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CROP PRODUCTION

Productivity, nutritional composition, and presence of mycotoxins in different corn hybrids

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ABSTRACT: An experiment was conducted to assess the crop yield, nutritional composition, and mycotoxin contamination in different corn hybrids. The impact of these variables on the feed formulation cost of starter diets for broilers was also evaluated. A total of 150 samples from 50 corn hybrids was obtained from a field experiment. Nutrients were predicted by NIRS and mycotoxins were analyzed by HPLC-MS/MS. Data were submitted to analysis of variance and corn hybrids were grouped using Scott-Knott test at 5% significance. Pearson correlation analysis was performed among the main variables. Most of the variables were different among corn hybrids ($P < 0.05$), with exception of available phosphorus (Av. P), damaged grains, and DON and ZEA contaminations ($P > 0.05$). Crop yield had a positive correlation ($P < 0.05$) with feed formulation cost ($r = 0.35$) and a negative correlation ($P < 0.05$) with crude protein (-0.42), digestible (dig.) Thr (-0.42), and dig. Met+Cys (-0.42). The feed cost correlated positively ($P < 0.05$) with FUM (0.33) and ZEA (0.29), and negatively ($P < 0.05$) with crude protein (-0.74). Different corn hybrids vary in their productivity, nutritional content and mycotoxins contamination. It was demonstrated that an increase in the crop yield might be related to a reduction in corn nutritional content and quality, resulting in an increase in feed formulation cost.
Key words: corn hybrid, aflatoxin, fumonisin, NIRS, amino acids.

Avaliação da produtividade, composição nutricional e presença de micotoxinas em diferentes híbridos de milho

RESUMO: Um experimento foi conduzido para avaliar a produtividade, a composição nutricional e a contaminação por micotoxinas em diferentes híbridos de milho. Essas medidas também foram correlacionadas com o impacto do custo do milho na formulação de ração inicial para frangos de corte. Um total de 150 amostras de 50 híbridos de milho foram obtidas em experimento de campo. As variáveis nutricionais foram preditas via NIRS e as micotoxinas foram analisadas por HPLC-MS/MS. Os dados foram submetidos à análise de variância e os híbridos agrupados pelo teste de Scott-Knott a 5% de significância. Correlação de Pearson foi realizada entre as principais variáveis. A maioria das variáveis foi diferente entre os híbridos de milho ($P < 0,05$), com exceção de fósforo disponível, grãos avariados e contaminações por DON e ZEA ($P > 0,05$). A produtividade teve correlação positiva ($P < 0,05$) com o custo de formulação da ração ($r = 0,35$) e correlação negativa ($P < 0,05$) com proteína bruta (-0,42), Tre digestível (dig.) (-0,42) e Met+Cis dig. (-0,42). O custo da formulação de rações apresentou correlação positiva ($P < 0,05$) com FUM (0,33) e ZEA (0,29), e negativa ($P < 0,05$) com proteína bruta (-0,74). Diferentes híbridos de milho variam em produtividade, conteúdo nutricional e contaminação por micotoxinas. Foi demonstrado que um aumento no rendimento à campo pode estar relacionado com redução no conteúdo nutricional e na qualidade do milho, resultando em um aumento no custo da formulação de ração.
Palavras-chave: híbrido de milho, aflatoxina, fumonisinas, NIRS, aminoácidos.

INTRODUCTION

Due to its nutritional value, corn (*Zea mays* L.) is one of the main ingredients used in the diets for poultry worldwide. Brazil is one of the largest corn producer and exporter countries (USDA, 2021), and, according to ABIMILHO (2023), about 50% of the corn produced in Brazil in the 2019/2020 harvest was used for animal consumption, reaching more than 54% in the 2022/2023 harvest. The grain is globally traded as a commodity because it is a homogeneous product from which is expected small variability in its characteristics (PRATES, 2007) and its price is regulated by the supply and demand principle. However, high prices scenarios have an impact on the cost of feed formulations, affecting the whole animal production chain, and, consequently, meat prices.

