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CROP PRODUCTION

Univariate and multivariate linear relationships among traits in sunflower cultivation

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ABSTRACT. Evaluating characteristics in sunflower cultivation through univariate and multivariate selection of agronomic traits and grain yield helps choose cultivars and hybrids, and supports crop breeding studies. Yet, the scientific literature relies on data from limited cultivation environments, potentially undermining result reliability. In this context, this study aimed to evaluate the linear relationships among morphological traits of sunflower in a low-altitude subtropical environment and identify traits that can assist in the indirect selection of cultivars, hybrids, and genotypes in field trials of the national sunflower genotype evaluation network. Data from five experimental years conducted annually between 2017/2018 and 2022/2023 were used. The experiments were conducted at the Federal University of Santa Maria (UFSM). The experimental design consisted of randomized blocks with four replications, considering 34 treatments (genotypes) evaluated over five experimental years, totaling 1,754 plants evaluated during the period. The evaluated traits were plant height (cm), capitulum diameter (cm), thousand-achene mass (g), number of achenes per capitulum, and individual achene yield per plant (g). Subsequently, the relationship among traits was investigated using Pearson correlation (r) and path (cause and effect) analyses. The traits number of achenes per capitulum, thousand-achene mass, and capitulum diameter are positively related. The magnitude of Pearson correlations among evaluated traits changes in an environment with prolonged water deficit conditions. The number of achenes per capitulum and thousand-achene mass have a linear relationship and a direct effect on individual achene yield. Capitulum diameter has a direct effect on the number of achenes per capitulum and can be used to assist in the indirect selection of sunflower genotypes, hybrids, and cultivars.

Keywords: *Helianthus annuus* L., Pearson correlation, path analysis, subtropical environment.

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Introduction

Sunflower (*Helianthus annuus* L.) stands out worldwide as the third oilseed crop in raw material production, following soybean and canola in the ranking (Qadir et al., 2020). The area cultivated with sunflower in the world was 28.82 million hectares, with a production of 57.31 million tons and a mean yield of 1999 kg ha^{-1} in the 2021/22 growing season, while the projection in the 2022/23 growing season is 26.96 million hectares, with an expected production of 50.77 million tons and a mean yield of 1888 kg ha^{-1} (United States Department of Agriculture [USDA], 2023).

The world's largest producers are Ukraine, Russia, and the European Union, with Brazil ranking 26th among the main sunflower producers (Food and Agriculture Organization [FAOSTAT], 2020). The limited investment in research into sunflower cultivation compared to investments in other crops such as soybean and corn is one of the factors that justifies Brazil's position in the world ranking.

The estimated sunflower cultivated area in Brazil for the 2022/23 growing season is 42.0 thousand hectares, representing an increase of six percent compared to the cultivated area in the 2021/22 growing, with the Midwest region being the main producing region in Brazil (Companhia Nacional de Abastecimento [CONAB], 2023). The mean Brazilian yields in the 2020/21 and 2021/22 growing seasons were 1143 and 1042 kg ha^{-1}, respectively (CONAB, 2022). This yield can be considered low compared to other sunflower-producing countries (Soares et al., 2019).

Sunflower grain yield can be influenced by several factors, including climate conditions, phytosanitary and soil management, and the correct cultivar choice (Nobre et al., 2015; Hiolanda et al., 2018). The adoption of cultivars with better adaptability to the production environment provides an increase in crop yield (Dalchiavon et al., 2016; Birck et al., 2017).

Therefore, experiments with new hybrids developed each year need to be conducted to identify the most adapted genotypes and verify how they respond together in productive terms, aiming for new progress in crop breeding (Oliveira et al., 2017). Continuous evaluation of new materials in different cultivation systems and producing regions is necessary (Valadão et al., 2020).

The selection stage represents a pivotal and intricate phase in the development of new cultivars, primarily owing to the intricacies associated with yield-related complex traits (Carvalho et al., 2015), as yield is a quantitative trait with low heritability. In this context, crop breeding frequently uses correlations to identify associations among traits, mainly for the indirect selection of cultivars (Riaz et al., 2019).

The presence or absence of univariate and multivariate relationships among traits can contribute to improving the efficiency of sunflower variety selection criteria (Radić et al., 2021). Direct selection for this trait has a lower efficiency due to the low heritability of yield; thus, indirect selection considering other traits can improve the yield of sunflower achenes and oil (Ghaffari et al., 2019). In this context, knowledge of trait relationships is of great importance for plant improvement studies in sunflower cultivation (Nobre et al., 2018).

Correlation coefficients and direct and indirect effects in path analysis were used in studies of associations among sunflower traits by Chambó et al. (2017), Riaz et al. (2019), and Follmann et al. (2019). However, the results available in the literature are often based on one environment (Chambó et al., 2017; Riaz et al., 2019; Follmann et al., 2019) and consider a small number of samples, ranging between 24 (Abro et al., 2020) and 400 plants (Nobre et al., 2018), which may compromise the reliability of results and the inferences considering them.

This study aimed to evaluate the linear relationships among sunflower morphological traits in a low-altitude subtropical environment and identify traits that can assist in the indirect selection of cultivars, hybrids, and genotypes in field trials of the national sunflower genotype evaluation network.

