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Mathematics

Genetic bases and meteorological variables determine the variability of digestible amino acids for poultry in maize grains

Bases genéticas e as variáveis meteorológicas determinam a variabilidade dos aminoácidos digestíveis para aves em grãos de milho

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ABSTRACT

The objectives of this study were to investigate whether there is variability in the protein nutritional composition of grains between maize genetic bases (single hybrids, triple hybrids, double hybrids and varieties) and sowing dates, and to verify whether there is a possibility of predicting digestible amino acids for poultry based on crude protein and meteorological variables. 773 grain samples from four maize genetic bases, cultivated with ten sowing dates, were evaluated. Descriptive statistics were calculated and principal component, correlation and regression analyses were performed. There is variation in the contents of digestible amino acids for poultry in maize grains between genetic bases and sowing dates. Open-pollinated varieties and sowings carried out in October and November led to the highest contents of digestible amino acids for poultry in maize grains. Digestible amino acid contents for poultry can be predicted using crude protein and meteorological variables. Global solar radiation and rainfall influence positively and negatively, respectively, the contents of digestible amino acids for poultry.

Keywords: *Zea mays*; Digestible amino acids; Poultry farming

RESUMO

Os objetivos deste estudo foram investigar se há variabilidade da composição nutricional proteica de grãos entre as bases genéticas de milho (híbridos simples, híbridos triplo, híbridos duplo e variedades) e as datas de semeadura, e verificar se há possibilidade de predizer os aminoácidos digestíveis para aves com base na proteína bruta e nas variáveis meteorológicas. Foram avaliadas 773 amostras de grãos de quatro bases genéticas de milho, cultivadas em dez datas de semeadura. Foram calculadas estatísticas descritivas e realizadas análises de componentes principais, correlação e regressão. Há variação dos teores dos aminoácidos digestíveis para aves nos grãos de milho entre as bases genéticas e as datas de

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semeadura. As variedades de polinização aberta e as semeaduras de outubro e novembro apresentam os maiores teores de aminoácidos digestíveis para aves nos grãos de milho. Os teores dos aminoácidos digestíveis para aves podem ser preditos por meio da proteína bruta e variáveis meteorológicas. A radiação solar global e a precipitação pluviométrica influenciam, respectivamente, de forma positiva e negativa, os teores de aminoácidos digestíveis para aves.

Palavras-chave: *Zea mays*; Aminoácidos digestíveis; Avicultura

1 INTRODUCTION

Maize is the main source of energy in poultry diets, providing protein and essential amino acids (Simões et al., 2023). The contents of digestible amino acids for poultry, such as lysine, methionine and threonine, vary respectively between 0.20 and 0.24, 0.12 and 0.15, and 0.25 and 0.26 g/100 g in maize grains (Gomes et al., 2010; Dalólio et al., 2024). Crude protein and amino acid contents in maize grains may vary due to genetic factors (Zuber & Rodehutscord, 2017; Mehta et al., 2020) and environmental factors (Guo et al., 2023), posing a challenge for feed formulation.

The diversity of maize genotypes, classified as single hybrids, triple hybrids, double hybrids and open-pollinated varieties, can lead to variations in protein and digestible amino acid contents. Meteorological variables such as air temperature, global solar radiation, and rainfall influence plant metabolism and nutrient allocation in grains (Guo et al., 2023). Low rainfall volumes promote increased protein in grains (Safian et al., 2022), and air temperature is positively correlated with the synthesis of essential amino acids (Wang et al., 2023; Wu et al., 2024).

The formulation of more economical and accurate feeds can be made possible by predicting the content of digestible amino acids for poultry. Regression models make it possible to estimate total amino acids in soybean (Sriperm et al., 2010), wheat (Olukosi & Adebiyi, 2013) and maize grains (Sriperm et al., 2010; Olukosi & Adebiyi, 2013). These models have also been used to determine the amino acid digestibility coefficient in maize (Zuber & Rodehutscord, 2017) and the digestible amino acid contents in maize (Sheikhhasan et al., 2020) and sorghum (Ebadi et al., 2011), considering crude protein

as a predictor variable. For these models to be efficient in the prediction, it is important that the samples contemplate genetic and environmental diversity.

Understanding the relationships between protein nutritional traits and meteorological variables promotes greater production efficiency in the poultry sector. Thus, the objectives of this study were to investigate whether there is variability in the protein nutritional composition of grains between maize genetic bases (single hybrids, triple hybrids, double hybrids and varieties) and sowing dates, and to verify whether there is a possibility of predicting digestible amino acids for poultry based on crude protein and meteorological variables.

2 MATERIAL AND METHODS

The experiments were carried out in the area of the Plant Science Department of the Federal University of Santa Maria (UFSM), located at 29º42'S and 53º49'W, at 95 m altitude. In the 2021/2022 season, maize genotypes were evaluated considering five sowing dates: September 21, 2021, October 20, 2021, November 20, 2021, December 20, 2021, and January 30, 2022. Except for sowing on September 21, 2021, which was composed of 71 genotypes, on all other dates, 78 maize genotypes of different genetic bases (single hybrids, triple hybrids, double hybrids and varieties) were sown. In the 2022/2023 season, the same 78 maize genotypes were evaluated considering five sowing dates: September 6, 2022, October 14, 2022, November 24, 2022, December 30, 2022, and February 6, 2023. The experiments were conducted without using supplemental irrigation.

On each sowing date, the maize genotypes were sown in one-row plots, side by side. Each plot consisted of one row of 5 m in length at spacing of 0.80 m between rows and 0.20 m between plants in the row, totaling 25 plants per plot. The area was harrowed and fertilized with 415 kg ha^{-1} of chemical fertilizer with the formula (NPK) 05-20-20. Nitrogen fertilization with urea (N - 46%) was split, with the first application

of 250 kg ha^{-1} at the V4 stage and the second application of 150 kg ha^{-1} at the V6 stage of the crop.

A 100 g sample of maize grains from each genotype considering each sowing date (773 samples) was collected, packed in a paper bag, and taken to a forced air circulation oven to reach 13% moisture. Subsequently, the grains were ground in a Retsch mill (model ZM 200) coupled with a 1-mm-mesh sieve. Then, these ground samples were scanned using Near Infrared Reflectance Spectroscopy in a FOSS NIRS™ DS2500 analyzer belonging to the company Adisseo Brasil Nutrição Animal. With the absorbance spectra generated for each sample, the nutritional contents were determined using multivariate calibration for ground maize on the Precision Nutrition Evaluation (PNE) platform. Thus, for each sample, the crude protein (CP) and the following digestible amino acids for poultry were determined in g/100 g: lysine (Lys), methionine (Met), cystine (Cys), threonine (Thr), tryptophan (Trp), valine (Val), isoleucine (Ile), leucine (Leu), phenylalanine (Phe), histidine (His) and arginine (Arg).