The natural composition of corn is susceptible to mycotoxin contamination. The contamination by mycotoxins depends on several factors such as seed genetics, growing location, soil fertility, climate conditions, and pre- and post-

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harvest handling (FAO, 2024). The main mycotoxin-producing fungi found in corn are *Aspergillus* and *Fusarium*, which can produce mycotoxins from the groups of aflatoxins, fumonisins, and trichothecenes, respectively (MALLMANN & MALLMANN, 2020). Therefore, it is important to provide current information on how some of these factors can impact the characteristics of corn and; consequently, its utilization. Furthermore, it is important to consider the use of antimycotoxin additive (AMA) when identifying mycotoxin contamination, seeking tested products with guaranteed efficacy for the groups of mycotoxins and animal species being worked with.

In the 2020/2021 harvest, 98 new corn cultivars were introduced in the Brazilian market (EMBRAPA, 2021); however, technical improvement of corn has primarily focused on developing high-yield hybrids with resistance to lodging and pathogens. There are no nutritionally certified hybrids available in the market, and there is limited information regarding resistance to fungal attacks and potential mycotoxins contamination.

In this context and considering that corn is the primary cereal in the global animal nutrition chain, the nutritional composition and the quality of corn hybrids should therefore be considered in the genetic selection and improvement processes. Therefore, this study assessed the productivity, nutritional composition, and presence of mycotoxins in different corn hybrids cultivated in the same harvest in Brazil, focusing on poultry nutrition. Information on nutrients composition and mycotoxins contamination from each corn hybrid was also considered to formulate starter diets for broilers and to evaluate the impact of these variables on feed formulation cost.

MATERIALS AND METHODS

Field experiment

The experiment was conducted at the Agricultural Research Center (24°37'18"S; 53°18' 20"W; 580 m altitude) of the Cooperativa Agroindustrial Consolata (COPACOL), in Cafelândia city, western region of the Paraná State, Brazil. The soil was classified as dystroferric red latosol. In February 2020, 50 commercial and pre-commercial corn hybrids were cultivated in a consolidated no-tillage system under the same agro-climatic conditions and soil type. The identification of corn hybrids was done numerically (from 1 to 50) and the commercial names have been withheld to ensure confidentiality. The experiment was design in a randomized blocks design with three replicates of each corn hybrid. Experimental plots consisted of four corn rows with a spacing of 68 cm, having 2.72 m in width by 10 m in length. Crop phytosanitary management was conducted according to the technical recommendations on pest and weed control. The soil fertilization was conducted according to chemical analyses, employing a base fertilization of 300 kg/ha of 10-15-15 (NPK).

Harvesting was performed in July using a Wintersteiger combine® experimental plot harvester-classic model, where the two central lines of each plot were harvested, totaling 13.6 m^2 of useful plot. The mass of grains and gravimetric moisture content were automatically determined by the Easy Harvest weighing system (Grain Gage®) coupled to the harvesting system. The crop yield of the experimental plots was calculated in kg/ha and adjusted for 13% moisture. Grains that were damaged were classified according to MAPA recommendations (BRASIL, 2011) and the percentage of damaged grains was obtained by the equation: [weight of damaged grains (g)/weight of the sample (g)]* 100.

Quantification of mycotoxins by high-performance liquid chromatography coupled to tandem mass spectrometry (HPLC-MS/MS)

After harvesting, samples were dried in a forced-air oven at 55 °C for 12 h and prepared for mycotoxins and nutrients analyses. Mycotoxins quantification was conducted in the Laboratory of Mycotoxicological Analyses at Federal University of Santa Maria, Brazil. Analytical standards for aflatoxins (AFLA) AFB_1, AFB_2, AFG_1, AFG_2, fumonisins (FUM) B_1 (FB_1) and B2 (FB_2), deoxynivalenol (DON), and zearalenone (ZEA) were purchased from Sigma Aldrich (St Louis, MO, USA). Methanol, acetonitrile, formic acid, and ammonium acetate (HPLC grade) were purchased from JT Baker (Center Valley, PA, USA). Ultrapure water was obtained from a Milli-Q Water Purification System. The limits of detection (LOD) and quantification (LOQ) (in µg/kg) for the assessed mycotoxins were, respectively: 0.4 and 1 for AFB_1; 0.6 and 1 for AFB_2, AFG_1 and AFG_2; 10 and 125 for FB_1; 20 and 125 for FB_2; 3 and 20 for ZEA; and 50 and 200 for DON.