Material and methods

Location and field conditions

The experiments were conducted in the agricultural years 2017/2018, 2018/2019, 2020/2021, 2021/2022, and 2022/2023 in an experimental area located at the Federal University of Santa Maria (UFSM), Santa Maria (latitude 29°71′ S, longitude 53°70′ W, and altitude of 90 meters), located in the central region of the State of Rio Grande do Sul, Brazil.

According to the Köppen classification, the predominant climate in the region is Cfa, that is, a humid subtropical climate with hot summers and no defined dry season (Alvares et al., 2013). The soil in the experimental area is managed under a no-tillage system and classified as an Ultisol (Santos et al., 2018).

Experimental design and treatments

The adopted experimental design consisted of randomized blocks with four replications, in which the treatments were composed of different sunflower genotypes (Table 1).

Table 1. Genotypes sown in each experimental year. Santa Maria, State of Rio Grande do Sul, Brazil, 2024.

2017/2018		2018/2019		2020/2021		2021/2022		2022/2023	
Genótipo	EMF	Genótipo	EMF	Genótipo	EMF	Genótipo	EMF	Genótipo	EMF
BRS G58	85	BRS G46	91	BRS G62	101	BRS G73	105	BRS G73	104
BRS G59	85	BRS G52	83	BRS G63	101	BRS G74	103	BRS G74	102
BRS G60	84	BRS G54	83	BRS G64	98	BRS G75	104	BRS G75	103
BRS G61	89	BRS G55	85	BRS G65	82	BRS G76	96	BRS G76	95
SYN 045	103	BRS G61	95	BRS G66	82	BRS G77	94	BRS G77	93
BRS 323	86	BRS G62	98	BRS G67	84	BRS G78	100	BRS G78	99
MULTISSOL 02	86	BRS G67	88	BRS G68	84	BRS G79	107	BRS G79	105
CATISSOL 03	88	SYN 045	106	BRS G69	91	BRS G80	104	BRS G80	103
		BRS 323	91	BRS G70	91	BRS G81	104	BRS G81	103
				BRS G71	82	BRS 323	95	BRS 323	83
				BRS G72	87	ALTIS 99	108	ALTIS 99	106
				BRS 323	84	HELIO 250	100	HELIO 250	98
				ÁGUARÁ 06	98				
				HELIO 250	87				

EMF - Days elapsed from emergence to physiological maturity.

The experimental units were composed of four sowing rows 6 m long with spacings of 0.43 m between plants and 0.50 m between rows, totaling an area of 12.0 m^2. The useful area of each plot was 5.0 m^2, after excluding the borders.

Sowing for both experimental years was carried out manually from September to October, with the opening of 14 holes per row. Each hole received three seeds. Thinning was conducted seven days after emergence, keeping one plant per hole, equivalent to a population of 45,000 plants ha^{-1}. The seeds were made available by Embrapa Soybean for the network of collaborative trials to evaluate sunflower genotypes.

Evaluations and statistical analyses

Eight plants were marked in the useful area of each experimental plot during the period of phenological crop development. These plants were used to measure plant height (PH, in m) using a measuring tape when the crop was at the R6 stage (Castiglioni et al., 1994). Then, the capitula of these eight plants marked per plot were harvested when the crop was at the harvest point and the following traits were measured in the Laboratory of the Research Group on Ecophysiology and Management of Annual Crops (GEMCA): capitulum diameter (CD, in cm), thousand-achene mass (TAM, in g), and individual production per plant (PROD, in g) corrected for 13% moisture. The number of achenes per capitulum (NAC) was estimated using the equation NAC = PROD.1000 / TAM.

Considering the five agricultural years, 34 treatments were evaluated (genotypes, hybrids, and cultivars) and 1754 plants were evaluated individually. Correlations and diagnosis of multicollinearity among the measured variables were performed individually within each year.

The matrix of Pearson's linear correlation coefficients (r) among the traits PH, CD, TAM, NAC, and PROD was estimated and the significance of coefficients was verified using Student's t-test. Multicollinearity diagnosis was performed using two methods: variance inflation factor (VIF) and condition number (CN).

VIF indicates the effect that other independent variables have on the standard error of a regression coefficient, and high VIF values (generally above 10) indicate a high degree of collinearity or multicollinearity (Hair et al., 2019). The matrix of Pearson's linear correlation coefficients (r) among the explanatory variables PH, CD, TAM, and NAC was considered to estimate CN. The criteria described by Montgomery et al. (2021) were adopted to interpret the multicollinearity diagnosis. The correlation matrix with CN < 100 is classified as having a weak multicollinearity, 100 ⩽ CN ⩽ 1,000 is moderate to strong, and CN > 1,000 is severe. Finally, a cause-and-effect analysis of the main variable (PROD) was performed as a function of the explanatory variables (PH, CD, TAM, and NAC).

The analyses were conducted by the Microsoft Office Excel® application and the R software version 4.0.4 (R Development Core Team, 2021) using the *Metan* (Olivoto & Lúcio, 2020), *Agricolae* (Mendiburu & Yaseen, 2020), *Dplyr* (Hadley et al., 2021), and *Corrplot* (Taiyun & Viliam, 2021), adopting a 5% significance level in all statistical analyses.

Meteorological data and graphical representation

The data and information for calculating the water balance of sunflower cultivation were collected from the National Institute of Meteorology (INMET), recorded by the automatic weather station in Santa Maria, Rio Grande do Sul State, Brazil, located at UFSM, 500 m away from the experimental area. The software Sigma Plot 14.5 was used for graphical representations of mean temperature (°C), precipitation (mm), and water balance (mm) of the different cultivation environments.

