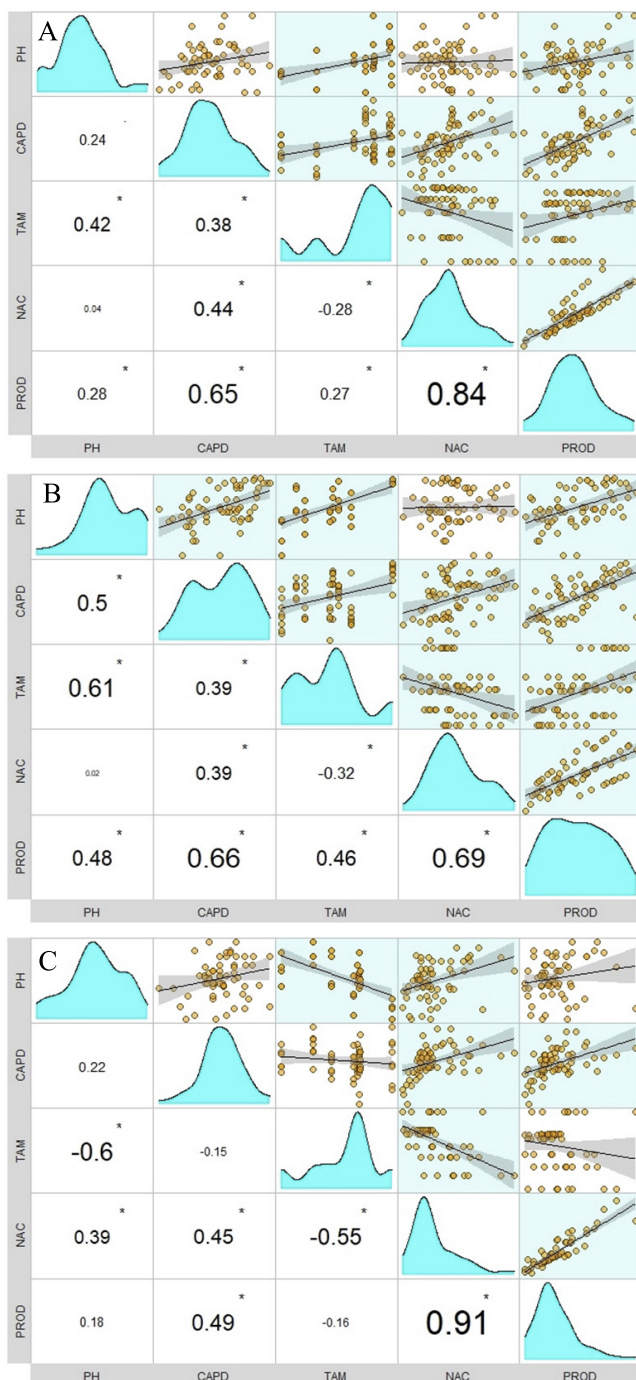


Figure 2. Frequency distribution (on the diagonal), dispersion of observations (on the right of the diagonal), and Pearson's correlation (on the left of the diagonal) between sunflower (*Helianthus annuus*) traits evaluated at low (A), medium (B), and high (C) sowing densities, in 2024, in the municipality of Santa Maria, in the state of Rio Grande do Sul, Brazil. *Significant by the t-test, at 5% probability. PH, plant height; CAPD, capitulum diameter; TAM, thousand-achene mass; NAC, number of achenes per capitulum; and PROD, individual production per plant.

changes in the groups with a low ($r = 0.44$), medium ($r = 0.39$), and high ($r = 0.45$) sowing density.

The magnitude of the correlation between plant height and thousand-achene mass was increased when comparing the groups with a low ($r = 0.42$) and medium ($r = 0.61$) density. However, in the high-density group, the direction of the linear association between the aforementioned pair of traits changed, no longer being positive but becoming negative with a moderate magnitude ($r = -0.6$).

The components related to achene yield and sunflower production are influenced by technological and environmental factors. The technological factors include inter-row spacing and plant population (Ion et al., 2015), whereas the environmental factors highlight the relationship between light interception and plant population. A lower population allows plants to receive more resources (water, sunlight, and nutrients) and to, consequently, have more leaves and achenes in their capitulum (Li et al., 2019). Contrastingly, an increased plant population leads to a reduction in the availability of resources per plant, causing the observed reduction in number of achenes per capitulum and individual production per plant.

The reduction in a certain component can be compensated by an increase in the influence of another (Bezerra et al., 2016). A reduction in the number of capitula can, for example, result in a larger capitulum diameter and in an increase in the number or mass of achenes per capitulum (Bezerra et al., 2016). These results are aligned with those obtained in the present study, in which changes were observed in the magnitude and direction of the linear associations between sunflower morphological traits depending on sowing densities, possibly due to the compensatory behavior of these traits in response to the modifications caused by the different tested densities.

Conclusions

1. The sowing density of sunflower (*Helianthus annuus*) influences capitulum diameter, number of achenes per capitulum, individual production per plant, and yield per hectare.

2. The use of a higher sowing density under second-crop conditions is recommended for the state of Rio Grande do Sul, Brazil, considering that the maximum

yield per hectare under these conditions occurs at a sowing density of 51.45 thousand plants per hectare.

3. Sowing density negatively influences the magnitude and direction of the linear associations between the studied traits.

4. The traits number of achenes per capitulum and capitulum diameter show the highest magnitudes of linear association with individual production per plant regardless of sowing density, and, therefore, can be used for the selection of sunflower hybrids.

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No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

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