Samples of 1 kg were milled at 1 mm using an ultra-centrifugal mill (RETSCH®, model ZM 200), homogenized and then analyzed for mycotoxins presence. Analyses of AFLA, FUM, DON and ZEA were performed according to MALLMANN et al. (2020). For AFLA, a 5 g sample was mixed with 20 mL acetonitrile–water solution (84:16, v/v) and shaken on a shaking table for 60 min. The resulted extract was spun (Eppendorf 5804R) at 2,500 rpm, 20 °C, for 5 min, and then 60 µL was diluted with 840 µL methanol–water (1:1, v/v) solution. For FUM, 3 g of sample was mixed with 15 mL acetonitrile–water solution (1:1, v/v) and vortexed for 20 min in an orbital shaker. The extract was spun at 2,500 rpm, 20 °C, for 5 min, and then 20 µL was diluted in 980 µL acetonitrile–water–formic acid solution (50:40:10, v/v/v). For DON and ZEA, a 3 g sample was mixed with 24 mL methanol–water (70:30, v/v) solution and vortexed for 20 min using an orbital shaker. The resulted extract was spun at 2,500 rpm, 20 °C, for 5 min, and then 40 µL was diluted in 960 µL methanol–water–ammonium acetate solution (90:9:1, v/v/v). For the four mycotoxins, 20 µL of the diluted solution was injected into a 1200 Series Infinity HPLC instrument (Agilent, Palo Alto, CA, USA) coupled to a 5500 QTRAP mass spectrometer (Applied Biosystems, Foster City, CA, USA) equipped with an electrospray ionization source in positive mode. Chromatographic separation for AFLA and FUM was performed at 30 °C using an Eclipse XDB-C8 column (4.6 × 250 mm, 5 µm particle diameter) (Agilent) and for DON an ZEA at 40 C with a Zorbax SB-C18 column (4.6 × 150 mm, 5 µm) (Agilent).

NIRS nutritional predictions

For predictions by near infrared spectroscopy (NIRS), samples were milled through a 0.5 mm sieve in an ultra-centrifugal mill (RETSCH®, model ZM 200). Samples were then placed in plastic bags and left for 15 min to reach room temperature (between 18 °C and 22 °C) and humidity (between 40% and 60%). Subsequently, manual homogenization of each sample was performed for two min in a plastic bag using circular movements. Nutritional predictions were performed by reading the spectra of the samples in a Bruker® instrument, model Tango-R, with a wavelength range of 3,952 - 11,536 cm^{-1}, using the calibration curves from the AMINONRG® and AMINONir® programs (Evonik Nutrition & Care GmbH, Hanau, Germany). The following variables were predicted: dry matter (DM) (%), crude protein (CP) (%), ether extract (EE) (%), ash (%), total phosphorus (TP) (%), phytic phosphorus (PP) (%), total and digestible (dig.) amino acids (AA, %) for poultry, and apparent metabolizable energy (AME_n) (kcal/kg) for poultry. For study and comparison purposes, all values were adjusted to 87% DM basis.

Feed formulation and AMA inclusion in the diet

Average nutrient composition and mycotoxins contamination were calculated for each corn hybrid and used to calculate the cost of feed formulation of starter diets for broilers (8 to 21 days of age) using each hybrid as the corn source in the formula. The starter diet was used in this investigation due to the high susceptibility to mycotoxins that broilers present at this phase (MALLMANN & MALLMANN, 2020). Feeds were formulated using the PPFR spreadsheet (UNESP, SP, Brazil) and following recommendations of ROSTAGNO et al. (2017) for standard-high performance male broilers. Costs were obtained from market prices in the region of the study in November 2020 (Table 1). The inclusion of the AMA was calculated proportionally to mycotoxins concentration levels of each corn hybrid and based on the Mycotoxins Risk algorithm (MALLMANN & MALLMANN, 2020). The inclusion of AMA was adjusted as follows: 2.5 kg of AMA/t of feed for every 28 µg/kg of AFLA + 2.5 kg of AMA/t of feed for every 10,000 µg/kg of FUM.