Results and discussion

Mean temperatures during the experimental period ranged from 14.56 to 28.43°C for the 2017/2018 environment (Figure 1A), 14.30 to 30.43°C for the 2018/2019 environment (Figure 1B), 16.60 to 30.58°C for the 2020/2021 environment (Figure 1C), 14.12 to 33.37°C for the 2021/2022 environment (Figure 1D), and 14.56 to 28.43°C for the 2022/2023 environment (Figure 1E). The crop develops at temperatures varying between 10 and 34°C, with an optimal temperature range between 27 and 28°C (Castro et al., 1997). Therefore, the mean temperatures observed during the experimental periods are within the recommended temperature range.

Accumulated precipitation throughout the experimental period was 460 mm for the 2017/2018 environment (Figure 2A), 694.80 mm for the 2018/2019 environment (Figure 2B), 362.78 mm for the 2020/2021 environment (Figure 2C), 281.04 mm for the 2021/2022 environment (Figure 2D), and 459.80 mm for the 2022/2023 environment (Figure 2E). The water demand found in the literature to achieve maximum yields ranges between 500 and 700 mm (Borges et al., 2019) although it is not yet well established (Dutra et al., 2012). However, daily water demand varies depending on the phenological stage of sunflower cultivation (Silva et al., 2011). The demand ranges from 0.5 to 1 mm at germination stages, reaching 6 to 8 mm during flowering and filling of achenes (Castro & Farias, 2005).

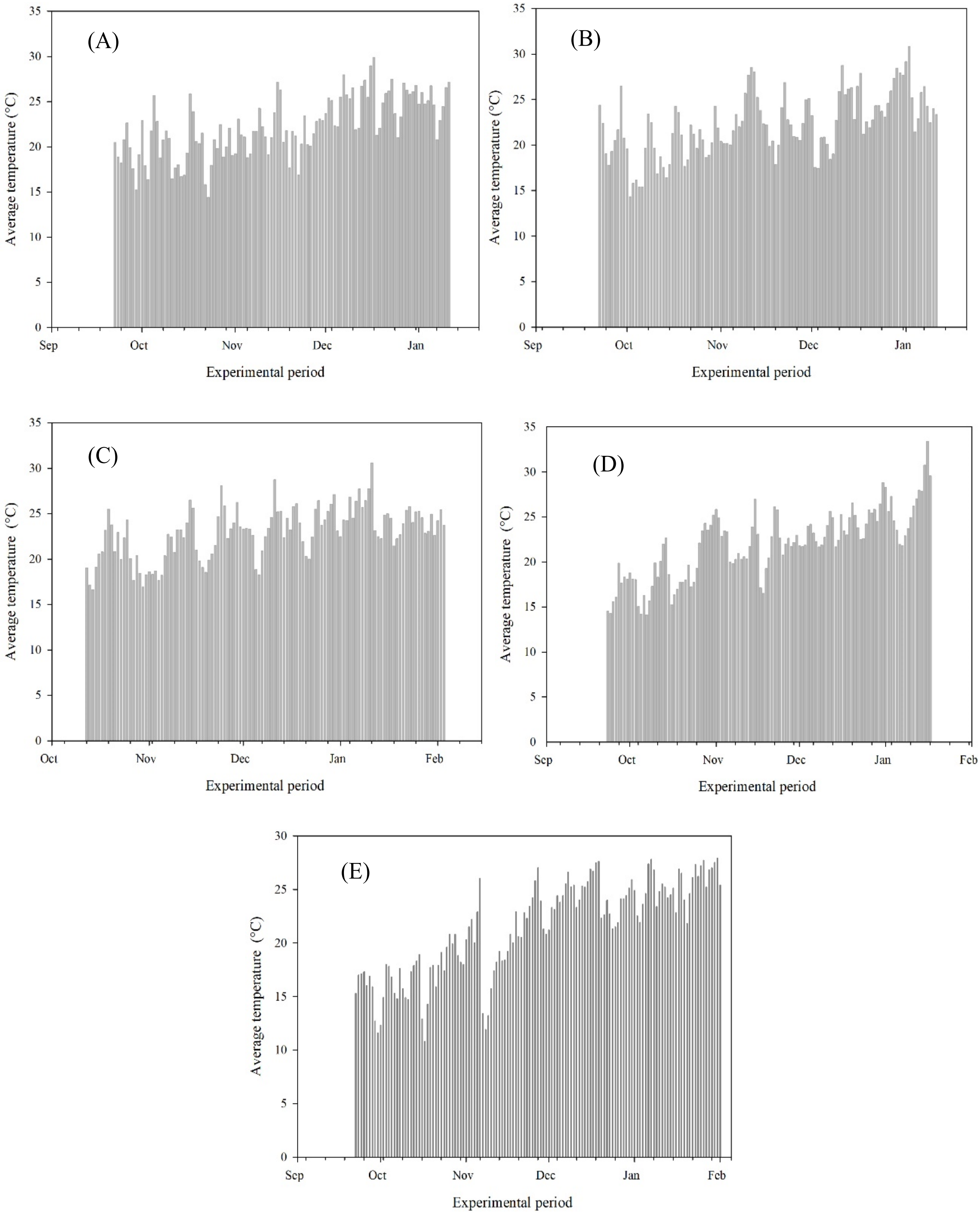

Figure 1. Average daily temperature over the experimental period of 2017/2018 (A), 2018/2019 (B), 2020/2021 (C), 2021/2022 (D), and 2022/2023 (E). Santa Maria, Rio Grande do Sul State, Brazil, 2024.

