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Canonical correlations between morphological, productive, and meteorological variables and the protein-nutritional quality in maize genotypes

Abstract − The objective of this work was to check whether there is a linear dependence between morphological, productive, meteorological, and protein nutritional variables in maize genotypes. Maize genotypes (78) were evaluated for ten sowing dates, at the Universidade Federal de Santa Maria, in the state of Rio Grande do Sul, Brazil. Morphological, productive, meteorological, and nutritional variables were evaluated. A multicollinearity analysis was performed for each group of variables. A canonical correlation analysis was applied to examine the relationships of morphological, productive, meteorological (for plants in the vegetative stage), meteorological (for plants in the reproductive stage) with the protein nutritional variables. Increase of the relative ear position in maize promotes increments in crude protein, lysine, methionine and tryptophan contents. Ear diameter, ear grain mass, and grain yield show a negative association with crude protein, lysine, methionine and tryptophan contents. Increase of cumulative global solar radiation and the reduction of precipitation, during the vegetative stage, promote increments in crude protein, lysine, methionine and tryptophan contents. Higher values of maximum daily air temperature and lower values of precipitation, during the reproductive stage, promote increments of crude protein, lysine, methionine and tryptophan contents.

Index terms: *Zea mays*, amino acids, crude protein, indirect selection, linear relationships.

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Correlações canônicas entre variáveis morfológicas, produtivas e meteorológicas e a qualidade proteico-nutricional em genótipos de milho

Resumo – O objetivo deste trabalho foi verificar, se há dependência linear entre variáveis morfológicas, produtivas e meteorológicas com variáveis nutricionais proteicas em genótipos de milho. Genótipos de milho (78) foram avaliados em 10 datas de semeadura, na Universidade Federal de Santa Maria, no estado do Rio Grande do Sul. Foram avaliadas as variáveis morfológicas, produtivas, meteorológicas e nutricionais. Uma análise de multicolinearidade foi realizada para cada grupo de variáveis. Aplicou-se uma análise de correlação canônica para examinar as relações entre as seguintes variáveis: morfológicas e nutricionais proteicas, produtivas e nutricionais proteicas, e meteorológicas e nutricionais proteicas (em plantas no estádio vegetativo); e entre variáveis meteorológicas e nutricionais proteicas (em plantas no estádio reprodutivo). O aumento da posição relativa da espiga em milho promove o incremento dos teores de

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proteína bruta, lisina, metionina e triptofano. O diâmetro da espiga, a massa de grãos da espiga e a produtividade de grãos apresentam associação negativa com os teores de proteína bruta, lisina, metionina e triptofano. O aumento da radiação solar global acumulada e a redução da precipitação pluvial, no estádio vegetativo, promovem o aumento dos teores de proteína bruta, lisina, metionina e triptofano. Maiores valores de temperatura máxima diária do ar e menores valores de precipitação pluvial, no estádio reprodutivo, promovem o aumento dos teores de proteína bruta, lisina, metionina e triptofano.

Termos para indexação: *Zea mays*, aminoácidos, proteína bruta, relações lineares, seleção indireta.

Introduction

Maize breeding programs have prioritized the increase of grain yield, as well as the adaptability and stability of genotypes in different environments, since grain yield is the main component of sustainability of the production system (Bocianowski et al., 2024). Nevertheless, incorporating improvements of the protein nutritional quality of grains to the selection goals can increase the nutritional value of feed, enhancing animal performance and contributing to the reduction of production costs.

The nutritional quality of maize grains results from complex interactions between morphological, productive (Alves et al., 2016a, 2016b; Amegbor et al., 2022; Carvalho et al., 2022; Jahangirlou et al., 2022), and meteorological (Safian et al., 2022; Wang et al., 2023; Wu et al., 2024; Loro & Cargnelutti Filho, 2025) variables, which act together throughout the crop cycle. The increase of grain yield is negatively correlated with protein content (Alves et al., 2016a; Loro & Cargnelutti Filho, 2026) and amino acid content (Alves et al., 2016a; Amegbor et al., 2022) in maize. The indirect selection has been proposed as a strategy for nutritional improvement, using easy-to-measure agronomic variables as indicators of grain quality. For instance, ear height and relative ear position are variables with a positive correlation with crude protein contents in maize (Alves et al., 2016b). Ear height also shows a positive correlation with tryptophan and crude protein contents (Amegbor et al., 2022). However, tall plants are associated with reduced protein content in grains (Jahangirlou et al., 2022).