Statistical analyses

Data were analyzed using the Statgraphics® software (Statgraphics Centurion 15.2.11, Manugistics Inc., Rockville, MD, USA). Different variables were submitted to analysis of variance and the Scott-Knott test was used to group hybrids with similar characteristics at 5% significance. To summarize the information in a smaller set of results that can be easily observed, Pearson correlation analysis was conducted among the main variables.

RESULTS AND DISCUSSION

Corn is one of the most produced cereals in the world, with a global production exceeding 1.1 billion tons in the 2020/2021 harvest season (USDA, 2021). Genetic improvement in the major corn-producing countries has led to a significant increase in productivity per cultivated area. Results of field traits and mycotoxins contamination of the corn hybrids are presented in table 2. For crop yield, the 50 corn hybrids were divided into 4 distinct groups ($P < 0.05$) with an average productivity of 7,407 kg/ha. The difference between the most and the least productive hybrid was 2,935 kg/ha. The average crop yield in the current study is 34% higher than the Brazilian average in the 2019/2020 harvest, which was 5,510 kg/ha, and 28% superior than the global average of 5,780 kg/ha (USDA, 2021).

SILVA et al. (2021) stated that the objective of genetic improvement in corn is mainly focused on productivity. Currently, the nutritional quality of the grain is not typically considered in

Table 1 - Nutritional requirements, ingredients, and costs used in feed formulations for broilers starter diets.

Nutrients and energy requirements[1]	Unit	Starter diet	Ingredients	R$/kg
AME_n[2]	kcal/kg	3,050	Corn	0.81
Crude Protein	%	23.3	Soybean meal, 46%	2.39
Dig. Met	%	0.51	Meat and bone meal, 45%	1.68
Dig. Met + Cys	%	0.93	Soybean oil	6.18
Dig. Lys	%	1.25	DL-hydroxy-Methionine 88%	8.89
Dig. Thr	%	0.83	L-Lysine HCl (55% lysine)	3.89
Dig. Trp	%	0.22	L-Threonine 98.5%	6.43
Dig. Arg	%	1.34	Limestone	0.31
Dig. Gly + Ser	%	1.84	Dicalcium phosphate	2.72
Dig. Val	%	0.96	Salt	0.43
Dig. Ile	%	0.84	Vitamin and mineral premix[3]	23.07
Dig. Leu	%	1.34	Antimycotoxin additive	7.80
Ca	%	0.88		
Available P	%	0.42		
Na	%	0.22		

[1]Nutrients and energy requirements according to ROSTAGNO et al. (2017) recommendations for standard-high performance male broilers.
[2]AME_n: Apparent metabolizable energy for birds, corrected for nitrogen balance (kcal/kg).
[3]Composition per kilogram of feed: iron, 40 mg; zinc, 80 mg; manganese, 80 mg; copper, 10 mg; iodine, 0.7 mg; selenium, 0.25 mg; vitamin A, 9,000 IU; vitamin D3, 2,500 IU; vitamin E, 20 IU; vitamin K3, 2,5 mg; thiamine, 2 mg; riboflavin, 6 mg; pyridoxine, 3.8 mg; cyanocobalamin, 0.015 mg, pantothenic acid, 12 mg; niacin, 35 mg; folic acid, 1,5 mg; biotin, 0.1 mg.

a genetic improvement program. In the present study, different cultivars of corn were grown under conditions similar to Brazilian production reality, and correlations among productivity and other variables related to corn quality and feed production cost were assessed. Interestingly, there was a positive correlation ($P < 0.05$) between crop yield and the final cost of the starter feed for broilers, suggesting that an increase in grain productivity might be related to an increase in the feed cost. This could be explained by the negative correlation ($P < 0.05$) of crop yield with CP ($r = -0.42$), dig. Met+Cys (-0.42), and dig. Thr (-0.42), nutrients that have an impact in the feed formulation cost. Such findings are in agreement with previous studies conducted by DUVICK (2005) and ALVAREZ-IGLESIAS et al. (2021), where the negative correlation among grain productivity and nutrients content, especially crude protein, was observed.