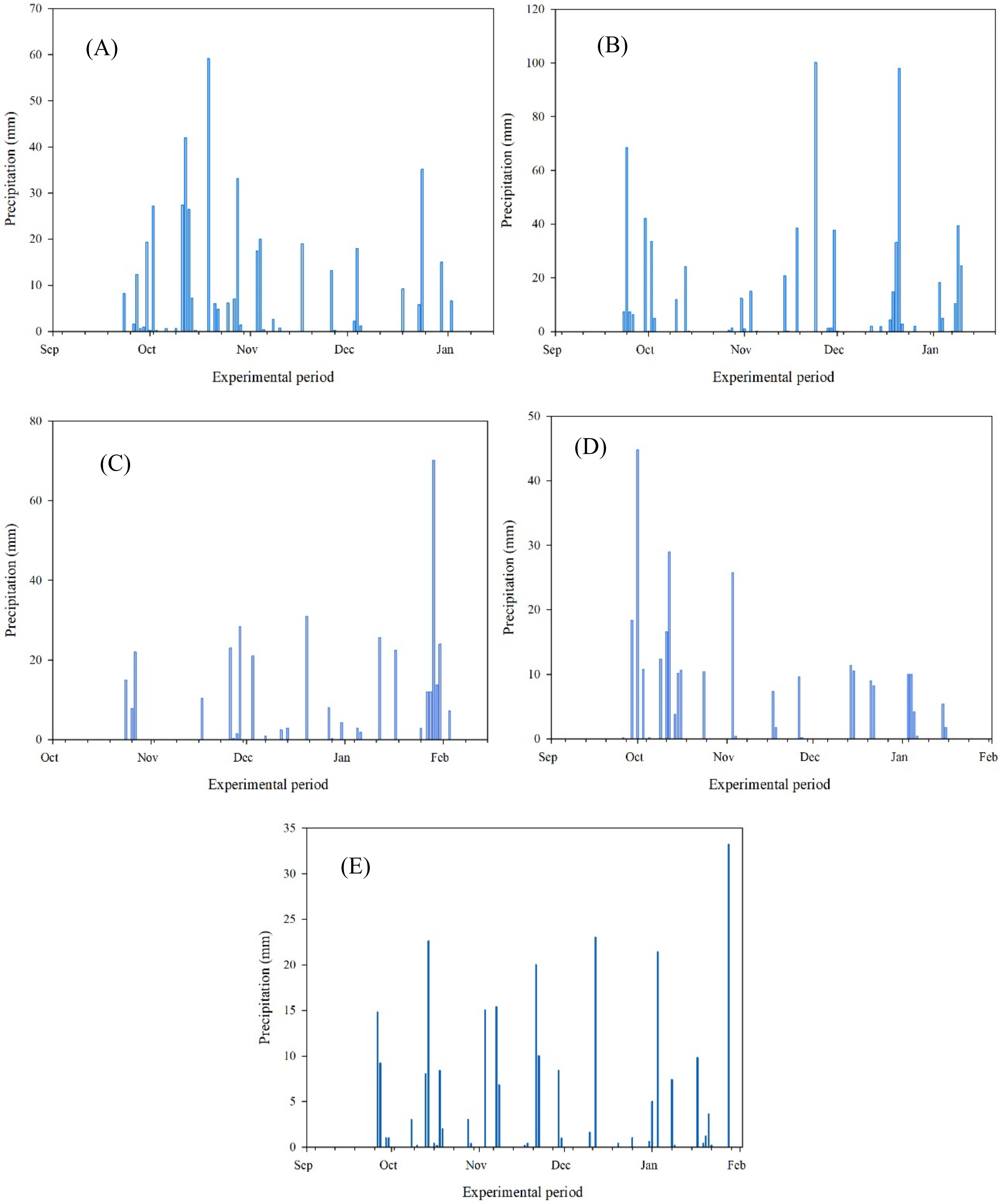

Figure 2. Daily precipitation throughout the experimental period of 2017/2018 (A), 2018/2019 (B), 2020/2021 (C), 2021/2022 (D), and 2022/2023 (E). Santa Maria, Rio Grande do Sul State, Brazil, 2024.

The water balance showed a water deficit for all cultivation environments (Figure 3A, B, C, D, and E) at specific times during the experimental period, although the accumulated precipitation is close to that recommended for the 2017/2018 and 2022/2023 agricultural years and within the recommended range for the 2018/2019 environment. It occurs due to the irregularity of rainfall distribution, which causes periods with water surpluses, with values exceeding the soil water retention capacity, and periods of water deficits, with soil water availability being lower than the crop evapotranspiration demand.