Meteorological variables such as air temperature, solar radiation, and precipitation influence the synthesis of proteins and amino acids. A lower volume of precipitation (Dong et al., 2020; Safian et al., 2022; Guo et al., 2023) and higher air temperature (Yang et al., 2018; Dong et al., 2020; Wang et al., 2023; Wu et al., 2024) favor the increase of protein content in grains. The integration of morphological, productive, and meteorological variables with groups of nutritional variables is still little explored under a multivariate approach.

The canonical correlation analysis is a statistical tool used to understand complex relationships between groups of variables. Number of days from sowing to female flowering, number of ears, and grain yield can act as indirect indicators of the protein quality of grains (Alves et al., 2016b). There is also evidence of the independence among groups of morphological and productive variables in relation to protein nutritional variables (Alves et al., 2016a). Positive associations between yield components and morphological traits − plant height, grain mass, and grain width − with essential amino acid contents, have been reported (Carvalho et al., 2022). Nevertheless, taller plants tend to have lower-amylose content and lower nitrogen-corrected apparent metabolizable energy, longer duration of the period until female flowering, higher-ear-insertion height and lower number of ears are associated with the content increase of ether extract in grains (Alves et al., 2017).

Despite the use of canonical correlation analysis to evaluate associations between agronomic and nutritional variables in maize, some studies have been integrating morphological, productive, and meteorological variables with protein nutritional variables.

The objective of this work was to check whether there is a linear dependence between morphological, productive, and meteorological variables and protein nutritional ones in maize genotypes using the canonical correlation analysis.

Materials and Methods

The experiments were carried out in the area of the Plant Science Department of the Universidade Federal de Santa Maria (29º43’28’’S, 53º43’12’’W, at 95 m altitude), in Santa Maria municipality, in Rio Grande do Sul state, Brazil. According to the Köppen’s climate classification, the region has a humid subtropical climate of the Cfa type, characterized by hot summers

and absence of a defined dry season (Alvares et al., 2013). The soil of the experimental area is classified as Argissolo Vermelho distrófico arênico (Ultisol), according of the Brazilian Soil Classification System (Santos et al., 2025).

Evaluations were performed in the years 2021, 2022 and 2023, according to the following descriptions. The sowing of 71 maize genotypes took place on September 21, 2021; and the sowing of 78 maize genotypes was performed as follows: in 2021 (on October 20, November 20, and December 20); in 2022 (on January 30, September 06, October 14, November 24, and December 30); and, in 2023, on February 06).

On each sowing date, the genotypes were sown in plots consisting of a 5 m row in length, at spaced at 0.80 m between rows and 0.20 m between plants, totaling 25 plants per plot. Basal fertilization was carried out with 415 kg ha^{-1} of N-P-K 05-20-20 formula; and N supplementation, in the form of urea (46% N), was split into two applications: 250 kg ha^{-1} at the V_4 stage, and 150 kg ha^{-1} at the V_6 stage.

The genotypes were phenologically characterized considering the respective sowing dates. For the characterization, the dates of female flowering (50% plants in each plot with visible stigmas on the ear) and the point of harvest (ear straw and ear base leaves were 100% senescent) were recorded. Thus, the following phenological variables were obtained: days from sowing to female flowering (SFF, days) and days from female flowering to harvest (FFH, days).

After the emergence, five plants of each genotype were randomly marked, considering each sowing date, totaling 3,865 plants (71 genotypes × 1 sowing date × 5 plants = 355 plants + 78 genotypes × 9 sowing dates × 5 plants = 3,510 plants). In these plants, the following morphological variables were evaluated: plant height (PH, cm), corresponding to the distance between the soil surface and the flag leaf insertion; ear height (EH, cm), corresponding to the distance between the soil surface and the ear insertion; relative ear position (REP = EH/PH); number of leaves above the primary ear (NLA), corresponding to the count of the number of leaves above the ear insertion; and tassel length (TL, cm), corresponding to the distance between the insertion of the first tassel branch and the tassel apex.

At the physiological maturity of the plants, the five plants marked in each plot were harvested, to evaluate the following productive variables: ear diameter (ED, cm); number of ear rows (NER); and ear grain mass (GM, g). Grain yield (GY, Mg ha^{-1}) was obtained from the harvest of all plants in the plot, and subsequently corrected to 13% moisture content.