The percentage of damage grains and the average contamination of DON and ZEA was not different among the corn hybrids ($P > 0.05$) whereas contaminations of AFLA and FUM were affected by corn technology ($P < 0.05$). FUM was the most prevalent mycotoxin, affecting 68% of the crop, with a contamination average of 197 µg/kg. In addition to the nutritional composition of the corn, humidity and temperature conditions are factors that may have influenced this result. The average of AFLA, ZEA and DON were 0.045 µg/kg, 4.08 µg/kg, and 9.11 µg/kg, respectively. The prevalence of FUM observed herein corroborates with previous studies (MALLMANN et al., 2019; SIMÕES et al., 2023) and highlights the current need for reliable information on susceptibility of corn hybrids to *Fusarium*. In the 2019/2020 crop season, 90% of the corn hybrids available in the Brazilian market lacked data on fusariosis resistance (EMBRAPA, 2021).

The inclusion of AMA in the diet was based on technical recommendations and was directly proportional to the contamination of grains by mycotoxins. The average inclusion of AMA was 0.34 kg/ton of feed, with a maximum of 1.79 kg/ton (Table 3). As expected, the cost of the feed increased as the AMA was added in the diet, and a positive correlation ($P < 0.05$) was observed between the feed cost and contamination by FUM (0.33) and ZEA (0.29).

Results on nutrients concentration are presented in table 3. Contents of starch, EE, AME_n, CP, dig. Lys, dig. Thr and dig. Met+Cys were different among ($P < 0.05$) corn hybrids. The average AME_n content was 3,294 kcal/kg with a difference of 81 kcal/kg between the minimum and maximum values. The average CP was 7.8% with a difference higher than 30% between the minimum and maximum

Table 2 - Damaged grains, crop yield, aflatoxins (B_1+B_2+G_1+G_2), fumonisins (B_1+B_2), zearalenone and deoxynivalenol of 50 corn hybrids.