Based on data from the National Institute of Meteorology (INMET) station, located 100 meters away from the experimental area, the following parameters were calculated for each genotype on each sowing date: cumulative global solar radiation from sowing to female flowering (RSFF, MJ m^{-2}) and from female flowering to harvest (RFFH, MJ m^{-2}); thermal sum, considering the base temperature of 10 ºC, from sowing to female flowering (SSFF, °C day) and from female flowering to harvest (SFFH, °C day); and cumulative precipitation from sowing to female flowering (PSFF, mm) and from female flowering to harvest (PFFH, mm).

For each protein nutritional trait, considering each sowing date, the following statistics were calculated: minimum, mean, maximum and coefficient of variation. Then, the mean was calculated for each trait, considering each sowing date and genetic base. The trait means between sowing dates regardless of genetic bases, harvests regardless of sowing dates and genetic bases, genetic bases on each sowing date and between genetic bases regardless of sowing dates were compared using the

Scott-Knott test at 5% significance. Principal component analysis was applied to group genetic bases and sowing dates based on protein nutritional traits and meteorological variables, with the aim of exploring the contribution of traits to distinguishing groups, facilitating the understanding of nutritional variability. The data were standardized for application of principal component analysis. For each maize genetic base, networks of Pearson's linear correlation between the pairs of traits were developed. For each genetic base of maize, simple linear regression of Lys (y), Met (y), Cys (y), Thr (y), Trp (y), Val (y), Ile (y), Leu (y), Phe (y), His (y) and Arg (y) was performed as a function of CP (x).

Multicollinearity was observed in the matrix of independent variables. For each genetic base, the parameters of the stepwise multiple linear regression model with backward selection were estimated (Hair et al., 2009). For the dependent variables, CP (y), Lys (y), Met (y), Cys (y), Thr (y), Trp (y), Val (y), Ile (y), Leu (y), Phe (y), His (y) and Arg (y) were considered, while the meteorological variables (RSFF, RFFH, SSFF, SFFH, PSFF, PFFH) were considered as independent variables (x). The assumptions of regression analysis were verified. The coefficient of determination (R^2) and the coefficient of determination of the leave-one-out cross-validation (R^2_{cv}) were calculated, which generates the model with n-1 observations and evaluates it using the remaining observation. This procedure was repeated n times, excluding a different observation at each moment. All statistical analyses were performed using R software (R Core Team, 2025), with package ExpDes.pt (Ferreira; Cavalcanti & Nogueira, 2021), metan (Olivoto & Lúcio, 2020) and caret (Kuhn, 2008).

3 RESULTS AND DISCUSSION

The coefficient of variation (CV) ranged from 8.57 to 16.61% (Lys and Leu, respectively) between the sowing dates. The amino acids Leu, Phe, Ile and Thr showed the highest variations, with CV higher than 13.45% (Table 1). Sowing on September 21, 2021 led to the highest CV in nine of the 11 digestible amino acids for poultry (CV ≥

7.22%). In the 2021/2022 season, sowing on October 20 led to the highest means of CP and digestible amino acids for poultry, differing from the other dates.

Table 1 – Minimum (Min), mean (Mean) and maximum (Max) contents and coefficient of variation (CV, %) of protein nutritional traits in grains of single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates*	CP (g/100 g)				Lys (g/100 g)			
	Min	Mean	Max	CV	Min	Mean	Max	CV
09/21/2021	6.81	8.244e	10.29	10.08	0.18	0.203f	0.24	6.66
10/20/2021	7.55	9.572b	11.57	8.29	0.19	0.227b	0.25	5.42
11/20/2021	7.20	8.705d	10.76	7.97	0.18	0.212d	0.24	5.55
12/20/2021	7.19	8.858d	10.66	7.86	0.18	0.207e	0.24	6.15
01/30/2022	7.37	8.762d	10.65	8.99	0.18	0.208e	0.25	7.46
09/06/2022	7.80	9.584b	11.87	7.69	0.17	0.219c	0.25	7.60
10/14/2022	7.71	9.616b	11.93	7.79	0.21	0.239a	0.28	5.56
11/24/2022	8.34	9.975a	11.67	7.32	0.21	0.238a	0.26	4.63
12/30/2022	7.30	9.149c	11.44	8.03	0.20	0.223b	0.26	6.11
02/06/2023	6.34	7.967f	10.65	9.56	0.16	0.202f	0.24	6.58
2021/2022	6.81	8.839b	11.57	9.82	0.18	0.211b	0.25	7.37
2022/2023	6.34	9.258a	11.93	10.97	0.16	0.224a	0.28	8.61
Overall	6.34	9.051	11.93	10.70	0.16	0.218	0.28	8.57
Dates	**Thr (g/100 g)**				**Trp (g/100 g)**			
	Min	Mean	Max	CV	Min	Mean	Max	CV
09/21/2021	0.19	0.243e	0.32	12.34	0.05	0.062c	0.07	10.86
10/20/2021	0.21	0.284c	0.35	9.65	0.05	0.067b	0.08	9.17
11/20/2021	0.21	0.258d	0.32	9.07	0.05	0.063c	0.08	8.59
12/20/2021	0.20	0.262d	0.34	9.67	0.05	0.062c	0.07	8.85
01/30/2022	0.19	0.248e	0.31	10.77	0.05	0.061c	0.08	10.96
09/06/2022	0.21	0.279c	0.32	9.49	0.06	0.071a	0.09	10.13
10/14/2022	0.23	0.308a	0.38	8.01	0.06	0.070a	0.09	8.17
11/24/2022	0.26	0.316a	0.38	7.89	0.06	0.071a	0.08	8.56
12/30/2022	0.23	0.292b	0.35	8.18	0.05	0.067b	0.10	10.51
02/06/2023	0.16	0.236f	0.30	12.19	0.05	0.058d	0.08	11.25
2021/2022	0.19	0.259b	0.35	11.59	0.05	0.063b	0.08	10.26
2022/2023	0.16	0.286a	0.38	13.29	0.05	0.067a	0.10	12.12
Overall	0.16	0.273	0.38	13.50	0.05	0.065	0.10	11.73