Meteorological information was obtained at the National Institute of Meteorology (INMET) station located 100 m away from the experimental area. For each day, hourly global solar radiation (MJ m^{-2} per hour), hourly maximum and minimum temperatures (°C) and precipitation (mm) were recorded, considering the period between sowing and harvest of each genotype. Daily global solar radiation (MJ m^{-2} per hour) was calculated by summing the hourly measurements and, subsequently, used to estimate the cumulative solar radiation in the subperiods from sowing to female flowering (RSFF, MJ m^{-2}) and from female flowering to harvest (RFFH, MJ m^{-2}).

From the maximum and minimum hourly temperatures, the 24 values of average temperature for each day were calculated. Based on these data, the daily minimum (Tn), mean (Tm) and maximum (Tx) air temperatures (°C) were determined, obtained by the average of the respective hourly measurements. Then, the daily thermal accumulation (DD, °C) was calculated using the method of Arnold (1960), and applying the equation DD = Tm – Tb, where Tb represents the lower base temperature (10 °C). The values of Tm ≤ Tb were considered as DD equal to zero, since, below this threshold, plant development does not occur, or occurs in a very reduced way. For each genotype and sowing date, the thermal sum was obtained by summing the DD accumulated in the subperiods from sowing to female flowering (SSFF, °C day) and from female flowering to harvest (SFFH, °C day).

The average Tx was calculated in the subperiods from sowing to female flowering (TxSFF, °C) and from female flowering to harvest (TxFFH, °C). For each genotype, considering each sowing date, the cumulative precipitation was calculated in each of the following subperiods: sowing to female flowering (PSFF, mm) and female flowering to harvest (PFFH, mm). Therefore, the following meteorological variables were obtained: RSFF, SSFF, TxSFF, and PSFF in the vegetative stage; and RFFH, SFFH, TxFFH, and PFFH in the reproductive stage.

A sample of 100 g grains was collected from each genotype, considering each sowing date, totaling 773 samples (71 genotypes × 1 sowing date = 71 samples +

78 genotypes × 9 sowing dates = 702 samples). These samples were packed in paper bags and subjected to drying in an oven with forced-air circulation until they reached 13% moisture. Then, grains were ground in a Retsch mill (model ZM 200) equipped with 1 mm mesh sieve. The ground samples were analyzed by near-infrared reflectance spectroscopy (NIRS), using the FOSS DS2500 instrument (Adisseo Brasil Nutrição Animal). The resultant absorbance spectra allowed of the determination of nutritional contents, through the multivariate calibration for ground maize available on the Precision Nutrition Evaluation (PNE) platform. Thus, the contents of the following protein nutritional variables were quantified in each sample (g 100 g^{-1}) for crude protein (CP), lysine (Lys), methionine (Met), and tryptophan (Trp). Detailed information on the wet chemistry analysis used in the calibration of NIRS curves can be found in Oviedo-Rondón et al. (2024). The estimates obtained by NIRS were evaluated based on the spectral similarity index (GH) adopted by the PNE platform, considering 95% for GH ≤ 1.66 confidence levels.

Calculations were performed for minimum, mean, maximum, median, standard deviation, and coefficient of variation, using data from morphological, productive, meteorological (for plants in the vegetative stage), meteorological (for plants in the reproductive stage), and protein nutritional variables.

To evaluate the consistency of the correlation structure among sowing dates, crop seasons, and maize genetic bases, Mantel tests were performed between the correlation matrices using 9,999 permutations. Pearson linear correlation networks were constructed to evaluate the relationships of productive, meteorological (for vegetative-stage plants), and meteorological (for reproductive-stage plants) variables with protein nutritional variables.

The diagnosis of multicollinearity was applied to each group of morphological, productive, meteorological (for vegetative-stage plants), and meteorological (for reproductive-stage plants) variables, and protein nutritional variables, by means of the condition number (CN) – which represents the ratio between the highest and lowest eigenvalues of the correlation matrix (Cruz et al., 2014).

The canonical correlation analysis was performed between the protein nutritional (CP, Lys, Met, and Trp) group and the following variable groups: morphological (PH, REP, NLA, and TL); productive (ED, NER, GM, and GY); meteorological for plants in the vegetative stage (RSFF, SSFF, TxSFF, and PSFF); and meteorological for plants in the reproductive stage (RFFH, SFFH, TxFFH, and PFFH). The associations between these groups of variables were interpreted using canonical loads. The significance of the canonical correlations was assessed using the chi-square test (χ^2) at 5% probability. Statistical analyses were performed using the R software (R Core Team, 2025).