Hybrid[1]	Damaged grains (%)	Crop Yield (kg/ha)	AFLA[3] (µg/kg)	FUM[4] (µg/kg)	ZEA[5] (µg/kg)	DON[6] (µg/kg)
1[2]	0.29	7,826^b	0.000^b	529.6^b	0.00	0.00
2	0.84	7,933^a	0.382^a	361.6^b	0.00	0.00
3	0.30	7,704^b	0.510^a	272.1^b	0.00	0.00
4	0.54	7,495^b	0.000^b	319.4^b	0.00	0.00
5	0.35	7,606^b	0.000^b	265.1^b	0.00	0.00
6	0.21	7,738^b	0.000^b	1,347^a	135.28	0.00
7	0.99	7,688^b	0.000^b	0.0^b	0.00	0.00
8	0.38	7,605^b	0.000^b	0.0^b	0.00	0.00
9	0.32	6,569^d	0.000^b	0.0^b	0.00	0.00
10	0.26	7,704^b	0.000^b	0.0^b	0.00	0.00
11	0.48	6,426^d	0.000^b	0.0^b	0.00	0.00
12	0.96	8,134^a	0.000^b	397.6^b	0.00	0.00
13	0.17	7,143^c	0.000^b	39.7^b	0.00	0.00
14	0.42	8,870^a	0.000^b	347.9^b	0.00	0.00
15	0.24	7,549^b	0.000^b	41.0^b	0.00	0.00
16	0.33	8,749^a	0.000^b	503.3^b	0.00	0.00
17	0.42	7,469^b	0.000^b	0.0b	47.82	0.00
18	0.54	7,267^b	0.000^b	246.9^b	0.00	0.00
19	0.53	7,261^b	0.000^b	0.0b	0.00	0.00
20	0.75	6,984^c	0.000^b	0.0b	0.00	0.00
21	0.71	7,823^b	0.484^a	0.0b	0.00	0.00
22	1.16	8,336^a	0.000^b	189.5^b	0.00	0.00
23	0.35	7,510^b	0.481^a	207.0^b	0.00	0.00
24	0.37	7,185^c	0.413^a	302.0^b	0.00	0.00
25	0.52	7,107^c	0.000^b	0.0^b	0.00	0.00
26	0.48	8,011^a	0.000^b	451.8^b	0.00	0.00
27	0.52	6,543^d	0.000^b	267.0^b	0.00	0.00
28	1.12	7,082^c	0.000^b	1,278^a	0.00	0.00
29	0.67	7,628^b	0.000^b	174.2^b	0.00	0.00
30	0.21	7,546^b	0.000^b	44.0^b	6.78	126.97
31	0.36	7,480^b	0.000^b	0.0b	0.00	0.00
32	0.43	8,115^a	0.000^b	39.8^b	0.00	0.00
33	0.30	8,180^a	0.000^b	39.7^b	0.00	0.00
34	0.39	8,468^a	0.000^b	0.0^b	0.00	0.00
35	0.45	6,997^c	0.000^b	143.0^b	0.00	0.00
36	0.13	6,842^c	0.000^b	0.0^b	0.00	0.00
37	0.53	7,584^b	0.000^b	570.0^b	0.00	66.44
38	0.58	5,935^d	0.000^b	80.2^b	6.81	93.91
39	0.45	6,191^d	0.000^b	480.7^b	0.00	0.00
40	0.66	6,756^c	0.000^b	149.9^b	7.19	168.38
41	0.37	6,146^d	0.000^b	39.9^b	0.00	0.00
42	0.85	7,347^b	0.000^b	79.5^b	0.00	0.00
43	0.28	8,095^a	0.000^b	201.3^b	0.00	0.00
44	0.40	6,080^d	0.000^b	0.0^b	0.00	0.00
45	1.00	6,617^d	0.000^b	40.1^b	0.00	0.00
46	0.79	8,055^a	0.000^b	272.5^b	0.00	0.00
47	0.20	7,418^b	0.000^b	39.8^b	0.00	0.00
48	0.47	6,836^c	0.000^b	106.5^b	0.00	0.00
49	0.42	7,275^b	0.000^b	0.0^b	0.00	0.00
50	1.00	7,479^b	0.000^b	0.0^b	0.00	0.00
CV (%)	86.6	6.14	550	160	864	645
P-value	0.440	0.001	0.621	0.001	0.522	0.576

[1]Corn hybrid; [2]Number assigned to the corn hybrid. [3]AFLA: Aflatoxins (B_1+B_2+G_1+G_2) (µg/kg); [4]FUM: Fumonisins (B_1+B_2) (µg/kg). [5]ZEA: Zearalenone (µg/kg). [6]DON: Deoxynivalenol (µg/kg). $^{a-c}$ Means followed by different letters in the same column differ by the Scott-Knott test at 5% significance.

Table 3 - Nutrient composition, AMA inclusion, and cost of a starter feed for broilers obtained from 50 corn hybrids.