Table 1 – Minimum (Min), mean (Mean) and maximum (Max) contents and coefficient of variation (CV, %) of protein nutritional traits in grains of single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates*	Met (g/100 g)				Cys (g/100 g)			
	Min	Mean	Max	CV	Min	Mean	Max	CV
09/21/2021	0.14	0.158d	0.18	6.79	0.13	0.165e	0.21	10.40
10/20/2021	0.15	0.176b	0.20	6.62	0.15	0.192c	0.23	8.75
11/20/2021	0.14	0.164c	0.20	6.39	0.15	0.176d	0.22	8.12
12/20/2021	0.14	0.166c	0.19	6.27	0.14	0.176d	0.22	8.17
01/30/2022	0.14	0.159d	0.18	6.42	0.15	0.172d	0.21	8.86
09/06/2022	0.15	0.184a	0.23	9.03	0.15	0.189c	0.23	8.34
10/14/2022	0.14	0.175b	0.20	6.30	0.15	0.198b	0.24	8.28
11/24/2022	0.15	0.179b	0.20	6.15	0.17	0.204a	0.24	7.63
12/30/2022	0.14	0.165c	0.19	6.60	0.15	0.186c	0.22	7.84
02/06/2023	0.12	0.148e	0.22	9.49	0.12	0.158f	0.20	9.65
2021/2022	0.14	0.165b	0.20	7.56	0.13	0.177b	0.23	10.14
2022/2023	0.12	0.170a	0.23	10.65	0.12	0.187a	0.24	11.79
Overall	0.12	0.168	0.23	9.44	0.12	0.182	0.24	11.43
Dates	**Val (g/100 g)**				**Ile (g/100 g)**			
	Min	Mean	Max	CV	Min	Mean	Max	CV
09/21/2021	0.30	0.375e	0.48	11.56	0.21	0.267e	0.36	13.49
10/20/2021	0.33	0.444c	0.55	9.47	0.23	0.321c	0.42	11.07
11/20/2021	0.34	0.403d	0.52	8.61	0.23	0.287d	0.38	10.26
12/20/2021	0.32	0.409d	0.51	8.68	0.22	0.295d	0.38	10.60
01/30/2022	0.33	0.398d	0.49	9.46	0.23	0.290d	0.37	11.21
09/06/2022	0.35	0.439c	0.53	8.11	0.25	0.323c	0.41	9.51
10/14/2022	0.34	0.462b	0.59	8.96	0.24	0.333b	0.44	10.33
11/24/2022	0.38	0.479a	0.58	8.23	0.26	0.347a	0.44	9.88
12/30/2022	0.35	0.435c	0.52	8.37	0.23	0.313c	0.39	10.04
02/06/2023	0.28	0.362f	0.47	10.88	0.20	0.261e	0.37	12.37
2021/2022	0.30	0.406b	0.55	10.95	0.21	0.292b	0.42	12.71
2022/2023	0.28	0.436a	0.59	12.72	0.20	0.315a	0.44	13.93
Overall	0.28	0.421	0.59	12.44	0.20	0.304	0.44	13.92

Table 1 – Minimum (Min), mean (Mean) and maximum (Max) contents and coefficient of variation (CV, %) of protein nutritional traits in grains of single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates	Leu (g/100 g)				Phe (g/100 g)			
	Min	Mean	Max	CV	Min	Mean	Max	CV
09/21/2021	0.66	0.947e	1.38	17.01	0.30	0.397e	0.55	13.92
10/20/2021	0.77	1.183c	1.60	13.35	0.35	0.488c	0.64	11.49
11/20/2021	0.78	1.039d	1.48	13.27	0.34	0.431d	0.58	10.79
12/20/2021	0.77	1.082d	1.49	13.07	0.33	0.443d	0.58	10.95
01/30/2022	0.80	1.054d	1.38	13.40	0.35	0.436d	0.56	11.52
09/06/2022	0.85	1.198b	1.61	12.15	0.37	0.488c	0.63	10.08
10/14/2022	0.85	1.227b	1.68	11.62	0.35	0.504b	0.67	10.81
11/24/2022	0.93	1.293a	1.69	11.20	0.40	0.528a	0.67	10.14
12/30/2022	0.84	1.155c	1.44	11.48	0.36	0.474c	0.59	10.26
02/06/2023	0.59	0.921e	1.35	15.85	0.29	0.391e	0.55	13.21
2021/2022	0.66	1.063b	1.60	15.55	0.30	0.440b	0.64	13.33
2022/2023	0.59	1.159a	1.69	16.44	0.29	0.477a	0.67	14.55
Overall	0.59	1.111	1.69	16.61	0.29	0.458	0.67	14.59

Table 1 – Minimum (Min), mean (Mean) and maximum (Max) contents and coefficient of variation (CV, %) of protein nutritional traits in grains of single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates	His (g/100 g)				Arg (g/100 g)			
	Min	Mean	Max	CV	Min	Mean	Max	CV
09/21/2021	0.18	0.228f	0.28	9.92	0.33	0.386f	0.46	7.52
10/20/2021	0.20	0.266b	0.31	8.34	0.36	0.443b	0.50	6.47
11/20/2021	0.21	0.244d	0.30	7.28	0.35	0.409e	0.48	6.05
12/20/2021	0.20	0.245d	0.29	7.72	0.34	0.402e	0.47	6.24
01/30/2022	0.19	0.234e	0.28	8.27	0.33	0.382f	0.46	7.55
09/06/2022	0.21	0.259c	0.30	7.27	0.38	0.433c	0.48	5.62
10/14/2022	0.21	0.274a	0.33	7.86	0.37	0.454a	0.53	6.57
11/24/2022	0.23	0.279a	0.32	6.97	0.41	0.460a	0.52	5.79
12/30/2022	0.21	0.253c	0.30	7.55	0.36	0.420d	0.48	6.64
02/06/2023	0.16	0.211g	0.25	9.73	0.30	0.360g	0.44	7.74

Table 1 – Minimum (Min), mean (Mean) and maximum (Max) contents and coefficient of variation (CV, %) of protein nutritional traits in grains of single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(Conclusion)

Dates	His (g/100 g)				Arg (g/100 g)			
	Min	Mean	Max	CV	Min	Mean	Max	CV
2021/2022	0.18	0.244b	0.31	9.81	0.33	0.405b	0.50	8.60
2022/2023	0.16	0.255a	0.33	12.24	0.30	0.425a	0.53	10.59
Overall	0.16	0.250	0.33	11.40	0.30	0.415	0.53	10.01

*71 samples (09/21/2021); 78 samples (10/20/2021, 11/20/2021, 12/20/2021, 01/30/2022, 09/06/2022, 10/14/2022, 11/24/2022, 12/30/2022 and 02/06/2023); 383 samples (2021/2022); 390 samples (2022/2023); 773 samples (Overall). Means not followed by the same lowercase letter in the column differ by the Scott-Knott test at 5% significance level. Traits: crude protein (CP), lysine (Lys), methionine (Met), cystine (Cys), threonine (Thr), tryptophan (Trp), valine (Val), isoleucine (Ile), leucine (Leu), phenylalanine (Phe), histidine (His) and arginine (Arg). Source: Authorship (2025)

In the 2022/2023 season, the highest means of CP and digestible amino acids, except Met, were observed for the sowing on November 24, not differing from the sowing on October 14 for the amino acids Lys, Thr, Trp, His and Arg. The highest means of CP and digestible amino acids were observed in the 2022/2023 season. Variations in total amino acid contents were also observed between maize sowing dates (Mehta et al., 2020; Wu et al., 2024). Therefore, it can be inferred that the sowing dates influence the contents of CP and digestible amino acids.