Results and Discussion

The maize genotypes evaluated with ten sowing dates showed a high variability of morphological, productive, meteorological (for plants in the vegetative stage and plants in reproductive stage separately tested), and protein nutritional variables (Figures 1 and 2). The coefficient of variation ranged from 8.287% for the maximum air temperature from sowing to female flowering (TxSFF) to 50.611% for grain yield (GY). On average, the contents of protein nutritional variables (g 100 g^{-1}) were 9.051 for CP, 0.267 for Lys, 0.172 for Met, and 0.075 for Trp.

Mantel tests indicated significant similarity among most correlation (r) matrices obtained across sowing dates ($0.158 \leq r \leq 0.835$), crop seasons ($r = 0.744$), and maize genetic bases ($r \geq 0.887$), which indicate consistency of the associations among the evaluated variables across environments and genetic bases. Plant height (PH) showed a negative linear association with CP, Lys, Met, and Trp, while relative ear position (REP), number of leaves above the primary ear (NLA), and tassel length (TL) showed positive associations (Figure 2). These results are consistent with reports in the literature that indicate a positive correlation between REP and crude protein contents in maize (Alves et al., 2016b), as well as a positive association between ear height and tryptophan and crude protein contents (Amegbor et al., 2022).

In the group of productive variables, ED, NER, GM, and GY showed a negative association with CP, Lys, Met and Trp. This pattern corroborates the evidence that higher grain yield is associated with lower protein contents (Alves et al., 2016a; Loro & Cargnelutti Filho, 2026) and amino acids in maize (Alves et al., 2016a; Amegbor et al., 2022). Cumulative solar