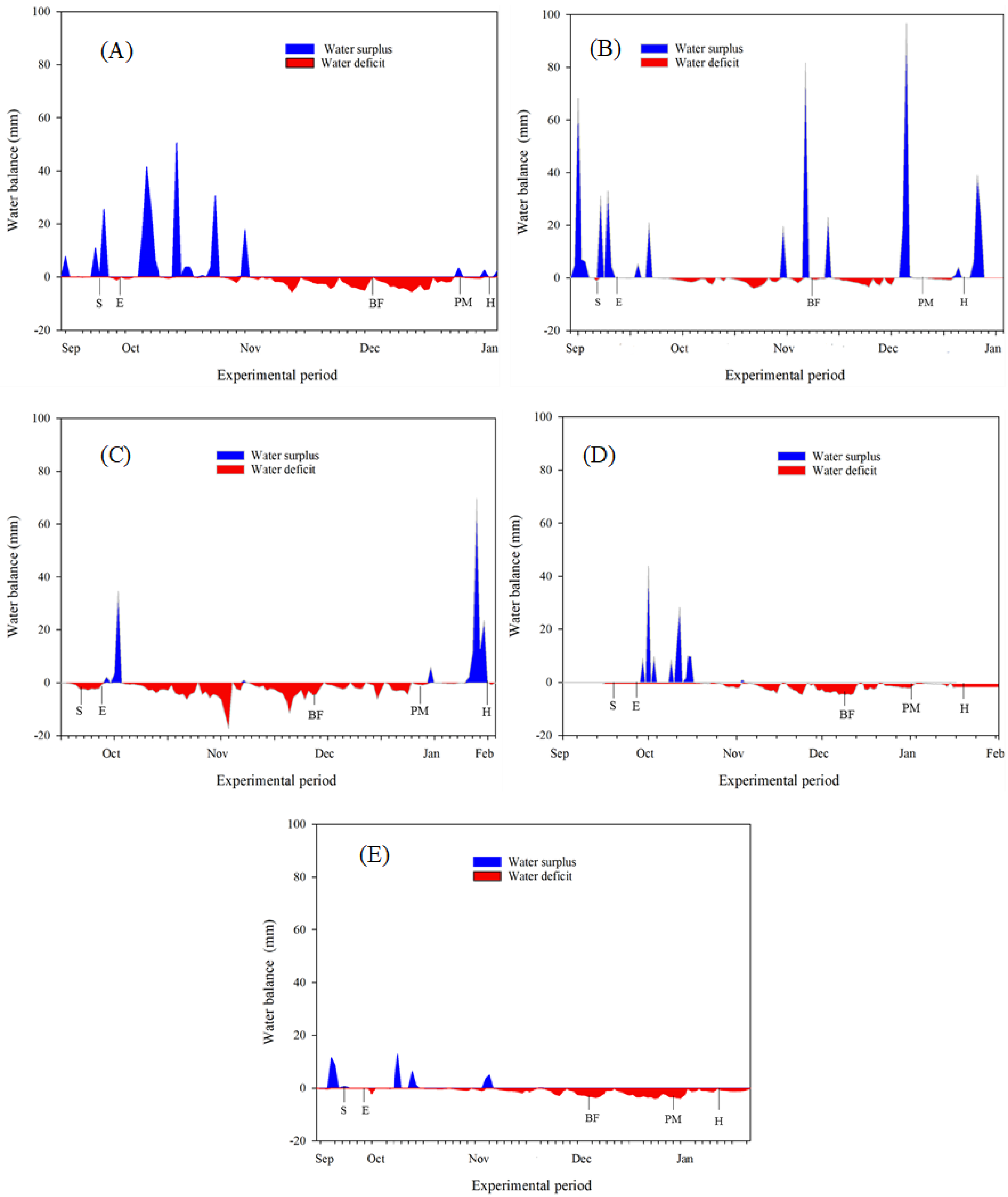

Figure 3. Daily water balance for sunflower crops throughout the experimental period of 2017/2018 (A), 2018/2019 (B), 2020/2021 (C), 2021/2022 (D), and 2022/2023 (E). Santa Maria, Rio Grande do Sul State, Brazil, 2024. Sowing (S), emergence (E), beginning of flowering (BF), physiological maturity (PM), and harvest (H).

Water deficit has been identified as one of the main factors causing a reduction in yield and quality of sunflower achenes and oil production (Castro & Leite, 2018). In general, the periods between 10 and 15 days before flowering and 10 to 15 days after the end of flowering are the most critical phases for the occurrence of water deficit, as it results in a considerable reduction in the production of achenes and the content of achene oil (Oliveira et al., 2022).

Pearson's linear correlation coefficients (r) among sunflower traits under the environmental conditions of 2017/2018 presented values of $-0.44 \leq r \leq 0.61$ (Figure 4A). The CD × NAC correlation showed a moderate magnitude of linear association (r = 0.61), and the CD X PROD and NAC X PROD correlations also stood out, with positive values and a moderate magnitude of linear association (r = 0.58). The NAC x TAM correlation was negative and with a moderate magnitude of linear association (r = −0.44).