The levels of protein nutritional traits ranged from 7.690 to 10.613 g/100 g for CP between the genetic bases and sowing dates, being above the averages commonly reported in the literature (Table 2). For example, the levels of Lys (0.198 to 0.258 g/100 g) and Met (0.145 to 0.203 g/100 g) are above the ranges described for corn (0.20 to 0.24 and 0.12 to 0.15 g/100 g, respectively (Gomes et al., 2010; Dalólio et al., 2024) and sorghum (0.169 g/100 g and 0.149 g/100 g, respectively (Ebadi et al., 2011). The average contents of Thr (0.233 to 0.333 g/100 g) and Val (0.358 to 0.513 g/100 g) were also higher than the contents described for maize (Sheikhhasan et al., 2020) and sorghum (0.276 g/100 g of threonine and 0.506 g/100 g of valine) (Ebadi et al., 2011). Open-pollinated

varieties stood out in terms of average CP and digestible amino acid levels across the ten sowing dates. In all protein nutritional traits, the varieties significantly surpassed the other genetic bases and the mean of the hybrids (single + triple + double). For instance, the varieties had an average CP content of 9.787 g/100 g, while the value for the hybrids was 8.966 g/100 g.

Table 2 – Average contents of protein nutritional traits in grains of single hybrids (SH), triple hybrids (TH), double hybrids (DH) and varieties (VA) sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates	GB	CP	Lys	Met	Cys	Thr	Trp
09/21/2021	SH	8.023b	0.199b	0.155b	0.161b	0.235b	0.060b
	TH	8.166b	0.202b	0.156b	0.163b	0.239b	0.061b
	DH	8.887a	0.213a	0.163b	0.180a	0.267a	0.067a
	VA	9.414a	0.220a	0.174a	0.188a	0.281a	0.069a
10/20/2021	SH	9.487a	0.227a	0.175a	0.191a	0.281a	0.066a
	TH	9.512a	0.225a	0.175a	0.192a	0.282a	0.067a
	DH	9.797a	0.226a	0.180a	0.195a	0.290a	0.070a
	VA	9.954a	0.232a	0.181a	0.200a	0.299a	0.071a
11/20/2021	SH	8.601b	0.211b	0.162b	0.174b	0.254b	0.062a
	TH	8.783b	0.210b	0.163b	0.177b	0.263b	0.065a
	DH	8.523b	0.210b	0.163b	0.171b	0.251b	0.062a
	VA	9.352a	0.224a	0.175a	0.190a	0.279a	0.068a
12/20/2021	SH	8.749b	0.206b	0.164b	0.174b	0.257b	0.062b
	TH	8.763b	0.204b	0.163b	0.175b	0.261b	0.061b
	DH	8.686b	0.205b	0.168b	0.175b	0.256b	0.060b
	VA	9.853a	0.217a	0.181a	0.198a	0.297a	0.069a
01/30/2022	SH	8.780a	0.210a	0.159a	0.172a	0.248a	0.062a
	TH	8.697a	0.207a	0.157a	0.171a	0.247a	0.060a
	DH	8.350a	0.198a	0.158a	0.166a	0.236a	0.057a
	VA	9.192a	0.212a	0.168b	0.182a	0.264a	0.064a
09/06/2022	SH	9.385b	0.217a	0.181b	0.185b	0.273b	0.070b
	TH	9.541b	0.217a	0.183b	0.187b	0.277b	0.071b
	DH	9.876b	0.222a	0.190b	0.195b	0.291a	0.073b
	VA	10.547a	0.230a	0.203a	0.212a	0.306a	0.077a
10/14/2022	SH	9.415b	0.235b	0.172b	0.194b	0.301b	0.069b
	TH	9.599b	0.239b	0.175b	0.199b	0.310b	0.070b
	DH	9.889b	0.241b	0.180a	0.207a	0.315b	0.069b
	VA	10.556a	0.258a	0.184a	0.215a	0.333a	0.076a

Table 2 – Average contents of protein nutritional traits in grains of single hybrids (SH), triple hybrids (TH), double hybrids (DH) and varieties (VA) sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates	Val	Ile	Leu	Phe	His	Arg
09/21/2021	0.364b	0.257b	0.907b	0.383b	0.221b	0.378b
	0.369b	0.263b	0.928b	0.391b	0.226b	0.383b
	0.413a	0.297a	1.067a	0.437a	0.247a	0.410a
	0.435a	0.316a	1.166a	0.475a	0.261a	0.429a
10/20/2021	0.440a	0.318a	1.168a	0.482a	0.264a	0.440a
	0.441a	0.318a	1.171a	0.485a	0.264a	0.443a
	0.455a	0.330a	1.222a	0.501a	0.271a	0.448a
	0.466a	0.338a	1.259a	0.514a	0.276a	0.455a
11/20/2021	0.397b	0.282b	1.019b	0.423b	0.240b	0.406b
	0.408b	0.291b	1.062b	0.438b	0.245b	0.407b
	0.394b	0.280b	1.000b	0.419b	0.241b	0.406b
	0.438a	0.311a	1.151a	0.471a	0.264a	0.435a
12/20/2021	0.401b	0.289b	1.053b	0.433b	0.241b	0.399b
	0.407b	0.292b	1.079b	0.440b	0.244b	0.396b
	0.404b	0.286b	1.058b	0.430b	0.246b	0.399b
	0.461a	0.339a	1.282a	0.515a	0.273a	0.438a
01/30/2022	0.397a	0.290a	1.049a	0.436a	0.232b	0.381a
	0.394a	0.288a	1.049a	0.432a	0.234b	0.382a
	0.383a	0.273a	1.001a	0.410a	0.232b	0.371a
	0.425b	0.310a	1.149a	0.468a	0.254a	0.401a
09/06/2022	0.429b	0.314b	1.159b	0.474b	0.253c	0.426b
	0.436b	0.323b	1.188b	0.486b	0.258c	0.431b
	0.458b	0.335b	1.260b	0.509b	0.270b	0.445b
	0.490a	0.364a	1.384a	0.555a	0.287a	0.466a
10/14/2022	0.451b	0.324b	1.193b	0.490b	0.268b	0.446b
	0.463b	0.333b	1.227b	0.505b	0.275b	0.455b
	0.480b	0.344b	1.282b	0.526b	0.285a	0.464b
	0.509a	0.370a	1.375a	0.564a	0.295a	0.494a