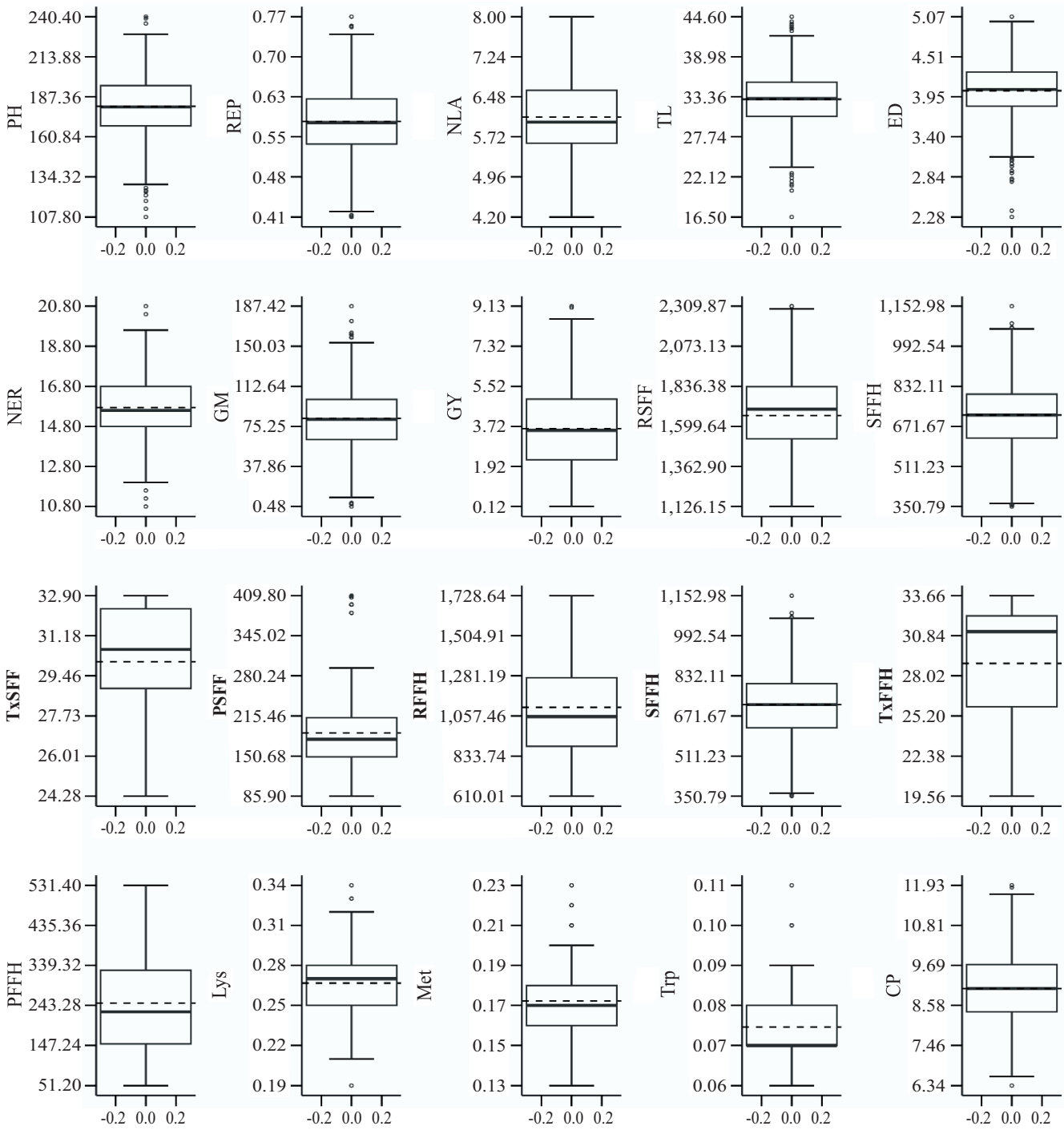

Figure 1. Boxplot representing the distribution of the following traits: PH (cm), plant height; REP, relative ear position; NLA, number of leaves above the primary ear; TL (cm), tassel length; ED (cm), ear diameter; NER, number of ear rows; GM (g), ear grain mass; GY (Mg ha^{-1}), grain yield; RSFF (MJ m^{-2}), cumulative global solar radiation from sowing to female flowering; SSFF (°C day), thermal sum from sowing to female flowering; TxSFF (°C), average maximum daily air temperature from sowing to female flowering; PSFF (mm), cumulative precipitation from sowing to female flowering; RFFH (MJ m^{-2}), cumulative global solar radiation from female flowering to harvest; SFFH (°C day), thermal sum from female flowering to harvest; TxFFH (°C), average maximum daily air temperature from female flowering to harvest; PFFH (mm), cumulative precipitation from female flowering to harvest; Lys (g 100 g^{-1}), lysine; Met (g 100 g^{-1}), methionine; Trp (g 100 g^{-1}), tryptophan; and CP (g 100 g^{-1}), crude protein.

radiation (RSFF) and thermal sum (SSFF) showed positive associations with CP, Lys, Met, and Trp, while cumulative precipitation (PSFF) showed a negative relationship with these variables. These results indicate that conditions of higher energy and thermal availability, associated with lower-water availability in this period, favor protein content in grains. RFFH, SFFH and TxFFH showed positive associations with CP, Lys, Met and Trp, while PFFH showed a negative relationship with these variables.

The condition numbers of the multicollinearity analysis were 1.889, 23.615, 46.936, 72.120, and 46.019 for the groups of morphological, productive, meteorological in the vegetative stage, meteorological in the reproductive stage, and protein nutritional variables, respectively, indicating weak multicollinearity (Cruz et al., 2014).