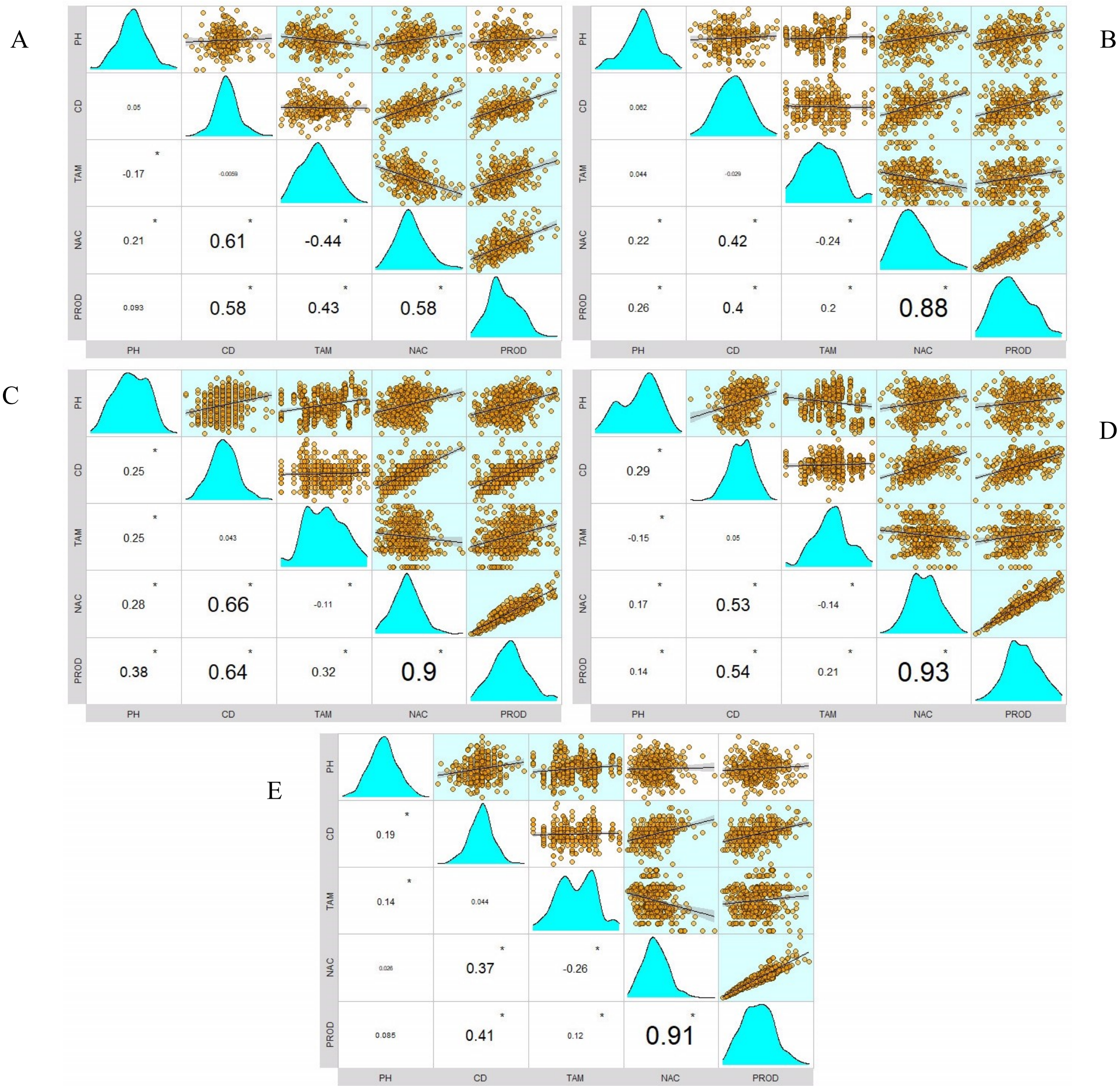

Figure 4. Frequency distribution (on the diagonal), dispersion of observations (on the right of the diagonal) and Pearson correlation (on the left of the diagonal) between sunflower traits evaluated under the environmental conditions of 2017/2018 (A), 2018/2019 (B), 2020/2021 (C), 2021/2022 (D), and 2022/2023 (E). Santa Maria, Rio Grande do Sul State, Brazil, 2024. *significant at 5% probability of error, respectively, by the t test, PH: plant height, CD: capitulum diameter, TAM: thousand-achene mass, NAC: number of achenes per capitulum, and PROD: individual production per plant.

Pearson's linear correlation coefficients (r) between sunflower traits under the environmental conditions of 2018/2019 presented values of −0.24 ⩽ r ⩽ 0.88 (Figure 4B). The NAC × PROD correlation showed a positive linear association of high magnitude (r = 0.88), the CD X PROD (r = 0.4) and NAC X CD (r = 0.42) correlations were positive, with a moderate to weak degree of association. The NAC x TAM correlation was negative and showed a weak magnitude of linear association (r = −0.24).

Pearson's linear correlation coefficients (r) between sunflower traits under the environmental conditions of 2020/2021 presented values of −0.11 ⩽ r ⩽ 0.90 (Figure 4C). The NAC × PROD correlation showed a positive linear association of high magnitude (r = 0.90) and the CD X PROD (r = 0.64) and NAC X CD (r = 0.66) correlations were positive with a moderate degree of association. The NAC x TAM correlation was negative and showed a weak magnitude of linear association (r = −0.11).

Pearson's linear correlation coefficients (r) between sunflower traits under the environmental conditions of 2021/2022 showed values of −0.15 ⩽ r ⩽ 0.93 (Figure 4D). The NAC × PROD correlation showed a positive linear association of high magnitude (r = 0.93) and the CD X PROD (r = 0.54) and NAC X CD (r = 0.53) correlations were positive with a moderate degree of association. The PH x TAM correlation was negative and with a weak magnitude of linear association (r = −0.15).

Pearson's linear correlation coefficients (r) between sunflower traits under the environmental conditions of 2022/2023 presented values of −0.26 ⩽ r ⩽ 0.91 (Figure 4E). The NAC × PROD correlation showed a positive linear association of high magnitude (r = 0.91), the CD X PROD correlation (r = 0.41) was positive with a moderate degree of association, and the NAC X CD correction (r = 0.37) was positive with a weak degree of association. The NAC x TAM correlation was negative and with a weak magnitude of linear association (r = −0.26).