Table 2 – Average contents of protein nutritional traits in grains of single hybrids (SH), triple hybrids (TH), double hybrids (DH) and varieties (VA) sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates	GB	CP	Lys	Met	Cys	Thr	Trp
11/24/2022	SH	9.768b	0.235b	0.176a	0.200a	0.308a	0.069a
	TH	10.277a	0.241b	0.182a	0.209a	0.328a	0.073a
	DH	9.991b	0.240b	0.182a	0.206a	0.323a	0.074a
	VA	10.613a	0.249a	0.188a	0.216a	0.331a	0.075a
30/12/2022	SH	9.104b	0.223a	0.164b	0.184b	0.289b	0.067b
	TH	9.015b	0.220a	0.163b	0.186b	0.293b	0.063b
	DH	8.995b	0.221a	0.166b	0.186b	0.287b	0.064b
	VA	9.821a	0.231a	0.176a	0.201a	0.315a	0.073a
02/06/2023	SH	7.976b	0.203a	0.147b	0.157b	0.235a	0.058b
	TH	7.767b	0.199a	0.145b	0.157b	0.234a	0.055b
	DH	7.690b	0.201a	0.146b	0.156b	0.232a	0.056b
	VA	8.570a	0.204a	0.165a	0.170a	0.250a	0.062a
Overall	SH	8.931b	0.217b	0.165c	0.179b	0.268b	0.064b
	TH	9.018b	0.217b	0.166c	0.182b	0.274b	0.065b
	DH	9.081b	0.218b	0.170b	0.184b	0.275b	0.065b
	VA	9.787a	0.228a	0.179a	0.197a	0.295a	0.070a

Table 2 – Average contents of protein nutritional traits in grains of single hybrids (SH), triple hybrids (TH), double hybrids (DH) and varieties (VA) sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(To be continued...)

Dates	Val	Ile	Leu	Phe	His	Arg
11/24/2022	0.467a	0.337b	1.254a	0.511b	0.274a	0.453b
	0.495a	0.363a	1.357a	0.553a	0.285a	0.468b
	0.487a	0.351b	1.304a	0.535b	0.284a	0.461b
	0.512a	0.374a	1.396a	0.569a	0.295a	0.487a
30/12/2022	0.431b	0.310b	1.143b	0.469b	0.250b	0.418b
	0.431b	0.311b	1.144b	0.471b	0.252b	0.415b
	0.430b	0.306b	1.130b	0.463b	0.255b	0.414b
	0.473a	0.341a	1.277a	0.522a	0.273a	0.442a
02/06/2023	0.360b	0.259b	0.915a	0.388b	0.209b	0.358a
	0.358b	0.257b	0.901a	0.385b	0.209b	0.354a
	0.357b	0.252b	0.890a	0.380b	0.211b	0.361a
	0.393a	0.284a	1.024a	0.429a	0.228a	0.381a

Table 2 – Average contents of protein nutritional traits in grains of single hybrids (SH), triple hybrids (TH), double hybrids (DH) and varieties (VA) sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

(Conclusion)

Dates	Val	Ile	Leu	Phe	His	Arg
Overall	0.414b	0.298b	1.086b	0.449b	0.245c	0.411b
	0.421b	0.304b	1.112b	0.459b	0.249c	0.414b
	0.427b	0.306b	1.125b	0.463b	0.255b	0.418b
	0.460a	0.335a	1.246a	0.508a	0.271a	0.443a

GB: genetic base. Sowing on 09/21/2021 (single hybrids: n = 46, triple hybrids: n = 14, double hybrids: n = 3, varieties: n = 8); sowing on 10/20/2021, 11/20/2021, 12/20/2021, 01/30/2022, 09/06/2022, 10/14/2022, 11/24/2022, 12/30/2022 and 02/06/2023 (single hybrids: n = 47, triple hybrids: n = 15, double hybrids: n = 8, varieties: n = 8). Means not followed by the same lowercase letter in the column differ by the Scott Knott test at 5% significance level. Traits: crude protein (CP, g/100 g), lysine (Lys, g/100 g), methionine (Met, g/100 g), cystine (Cys, g/100 g), threonine (Thr, g/100 g), tryptophan (Trp, g/100 g), valine (Val, g/100 g), isoleucine (Ile, g/100 g), leucine (Leu, g/100 g), phenylalanine (Phe, g/100 g), histidine (His, g/100 g), and arginine (Arg, g/100 g). Source: Authorship (2025)

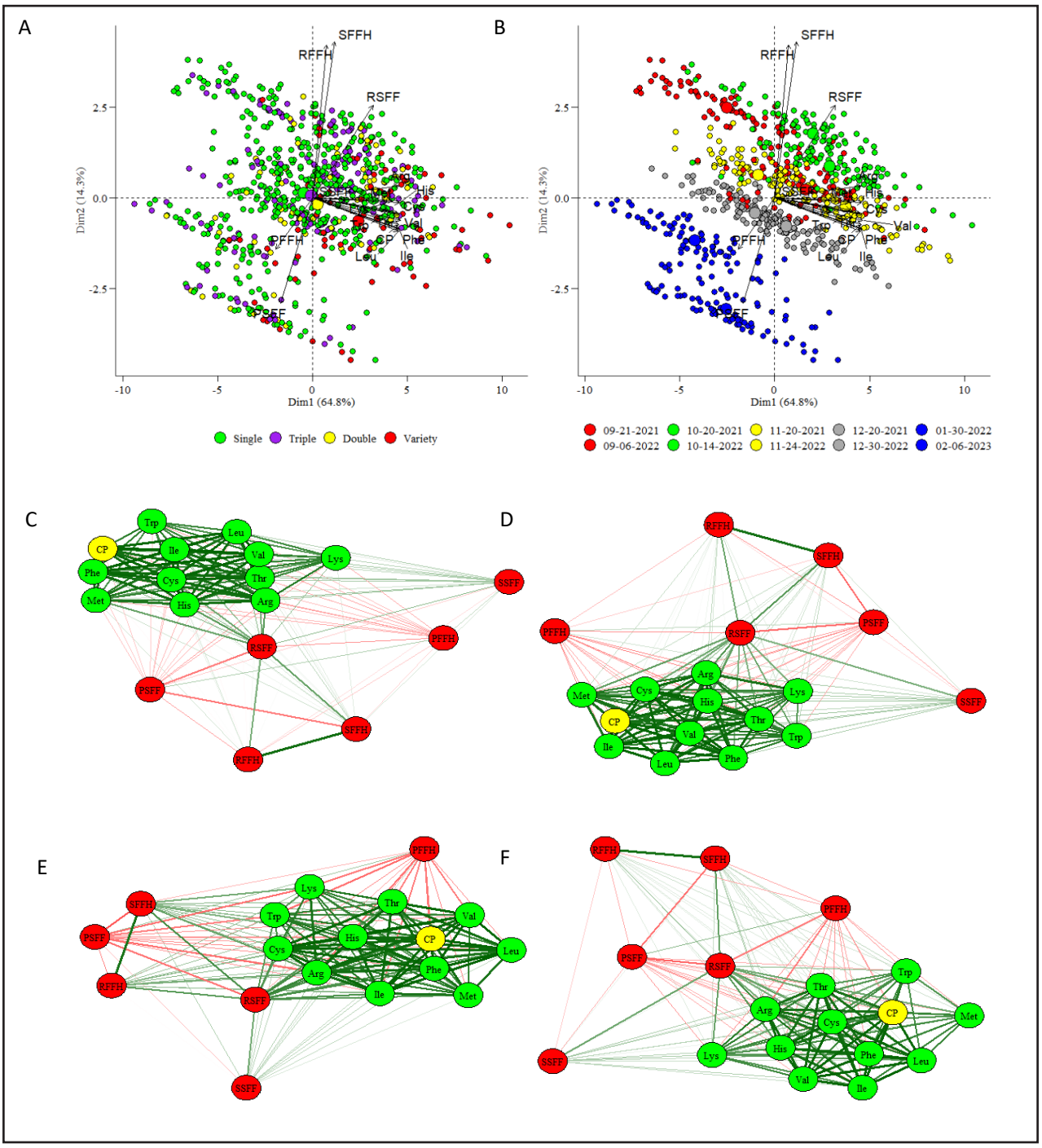
The superiority of the varieties over single, triple and double hybrids ranged from 5.11% to 15.05%, 5.24% to 12.67%, and 4.56% to 11.56%, respectively. The largest differences were observed, in descending order, for Leu, Phe, Ile, Val and CP, Thr, His, Cys, Trp, Met, Arg and Lys. The variations in nutritional contents reflect influences of the genetic base and sowing dates and indicate that the varieties can be used as a source of alleles in breeding programs. Research has identified variations in the contents of digestible amino acids in maize grains from different countries (Brazil, Ukraine, Russia, and Iran) (Sheikhhasan et al., 2020). Variability of total contents and digestibility coefficients of amino acids were observed among 20 (Zuber & Rodehutscord, 2017) and 22 (Mehta et al., 2020) maize genotypes.