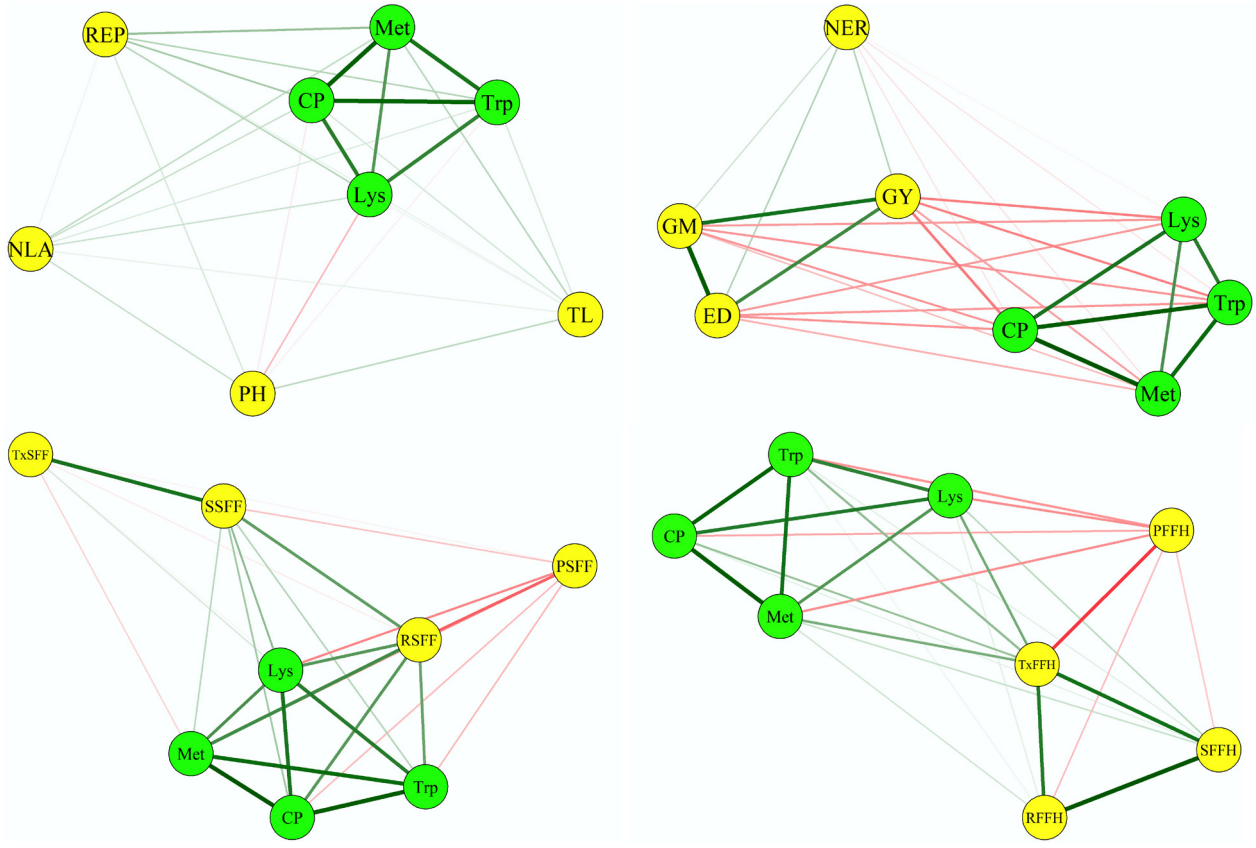

Figure 2. Pearson linear correlation networks for the relationships of morphological, productive, meteorological in the vegetative stage, and meteorological in the reproductive stage variables with protein nutritional variables, in 78 maize genotypes evaluated in ten sowing dates in the years 2021, 2022, and 2023. Traits: PH (cm), plant height; REP, relative ear position; NLA, number of leaves above the primary ear; TL (cm), tassel length; ED (cm), ear diameter; NER, number of ear rows; GM (g), ear grain mass; GY (Mg ha^{-1}), grain yield; RSFF (MJ m^{-2}), cumulative global solar radiation from sowing to female flowering; SSFF (°C day), thermal sum from sowing to female flowering; TxSFF (°C), average maximum daily air temperature from sowing to female flowering; PSFF (mm), cumulative precipitation from sowing to female flowering; RFFH (MJ m^{-2}), cumulative global solar radiation from female flowering to harvest; SFFH (°C day), thermal sum from female flowering to harvest; TxFFH (°C), average maximum daily air temperature from female flowering to harvest; PFFH (mm), cumulative precipitation from female flowering to harvest; CP (g 100 g^{-1}), crude protein; Lys (g 100 g^{-1}), lysine; Met (g 100 g^{-1}), methionine; Trp (g 100 g^{-1}), tryptophan. Red lines represent negative linear correlations between the traits, while green lines indicate positive linear correlations. Line thickness reflects the magnitude of the correlation coefficients: thin lines correspond to lower-intensity correlations, while thicker lines indicate stronger correlations.

The first two coefficients of the canonical pairs were significant for the relationship between morphological and protein nutritional variables (Table 1). For interpretation purposes, emphasis was given to canonical loads of ≥ |0.60| magnitude. In the first canonical pair, REP was positively correlated with CP, Lys, Met and Trp contents. Therefore, REP can be used to indirectly select plants with higher CP, Lys, Met and Trp contents. This result is consistent, as the relative ear position is positively correlated with crude protein contents in maize (Alves et al., 2016b).