Hybrid[1]	Starch (%)	Av. P[3] (%)	EE[4] (%)	AME_n[5] (kcal/kg)	CP[6] (%)	Dig.Lys[7] (%)	Dig. Met+ Cys[8] (%)	Dig. Thr[9] (%)	AMA[10] (kg/t)	R$/t feed[11]
1[2]	62.9^{b}	0.047	4.20^{c}	3,308^{c}	7.79^{e}	0.204^{b}	0.311^{d}	0.248^{d}	0.92	1,669
2	64.5^{a}	0.047	3.90^{e}	3,296^{d}	6.63^{j}	0.185^{d}	0.275^{g}	0.213^{i}	0.79	1,717
3	63.3^{b}	0.047	4.28^{c}	3,319^{b}	7.58^{f}	0.196^{c}	0.303^{e}	0.242^{e}	0.46	1,665
4	63.6^{b}	0.043	3.85^{e}	3,298^{d}	7.30^{g}	0.191^{d}	0.290^{f}	0.232^{g}	0.49	1,689
5	62.9^{b}	0.050	4.39^{b}	3,318^{b}	7.87^{e}	0.206^{b}	0.314^{d}	0.251^{d}	0.46	1,654
6	64.9^{a}	0.043	3.78^{e}	3,300^{d}	7.19^{h}	0.192^{d}	0.290^{f}	0.228^{g}	1.79	1,707
7	63.2^{b}	0.050	3.42^{g}	3,274^{g}	8.35^{c}	0.209^{a}	0.321^{c}	0.263^{b}	0.00	1,664
8	62.7^{b}	0.047	3.94^{e}	3,293^{e}	8.34^{c}	0.209^{a}	0.326^{c}	0.264^{b}	0.00	1,650
9	63.2^{b}	0.047	4.01^{d}	3,305^{c}	8.03^{d}	0.206^{b}	0.316^{d}	0.254^{c}	0.00	1,654
10	63.4^{b}	0.047	3.87^{e}	3,293^{e}	8.08^{d}	0.202^{b}	0.317^{d}	0.255^{c}	0.00	1,659
11	63.1^{b}	0.050	3.34^{g}	3,271^{g}	8.62^{b}	0.213^{a}	0.333^{b}	0.270^{a}	0.00	1,656
12	62.7^{b}	0.047	3.95^{e}	3,299^{d}	7.98^{d}	0.207^{a}	0.319^{d}	0.252^{c}	0.54	1,665
13	63.4^{b}	0.050	3.96^{e}	3,302^{d}	8.21^{c}	0.203^{b}	0.323^{c}	0.259^{b}	0.18	1,650
14	62.9^{b}	0.050	4.11^{d}	3,309^{c}	7.69^{f}	0.203^{b}	0.307^{e}	0.244^{e}	0.25	1,666
15	63.8^{a}	0.050	3.90^{e}	3,298^{d}	7.71^{f}	0.197^{c}	0.305^{e}	0.244^{e}	0.18	1,672
16	64.3^{a}	0.040	3.83^{e}	3,299^{d}	7.33^{g}	0.194^{c}	0.295^{f}	0.231^{g}	0.60	1,688
17	64.1^{a}	0.050	3.79^{e}	3,296^{d}	7.46^{g}	0.191^{d}	0.292^{f}	0.237^{f}	0.00	1,681
18	64.8^{a}	0.047	3.49^{f}	3,289^{e}	7.68^{f}	0.196^{c}	0.303^{e}	0.241^{e}	0.46	1,684
19	64.6^{a}	0.043	3.81^{e}	3,299^{d}	6.89^{i}	0.189^{d}	0.283^{g}	0.221^{h}	0.00	1,695
20	63.1^{b}	0.050	3.50^{f}	3,271^{g}	7.90^{e}	0.203^{b}	0.313^{d}	0.250^{d}	0.00	1,681
21	63.4^{b}	0.047	3.54^{f}	3,283^{f}	8.13^{d}	0.204^{b}	0.318^{d}	0.256^{c}	0.11	1,666
22	63.7^{a}	0.047	4.09^{d}	3,304^{c}	6.87^{i}	0.189^{d}	0.274^{g}	0.220^{h}	0.21	1,697
23	63.5^{b}	0.050	3.96^{e}	3,296^{d}	7.87^{e}	0.199^{c}	0.303^{e}	0.248^{d}	0.71	1,675
24	61.6c	0.050	4.08^{d}	3,296^{d}	7.69^{f}	0.208^{a}	0.301^{e}	0.245^{e}	0.75	1,681
25	64.1^{a}	0.050	3.76^{e}	3,290^{e}	7.42^{g}	0.192^{d}	0.297^{f}	0.236^{f}	0.00	1,685