The first two principal components explained 79.10% of the total variation in the data (Figures 1A and B). Sowing dates influenced CP and digestible amino acids more than the genetic base. Sowings in December, January and February led to higher volumes of PSFF and PFFH and lower values of RSFF, RFFH, SSFF and SFFH, reducing the nutritional contents. On the other hand, sowings in October and November led

to lower PSFF and PFFH, higher RSFF and SSFF, and better nutritional contents. This indicates that the highest contents of CP and digestible amino acids were obtained in environments with lower precipitation and higher values of global solar radiation and thermal sum. This is confirmed by the correlation network, in which the variables RSFF, RFFH, SSFF, and SFFH had a positive correlation with CP and digestible amino acids, while PSFF and PFFH showed a negative correlation, regardless of the genetic base (Figures 1C, D, E, and F). The results are consistent with those of Safian et al. (2022) and Guo et al. (2023), who reported higher protein content in maize grains under water deficit, associated with reduced starch synthesis and increased protein synthesis. Positive relationships were also observed between crude protein and cumulative temperature before anthesis (Wang et al., 2023) and between amino acid contents and global solar radiation (Wu et al., 2024).

The coefficient of determination (R^2) ranged from 0.53 to 0.96, being equal to or greater than 0.79 for eight digestible amino acids (Cys, Thr, Val, Ile, Leu, Phe, His and Arg), regardless of the genetic base (Table 3). This indicates that the contents of these amino acids can be predicted by CP for each genetic base of maize. For example, the digestible content of His in grains of single hybrids can be estimated by the equation: $y = -0.00106 + 0.0276CP$. Thus, for a CP content of 9.25 g/100 g, the predicted value of His would be 0.261 g/100 g.

Figure 1 – Data variability (n = 773 samples) represented by two principal components stratified by four genetic bases (A) and ten sowing dates (B), network of Pearson's linear correlation between meteorological variables and protein nutritional traits in single hybrids (C), triple hybrids (D), double hybrids (E) and varieties (F)



Cumulative global solar radiation from sowing to female flowering (RSFF, MJ m^{-2}), cumulative global solar radiation from female flowering to harvest (RFFH, MJ m^{-2}), thermal sum from sowing to female flowering (SSFF, °C day), thermal sum from female flowering to harvest (SFFH, °C day), cumulative precipitation from sowing to female flowering (PSFF, mm), cumulative precipitation from female flowering to harvest (PFFH, mm), crude protein (CP, g/100 g), lysine (Lys, g/100 g), methionine (Met, g/100 g), cystine (Cys, g/100 g), threonine (Thr, g/100 g), tryptophan (Trp, g/100 g), valine (Val, g/100 g), isoleucine (Ile, g/100 g), leucine (Leu, g/100 g), phenylalanine (Phe, g/100 g), histidine (His, g/100 g) and arginine (Arg, g/100 g). Source: Authors (2025)

Table 3 – Simple linear regression between crude protein (CP, g/100 g) (x) and lysine (Lys, g/100 g), methionine (Met, g/100 g), cystine (Cys, g/100 g), threonine (Thr, g/100 g), tryptophan (Trp, g/100 g), valine (Val, g/100 g), isoleucine (Ile, g/100 g), leucine (Leu, g/100 g), phenylalanine (Phe, g/100 g), histidine (His, g/100 g) and arginine (Arg, g/100 g) for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates in the 2021/2022 and 2022/2023 seasons

Traits	Intercept	LI b	b	LS b	R^2	Intercept	LI b	b	LS b	R^2
	Single hybrids					Triple hybrids				
Lys	0.0754	0.0148	0.0158	0.0168	0.67	0.0786	0.0135	0.0153	0.0171	0.6517
Met	0.0374	0.0137	0.0143	0.0150	0.79	0.0335	0.0137	0.0147	0.0158	0.8377
Cys	-0.0044	0.0200	0.0205	0.0211	0.91	-0.0030	0.0195	0.0205	0.0215	0.9206
Thr	-0.0432	0.0335	0.0349	0.0363	0.84	-0.0560	0.0340	0.0366	0.0392	0.8399
Trp	0.0056	0.0062	0.0066	0.0070	0.72	0.0020	0.0063	0.0070	0.0076	0.7713
Val	-0.0547	0.0512	0.0524	0.0536	0.94	-0.0561	0.0508	0.0529	0.0549	0.9468
Ile	-0.0840	0.0420	0.0428	0.0436	0.96	-0.0874	0.0419	0.0434	0.0449	0.9564
Leu	-0.5819	0.1829	0.1868	0.1907	0.95	-0.5867	0.1814	0.1883	0.1953	0.9510
Phe	-0.1544	0.0663	0.0676	0.0689	0.96	-0.1566	0.0659	0.0683	0.0706	0.9565
His	-0.0011	0.0265	0.0276	0.0286	0.85	0.0029	0.0258	0.0273	0.0288	0.8968
Arg	0.0552	0.0382	0.0398	0.0413	0.85	0.0531	0.0375	0.0400	0.0425	0.8694
Traits	**Intercept**	**LI b**	**b**	**LS b**	**R^2**	**Intercept**	**LI b**	**b**	**LS b**	**R^2**
	Double hybrids					**Varieties**				
Lys	0.0739	0.0132	0.0159	0.0186	0.65	0.0662	0.0130	0.0165	0.0200	0.53
Met	0.0284	0.0141	0.0156	0.0171	0.85	0.0481	0.0110	0.0134	0.0158	0.61
Cys	-0.0039	0.0190	0.0207	0.0224	0.89	0.0028	0.0182	0.0199	0.0215	0.88
Thr	-0.0398	0.0309	0.0347	0.0386	0.81	-0.0347	0.0298	0.0337	0.0376	0.79
Trp	0.0002	0.0062	0.0071	0.0081	0.75	-0.0027	0.0064	0.0075	0.0085	0.72
Val	-0.0492	0.0493	0.0524	0.0556	0.94	-0.0481	0.0489	0.0519	0.0549	0.94
Ile	-0.0774	0.0401	0.0422	0.0444	0.95	-0.0871	0.0410	0.0431	0.0451	0.96
Leu	-0.5168	0.1712	0.1808	0.1904	0.95	-0.5228	0.1695	0.1808	0.1920	0.93
Phe	-0.1443	0.0634	0.0668	0.0702	0.95	-0.1514	0.0639	0.0674	0.0709	0.95
His	0.0054	0.0253	0.0275	0.0296	0.90	0.0280	0.0223	0.0248	0.0273	0.83
Arg	0.0499	0.0372	0.0406	0.0440	0.88	0.0520	0.0355	0.0399	0.0444	0.80