In the analysis between productive and protein nutritional variables, the coefficients of the first two canonical pairs showed significant correlations. In the first canonical pair, negative relationships were observed between ED, GM, and GY and CP, Lys, Met, and Trp. These results indicate that increments in ED, GM, and GY cause reduction of CP, Lys, Met, and Trp contents in maize genotypes. Some studies have reported a negative relationship between productive variables and the contents of protein (Alves et al., 2016a; Loro & Cargnelutti Filho, 2026) and amino acids (Alves et al., 2016a; Amegbor et al., 2022) in maize. This negative relationship limits the simultaneous gain in yield and nutritional quality in breeding programs. The second canonical pair, although statistically significant, showed a low magnitude of correlation.

Table 1. Canonical loads constructed for the relationships of morphological and productive variables with protein nutritional variables, canonical correlations (ρ), value of the χ^2 test, and degrees of freedom, in 78 maize genotypes evaluated at ten sowing dates, in 2021, 2022, and 2023.

Variable	Canonical loads			
	1st	2nd	3rd	4th
	Morphological variables			
Plant height (PH, cm)	0.224	0.878	-0.405	0.122
Relative ear position (REP)	-0.706	0.286	-0.278	-0.585
Number of leaves above the primary ear (NLA)	-0.452	-0.026	-0.565	0.690
Tassel length (TL, cm)	-0.406	0.583	0.605	0.360
	Protein nutritional variables			
Crude protein (CP, g 100 g^{-1})	-0.818	-0.007	-0.352	-0.454
Lysine (Lys, g 100 g^{-1})	-0.813	-0.519	0.118	-0.238
Methionine (Met, g 100 g^{-1})	-0.890	0.343	-0.156	-0.256
Tryptophan (Trp, g 100 g^{-1})	-0.655	0.036	0.041	-0.754
Canonical correlation (ρ)	0.494*	0.328*	0.078^{ns}	0.033^{ns}
χ^2	307.214	92.958	5.539	0.861
Degrees of freedom	16	9	4	1
Variable	Canonical loads			
	1st	2nd	3rd	4th
	Productive variables			
Ear diameter (ED, cm)	-0.784	0.065	-0.303	0.538
Number of ear rows (NER)	-0.124	-0.289	-0.926	-0.209
Ear grain mass (GM, g)	-0.804	0.482	-0.266	0.223
Grain yield (GY, Mg ha^{-1})	-0.956	0.037	-0.082	-0.280
	Protein nutritional variables			
Crude protein (CP, g 100 g^{-1})	0.892	0.330	0.290	-0.105
Lysine (Lys, g 100 g^{-1})	0.868	0.240	-0.291	0.323
Methionine (Met, g 100 g^{-1})	0.636	0.620	0.455	0.062
Tryptophan (Trp, g 100 g^{-1})	0.840	0.035	0.458	0.288
Canonical correlation (ρ)	0.513*	0.137*	0.097^{ns}	0.030^{ns}
χ^2	257.061	22.565	7.943	0.693
Degrees of freedom	16	9	4	1

*Significant by the chi-square (χ^2) test at 5% probability. ^{ns}Nonsignificant.

The coefficients of the first three canonical pairs (plants in the vegetative stage) and the four canonical pairs (plants in the reproductive stage) were significant for the relationships between the meteorological and nutritional variables (Table 2). These results indicate that the expression of crude protein and essential amino acids is related to weather conditions. In the first canonical pair, RSFF had the highest positive canonical load (0.972), followed by PSFF with a negative canonical load (-0.638); and the canonical loads of CP, Lys, Met, and Trp were positive (≥ 0.702). Thus, it can be inferred that high-RSFF values and lower-PSFF values promote an increase of CP, Lys, Met, and Trp contents. Greater solar radiation during the vegetative stage may increase the photosynthetic activity and carbon assimilation, favoring nitrogen metabolism and amino acid synthesis. In addition, lower-water availability may reduce starch accumulation in

Table 2. Canonical loads constructed for the relationships of meteorological (for plants in the vegetative stage), and meteorological (for plants in the reproductive stage) variables with protein nutritional variables, canonical correlations (ρ), value of the χ^2 test, and degrees of freedom in 78 maize genotypes evaluated at ten sowing dates, in the years 2021, 2022, and 2023.