The NAC x TAM correlation was significant for the five experimental years but had a low practical significance. The same behavior was observed for the other correlations of low magnitude that present statistical significance. Low-magnitude correlations can be significant when the sample size is large. In this context, decision-making must be careful to verify whether there is a biological meaning in the significant association or, simply, the significance occurred due to the high sample size (Hair et al., 2019). Furthermore, experimental planning needs to ensure a sufficient sample size to estimate the correlation coefficients with an acceptable level of precision (Olivoto et al., 2018).

The comparison of Pearson's correlations among traits for the years 2017/2018 (Figure 4A), 2018/2019 (Figure 4B), 2020/2021 (Figure 4C), 2021/2022 (Figure 4D), and 2022/2023 (Figure 4E) showed a behavioral trend with the highest correlation among the NAC x PROD traits, indicating that an increase in the number of achenes per capitulum results in a maximization of individual sunflower yield.

The 2017/2018 environment was an exception, as the highest correlation was observed among NAC x CD traits (r = 0.61). The 2017/2018 environment also had higher correlations among the traits PROD x TAM (r = 0.43) and NAC x TAM (r = −0.44) relative to the other experimental years. It possibly occurred because the mean cycle of genotypes, hybrids, and cultivars under experimentation was shorter than the other experimental years. The mean cycle for the 2017/2018 environment was 103 days, while 2018/2019, 2020/2021, 2021/2022, and 2022/2023 environments had 112, 114, 117, and 114 days, respectively.

Therefore, low water availability, together with the occurrence of high temperatures throughout the experimental period, may have limited yield and mass of achenes in a different magnitude compared to other experimental years (Castro & Leite, 2018).

The occurrence of water deficit and high temperatures, especially during flowering, harm dry matter accumulation and yield of sunflower (Braz & Rossetto, 2010). In addition to the effects on gas exchange, water deficit can influence the transport of nutrients in the soil, their absorption, and the metabolism of minerals in the plant (Neves et al., 2019).

Also considering the five environments, the CD x PROD correlation stood out, indicating that larger capitulum diameters lead to higher individual yield. Finally, the CD x NAC correlation also stood out, indicating that the larger the capitulum diameter, the higher the number of achenes per capitulum.

Similarly, Reavanth et al. (2022) observed that achene production per plant had a positive linear correlation with capitulum diameter (r = 0.83) and 100 achene weight (r = 0.73). Amorim et al. (2008) obtained positive correlations between grain yield and capitulum diameter (r = 0.63) and thousand-achene mass (r = 0.55). Ahmed et al. (2020) also obtained positive correlations between grain yield and chapter diameter (r = 0.80) and mass of a thousand achenes (r = 0.65).

Abro et al. (2020) described a positive linear correlation (r = 0.83) between capitulum diameter and the number of achenes per capitulum. Radić et al. (2021) observed a significant correlation (r = 0.75) between the number of achenes per capitulum and achene yield per plant. The same behavior was described by Sahar et al. (2024) with a positive correlation (r = 0.80) between the number of achenes per chapter and the achene yield per plant.

Environments with longer water deficits (Figure 3D) had an increase in the magnitude of correlations among the traits NAC x PROD (Figure 4D), CD x PROD (Figure 4D), and CD x NAC (Figure 4D). The correlations among PH × PROD were positive and significant but with a lower magnitude. Therefore, PROD had a low linear relationship with this trait.

After carrying out the multicollinearity test among explanatory variables, condition numbers (CN) of 7.54, 3.13, 5.87, 4.15, and 2.75 were obtained for the experimental years 2017/2018, 2018/2019, 2020/2021, 2021/2022, and 2022/2023, respectively. This evidenced the occurrence of collinearity classified as weak, according to the criteria by Montgomery et al. (2021).

Furthermore, VIF values were lower than 10 for all environments under analysis. It confirms a degree of multicollinearity classified as weak (Hair et al., 2019). Thus, the cause and effect analysis (Figure 5A, B, C, D, and

E) of PROD as a function of the explanatory variables PH, CD, TAM, and NAC can be carried out properly, allowing the identification of the direct and indirect effects of the traits PH, CD, TAM, and NAC on the trait PROD.