The estimates of parameters of all simple linear regression models were significant by Student's t-test at 5% significance level. R^2: coefficient of determination and lower (LI) and upper (LS) limits of the 95% confidence intervals for the slope coefficient (b). The assumptions of regression analysis were met. Source: Authorship (2025)

Similar equations have been reported, such as the study conducted by Sheikhhassan et al. (2020), who presented the model y = -0.0877 + 0.0293CP (R^2 = 0.94)

to predict His in maize. Zuber & Rodehutscord (2017) identified a positive correlation between the digestibility coefficient of amino acids and the CP content in maize samples. In sorghum, Ebadi et al. (2011) developed regression models for prediction of digestible amino acids based on crude protein, ether extract, starch and total phenols, with R^2 ranging from 0.40 (Lys) to 0.87 (Cys). Coefficients of determination of 0.19 to 0.51 (Sriperm et al., 2010) and 0.23 to 0.66 (Olukosi & Adebiyi, 2013) have been reported for prediction of total amino acids in maize based on CP.

The R^2 and the coefficient of determination of the leave-one-out cross-validation (R^2cv) ranged from 0.27 to 0.73 and 0.25 to 0.67 between the models for predicting CP and digestible amino acids by means of meteorological variables (Table 4). The double hybrids exhibited the highest R^2 ($0.54 \leq R^2 \leq 0.73$) and R^2cv ($0.49 \leq R^2cv \leq 0.67$), suggesting greater stability and accuracy in the modeling of nutritional traits in response to meteorological variables. For example, Met content can be predicted by means of the following equation: y = 1.7E-01 + 7.6E-05RSFF – 5.2E-05RFFH – 9.4E-05SSFF + 3.1E-5SFFH, with R^2 and R^2cv of 0.66 and 0.61, respectively.

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Model	CP	Lys	Met	Cys	Thr	Trp
Single hybrids						
Intercept	7.2E+00	2.0E-01	1.3E-01	1.2E-01	2.1E-01	6.3E-02
RSFF	3.3E-03	3.1E-05	7.0E-05	6.6E-05	1.0E-04	2.0E-05
RFFH	-3.1E-03	-3.8E-05	-4.4E-05	-5.7E-05	-1.4E-04	-2.1E-05
SSFF	-2.3E-03	-	-6.2E-05	-2.7E-05	-4.9E-05	-2.0E-05
SFFH	2.5E-03	3.1E-05	3.4E-05	5.1E-05	1.4E-04	1.7E-05
PSFF	9.5E-04	-3.0E-05	2.1E-05	1.9E-05	-	-
PFFH	-	-3.2E-05	1.6E-05	-5.1E-06	-3.3E-05	-7.0E-06
R^2	0.33	0.32	0.45	0.38	0.41	0.27
R^2cv	0.31	0.30	0.43	0.36	0.40	0.26

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Model	Val	Ile	Leu	Phe	His	Arg
Single hybrids						
Intercept	2.9E-01	2.2E-01	7.2E-01	3.2E-01	1.3E-01	3.0E-01
RSFF	1.8E-04	1.4E-04	6.2E-04	2.2E-04	9.3E-05	1.4E-04
RFFH	-1.8E-04	-1.4E-04	-6.4E-04	-2.2E-04	-2.9E-05	-1.3E-04
SSFF	-9.6E-05	-9.4E-05	-4.0E-04	-1.4E-04	-	-8.2E-05
SFFH	1.7E-04	1.2E-04	5.4E-04	1.9E-04	-	1.4E-04
PSFF	6.1E-05	4.2E-05	2.4E-04	7.1E-05	-	-
PFFH	-1.0E-05	-	-	-	-	-1.7E-05
R^2	0.40	0.35	0.34	0.35	0.48	0.51
R^2cv	0.39	0.33	0.32	0.33	0.47	0.49

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Triple hybrids						
Intercept	8.2E+00	1.9E-01	1.6E-01	1.6E-01	2.7E-01	5.8E-02
RSFF	4.1E-03	3.6E-05	7.4E-05	7.0E-05	1.1E-04	2.8E-05
RFFH	-4.8E-03	-4.1E-05	-6.4E-05	-8.8E-05	-2.1E-04	-2.1E-05
SSFF	-4.2E-03	-	-8.6E-05	-5.7E-05	-1.1E-04	-2.6E-05
SFFH	4.3E-03	3.2E-05	4.7E-05	7.8E-05	2.2E-04	1.4E-05
PSFF	1.7E-03	-	-	-	-	-
PFFH	-4.1E-04	-4.9E-05	-	-2.0E-05	-5.9E-05	-8.1E-06
R^2	0.44	0.42	0.53	0.44	0.46	0.46
R^2cv	0.38	0.38	0.49	0.40	0.41	0.42
Double hybrids						
Intercept	8.0E+00	2.0E-01	1.7E-01	1.3E-01	2.7E-01	5.9E-02
RSFF	4.8E-03	2.4E-05	7.6E-05	4.1E-05	1.2E-04	2.8E-05
RFFH	-5.0E-03	-	-5.2E-05	-	-1.8E-04	-2.1E-05
SSFF	-6.2E-03	-	-9.4E-05	-	-1.5E-04	-2.7E-05
SFFH	5.3E-03	-	3.1E-05	-	2.0E-04	1.5E-05