Variable[(1)]	Canonical loads			
	1st	2nd	3rd	4th
	Meteorological variables for plants in the vegetative stage			
RSFF (MJ m^{-2})	0.972	0.018	0.174	-0.158
SSFF (°C day)	0.375	0.684	0.375	-0.500
TxSFF (°C)	-0.144	0.965	0.166	-0.141
PSFF (mm)	-0.638	-0.260	0.717	0.108
	Protein nutritional variables			
Crude protein (CP, g 100g^{-1})	0.752	0.153	0.622	0.155
Lysine (Lys, g 100g^{-1})	0.795	0.578	0.033	0.180
Methionine (Met, g 100g^{-1})	0.875	-0.215	0.435	0.016
Tryptophan (Trp, g 100g^{-1})	0.702	0.032	0.382	0.600
Canonical correlation (ρ)	0.701*	0.381*	0.286*	0.011^{ns}
χ^2	705.468	185.761	65.639	0.090
Degrees of freedom	16	9	4	1
Variables	Canonical loads			
	1st	2nd	3rd	4th
	Meteorological for plants in the reproductive stage			
RFFH (MJ m^{-2})	0.400	0.562	-0.609	-0.391
SFFH (°C day)	0.504	0.218	-0.677	-0.490
TxFFH (°C)	0.914	0.242	-0.275	-0.174
PFFH (mm)	-0.759	-0.211	0.104	-0.608
	Protein nutritional variables			
Crude protein (CP, g 100g^{-1})	0.660	-0.181	0.729	-0.001
Lysine (Lys, g 100g^{-1})	0.843	-0.526	0.115	0.001
Methionine (Met, g 100g^{-1})	0.762	0.233	0.599	-0.081
Tryptophan (Trp, g 100g^{-1})	0.689	-0.105	0.535	0.477
Canonical correlation (ρ)	0.691*	0.329*	0.219*	0.133*
χ^2	636.960	139.369	51.325	13.635
Degrees of freedom	16	9	4	1

[(1)]Variables: RSFF, cumulative global solar radiation from sowing to female flowering; SSFF, thermal sum from sowing to female flowering; TxSFF, average maximum daily air temperature from sowing to female flowering; PSFF, cumulative precipitation from sowing to female flowering; RFFH, cumulative global solar radiation from female flowering to harvest; SFFH, thermal sum from female flowering to harvest; TxFFH, average maximum daily air temperature from female flowering to harvest; and PFFH, cumulative precipitation from female flowering to harvest. *Significant by the chi-square (χ^2) test at 5% probability. [ns]Nonsignificant.

grains, increasing the relative concentration of proteins and amino acids.

In the first canonical pair, TxFFH had the highest positive canonical load (0.914), followed by PFFH with a negative canonical load (-0.759); and the canonical loads of CP, Lys, Met, and Trp were positive (≥ 0.660). Therefore, high values of TxFFH and lower values of PFFH promote the increase of CP, Lys, Met, and Trp contents. Higher air temperatures during grain filling may accelerate nitrogen remobilization and modify the balance between starch and protein deposition in grains, contributing to the content increases in crude protein and amino acid.

This pattern converges with reported results, according to which conditions of higher solar radiation (Wang et al., 2023), lower precipitation (Dong et al., 2020; Safian et al., 2022; Guo et al., 2023), and high air temperatures (Yang et al., 2018; Dong et al., 2020; Wang et al., 2023; Wu et al., 2024) are associated with high contents of protein and amino acids in maize. These results show that the influence of morphological, productive, and meteorological variables, on grain protein content, occurs in a complex and multifactorial way not restricted to a single variable.

Conclusions

1. The increase of relative ear position promotes increments in crude protein, lysine, methionine, and tryptophan contents, indicating a potential use of this trait for indirect selection in maize breeding programs.

2. Ear diameter, ear grain mass, and grain yield show a negative association with crude protein, lysine, methionine, and tryptophan contents, reinforcing the challenge of simultaneously increasing grain yield and protein nutritional quality.

3. The increase of cumulative global solar radiation and the reduction of precipitation for plants in the vegetative stage promote increments of crude protein, lysine, methionine, and tryptophan contents.

4. In the reproductive stage, higher values of maximum daily air temperature and lower values of precipitation promote an increase in crude protein, lysine, methionine, and tryptophan contents.

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

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The authors declare no conflicts of interest.

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