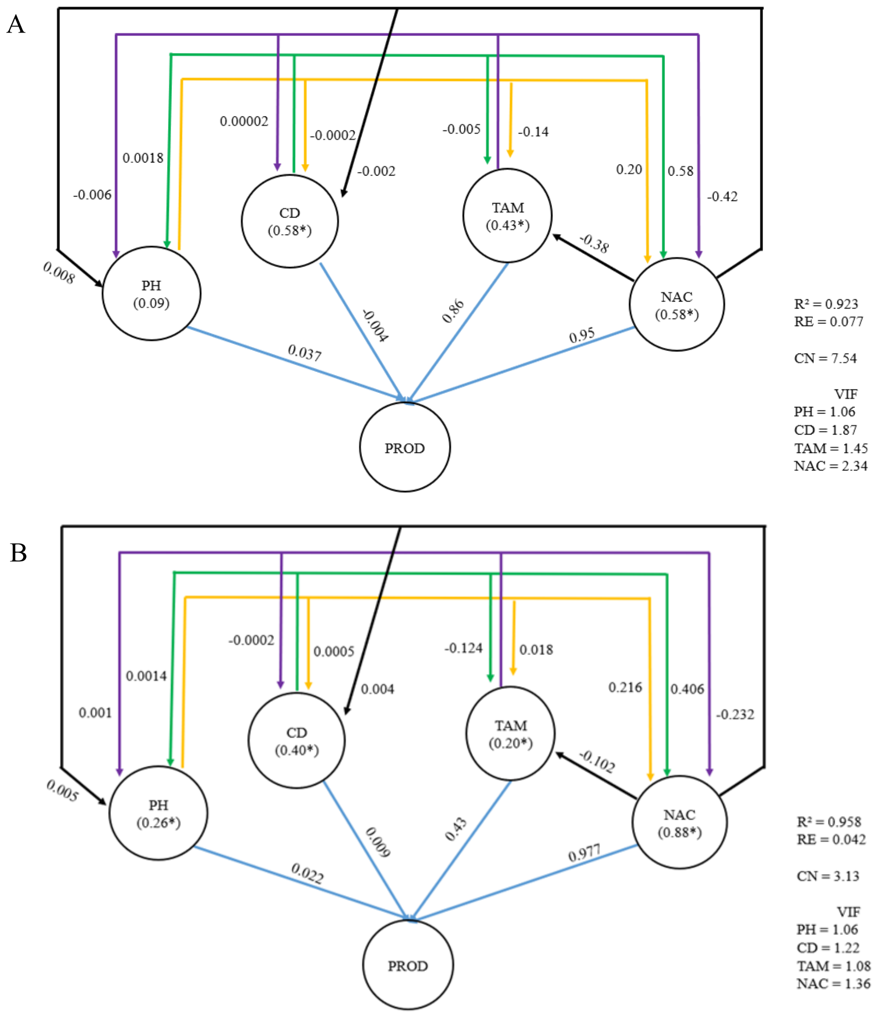

Figure 5. Cause and effect analysis (path analysis) between sunflower traits evaluated under environmental conditions in 2017/2018 (A), 2018/2019 (B), 2020/2021 (C), 2021/2022 (D), and 2022/2023 (E). Santa Maria, Rio Grande do Sul State, Brazil, 2024. Correlations are shown in parentheses for each variable. Direct effects are shown by the blue hue in direct connection to individual production per plant. The indirect effects are shown above, PH: plant height, CD: capitulum diameter, TAM: thousand-achene mass, NAC: number of achenes per capitulum, and PROD: individual production per plant. (*) indicates significant at 5% probability of error, respectively, by t test. R^2: Determination coefficient. RE: Residual effect. Variance inflation factor (VIF) and condition number (CN).

NAC had the highest direct effect on PROD for all environments, with a direct effect of 0.95 for the year 2017/2018 (Figure 5A), 0.977 for the year 2018/2019 (Figure 5B), 0.94 for the year 2020/2021 (Figure 5C), 0.97 for the year 2021/2022 (Figure 5D), and 0.878 for the year 2022/2023 (Figure 5E), confirming the previously observed Pearson's relationships (Figure 4A, B, C, D, and E). Also considering the five environments, the magnitude of the direct effect of PROD remained little changed (Figure 5A, B, C and D).

TAM also had a direct effect on PROD, with a direct effect magnitude of 0.86 for the year 2017/2018 (Figure 5A), 0.43 for the year 2018/2019 (Figure 5B), 0.423 for the year 2020/2021 (Figure 5C), 0.34 for the year 2021/2022 (Figure 5D), and 0.376 for the year 2022/2023 (Figure 5E), thus confirming that the increase in the number of achenes per capitulum and thousand-achene mass maximizes individual sunflower yield. Similarly, Darvishzadeh et al. (2011), Chambó et al. (2017), Follmann et al. (2019), Abro et al. (2020) and Shojaei et al. (2022) described a direct and positive effect of NAC and TAM on PROD.

The trait CD had no relevant direct effect on PROD, with the indirect effect on NAC being mainly responsible for the linear correlation between CD and PROD. CD under NAC showed an indirect effect of 0.58 for the year 2017/2018 (Figure 5A), 0.406 for the year 2018/2019 (Figure 5B), 0.62 for the year 2020/2021 (Figure 5C), 0.515 for the year 2021/2022 (Figure 5D), and 0.322 for the year 2022/2023 (Figure 5E). Similar results were reported by Santos et al. (2021), Naik & Ghodke (2020), and Riaz et al. (2020). Capitulum diameter can be used for indirect selection of more productive genotypes, hybrids, and cultivars when considering the direct effect of NAC on PROD and the difficulty of measuring the traits thousand-achene mass and number of achenes per capitulum.

A decrease in the direct effect of TAM was observed on PROD (Figure 5D) in years with prolonged water deficit during the crop cycle (Figure 3D) compared to years with less prolonged water deficit (Figure 5B).

Conclusion

The traits number of achenes per capitulum, thousand-achene mass, and capitulum diameter are positively correlated with the yield of achenes per plant. The magnitude of Pearson's correlations between the evaluated traits changes in an environment with conditions of prolonged water deficit. The number of achenes per capitulum and thousand-achene mass have a direct effect on achene yield per plant. Capitulum diameter has a considerable direct and negligible effect on achene yield per plant, but it has a direct effect on the number of achenes per capitulum and can be used for indirect selection of sunflower genotypes and cultivars.

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Data availability

Does not apply.

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