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Triple hybrids						
Intercept	3.9E-01	3.1E-01	1.0E+00	4.5E-01	1.6E-01	2.8E-01
RSFF	1.9E-04	1.6E-04	8.0E-04	2.5E-04	8.1E-05	1.2E-04
RFFH	-2.4E-04	-2.1E-04	-1.1E-03	-3.3E-04	-3.6E-05	-4.3E-05
SSFF	-1.6E-04	-1.6E-04	-8.9E-04	-2.4E-04	-	-
SFFH	2.1E-04	1.7E-04	1.0E-03	2.7E-04	-	-
PSFF	-	-	3.1E-04	-	-	-
PFFH	-4.7E-05	-3.2E-05	-	-4.8E-05	-3.5E-05	-7.6E-05
R^2	0.46	0.42	0.40	0.43	0.49	0.57
R^2cv	0.42	0.37	0.35	0.38	0.46	0.54
Double hybrids						
Intercept	3.7E-01	2.7E-01	1.0E+00	4.3E-01	2.2E-01	3.6E-01
RSFF	2.3E-04	1.9E-04	9.1E-04	2.8E-04	1.3E-04	1.5E-04
RFFH	-2.6E-04	-2.1E-04	-1.1E-03	-2.5E-04	-1.5E-04	-1.3E-04
SSFF	-2.6E-04	-2.3E-04	-1.2E-03	-3.0E-04	-1.7E-04	-1.6E-04
SFFH	2.7E-04	2.1E-04	1.1E-03	1.9E-04	1.7E-04	1.6E-04

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Double hybrids						
PSFF	2.8E-03	-5.8E-05	-	-	-	-
PFFH	-5.2E-06	-4.1E-05	-	-4.4E-05	-5.0E-05	-1.2E-05
R^2	0.68	0.54	0.66	0.56	0.62	0.62
R^2cv	0.62	0.49	0.61	0.53	0.55	0.56
Open-pollinated varieties						
Intercept	1.0E+01	1.9E-01	2.0E-01	2.0E-01	3.0E-01	7.9E-02
RSFF	5.1E-03	4.3E-05	8.1E-05	9.8E-05	1.5E-04	3.9E-05
RFFH	-7.7E-03	-2.0E-05	-1.2E-04	-1.4E-04	-2.9E-04	-7.5E-05
SSFF	-8.4E-03	-	-1.5E-04	-1.5E-04	-2.4E-04	-7.3E-05
SFFH	8.9E-03	-	1.3E-04	1.5E-04	3.7E-04	9.7E-05

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Double hybrids						
PSFF	1.1E-04	9.9E-05	5.6E-04	-	7.7E-05	1.2E-08
PFFH	-3.5E-05	-2.5E-05	-7.2E-06	-4.1E-05	1.5E-06	-3.4E-05
R^2	0.65	0.65	0.62	0.63	0.65	0.73
R^2cv	0.58	0.58	0.54	0.57	0.57	0.67
Open-pollinated varieties						
Intercept	4.6E-01	3.5E-01	1.4E+00	5.4E-01	2.4E-01	3.9E-01
RSFF	2.4E-04	2.0E-04	9.6E-04	3.1E-04	1.3E-04	1.8E-04
RFFH	-3.9E-04	-3.3E-04	-1.6E-03	-5.3E-04	-1.7E-04	-2.1E-04
SSFF	-3.7E-04	-3.2E-04	-1.7E-03	-5.1E-04	-1.8E-04	-2.1E-04
SFFH	4.6E-04	3.9E-04	1.9E-03	6.3E-04	2.0E-04	2.3E-04

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(To be continued...)

Double hybrids						
PSFF	4.5E-03	-	6.6E-05	6.9E-05	1.4E-04	4.7E-05
PFFH	1.1E-03	-5.1E-05	2.4E-05	9.7E-06	1.1E-05	1.2E-06
R^2	0.48	0.45	0.37	0.51	0.46	0.42
R^2cv	0.38	0.40	0.25	0.42	0.35	0.31

Table 4 – Stepwise forward multiple linear regression for prediction of contents of crude protein and digestible amino acids for poultry using meteorological variables for single hybrids, triple hybrids, double hybrids and varieties sown on ten sowing dates (2021/2022 and 2022/2023)

(Conclusion)

Double hybrids						
PSFF	2.4E-04	2.1E-04	9.4E-04	3.3E-04	1.4E-04	1.0E-04
PFFH	-	-	2.8E-04	-	-	-1.9E-05
R^2	0.49	0.44	0.42	0.44	0.56	0.63
R^2cv	0.42	0.35	0.31	0.36	0.50	0.56

The estimates of parameters of all multiple linear regression models were significant by Student's t-test at 5% significance level. R^2: adjusted coefficient of determination; R^2cv: coefficient of determination of the leave-one-out cross-validation. Crude protein (CP, g/100 g), lysine (Lys, g/100 g), methionine (Met, g/100 g), cystine (Cys, g/100 g), threonine (Thr, g/100 g), tryptophan (Trp, g/100 g), valine (Val, g/100 g), isoleucine (Ile, g/100 g), leucine (Leu, g/100 g), phenylalanine (Phe, g/100 g), histidine (His, g/100 g) and arginine (Arg, g/100 g), cumulative global solar radiation from sowing to female flowering (RSFF, MJ m^{-2}), cumulative global solar radiation from female flowering to harvest (RFFH, MJ m^{-2}), thermal sum from sowing to female flowering (SSFF, °C day), thermal sum from female flowering to harvest (SFFH, °C day), cumulative precipitation from sowing to female flowering (PSFF, mm) and cumulative precipitation from female flowering to harvest (PFFH, mm). The assumptions of regression analysis were met. Source: Authorship (2025)

Arg content can be predicted by meteorological variables in all genetic bases, with $R^2 \geq 0.51$. RSFF showed positive regression coefficients and was the only meteorological variable included in all models for predicting CP and digestible amino acids. Predictive models reinforce this relationship, showing positive correlations between amino acids and global solar radiation (Wu et al., 2024) and associations between CP and cumulative temperature before anthesis ($R^2 = 0.31$) and average daily temperature after anthesis ($R^2 = 0.83$) (Wang et al., 2023).

The application of prediction models in poultry feed formulation represents a promising opportunity for advancing precision nutrition, allowing estimates of digestible amino acid levels based on corn grain composition or meteorological variables. This approach may contribute to the efficient use of additives in the future, potentially reducing costs. However, its practical adoption will depend on further validation,

standardization of analyses, and integration with grain quality and environmental monitoring systems.

4 CONCLUSIONS

There is variation in the contents of digestible amino acids for poultry in maize grains between the genetic bases and sowing dates. Open-pollinated varieties and sowings carried out in October and November led to the highest contents of digestible amino acids for poultry in maize grains. Digestible contents of methionine, cystine, threonine, valine, isoleucine, leucine, phenylalanine, histidine and arginine in maize grains can be predicted from crude protein with high accuracy, in all maize genetic bases. In double hybrids, the digestible contents of all amino acids can be predicted by means of meteorological variables with a coefficient of determination higher than 0.54.

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