26	63.2^{b}	0.047	3.88^{e}	3,296^{d}	7.75^{e}	0.203^{b}	0.307^{d}	0.246^{e}	0.57	1,677
27	63.9^{a}	0.050	3.66^{f}	3,290^{e}	8.02^{d}	0.200^{b}	0.312^{d}	0.252^{c}	0.23	1,668
28	63.1^{b}	0.050	3.39^{g}	3,266^{g}	8.29^{c}	0.216^{a}	0.319^{d}	0.261^{b}	1.71	1,690
29	62.8^{b}	0.047	4.24^{c}	3,311^{c}	7.61^{f}	0.198^{c}	0.295^{f}	0.242^{e}	0.42	1,668
30	63.4^{b}	0.050	3.60^{f}	3,281^{f}	8.45^{c}	0.211^{a}	0.325^{c}	0.266^{b}	0.18	1,656
31	64.5^{a}	0.050	3.51^{f}	3,286^{e}	7.99^{d}	0.198^{c}	0.311^{d}	0.251^{d}	0.00	1,669
32	63.6^{b}	0.047	3.57^{f}	3,287^{e}	7.91^{e}	0.198^{c}	0.313^{d}	0.249^{d}	0.18	1,671
33	64.5^{a}	0.047	3.62^{f}	3,288^{e}	7.07^{h}	0.186^{d}	0.281^{g}	0.225^{g}	0.18	1,702
34	63.2b	0.047	4.07^{d}	3,307^{c}	7.81^{e}	0.202^{b}	0.303^{e}	0.247^{d}	0.00	1,661
35	64.4^{a}	0.050	3.46^{f}	3,278^{f}	7.95^{d}	0.203^{b}	0.310^{d}	0.251^{d}	0.40	1,679
36	63.8^{a}	0.050	3.59^{f}	3,286^{e}	8.17^{c}	0.201^{b}	0.323^{c}	0.257^{c}	0.00	1,662
37	63.3^{b}	0.050	3.86^{e}	3,291^{e}	7.81^{e}	0.203^{b}	0.305^{e}	0.247^{d}	0.64	1,678
38	62.1^{c}	0.050	4.88^{a}	3,336^{a}	7.88^{e}	0.203^{b}	0.308^{d}	0.252^{c}	0.37	1,642
39	63.1^{b}	0.050	4.54^{b}	3,327^{a}	8.32^{c}	0.208^{a}	0.321^{c}	0.264^{b}	0.58	1,632
40	64.4^{a}	0.047	4.45^{b}	3,329^{a}	7.30^{g}	0.193^{d}	0.294^{f}	0.233^{g}	0.20	1,664
41	63.9^{a}	0.047	3.06^{h}	3,255^{h}	8.85^{a}	0.210^{a}	0.346^{a}	0.276^{a}	0.18	1,658
42	61.9^{c}	0.050	3.67^{f}	3,278^{f}	8.25^{c}	0.209^{a}	0.324^{c}	0.260^{b}	0.37	1,667
43	62.4^{c}	0.047	4.41^{b}	3,320^{b}	7.57^{f}	0.201^{b}	0.300^{e}	0.242^{e}	0.65	1,666
44	64.2^{a}	0.043	3.35^{g}	3,279^{f}	7.80^{e}	0.194^{c}	0.308^{d}	0.244^{e}	0.00	1,681
45	63.9^{a}	0.047	3.58^{f}	3,283^{f}	7.75^{e}	0.197^{c}	0.305^{e}	0.244^{e}	0.18	1,680
46	63.5^{b}	0.050	3.79^{e}	3,288^{e}	7.62^{f}	0.200^{b}	0.292^{f}	0.240^{e}	0.47	1,687
47	64.4^{a}	0.050	3.85^{e}	3,297^{d}	7.70^{f}	0.195^{c}	0.303^{e}	0.243^{e}	0.18	1,673
48	63.3^{b}	0.050	3.86^{e}	3,289^{e}	8.09^{d}	0.204^{b}	0.316^{d}	0.255^{c}	0.19	1,665
49	64.4^{a}	0.047	3.61^{f}	3,288^{e}	7.85^{e}	0.197^{c}	0.315^{d}	0.248^{d}	0.00	1,670
50	64.7^{a}	0.047	3.50^{f}	3,279^{f}	7.46^{g}	0.193^{d}	0.303^{e}	0.237^{f}	0.00	1,690
CV (%)	1.04	9.03	3.22	0.21	2.46	2.51	2.45	2.71	-	-
P-value	0.001	0.604	0.001	0.001	0.001	0.001	0.001	0.001	-	-

[1]Corn hybrid; [2]Number assigned to the corn hybrid. [3]Av. P (Available phosphorus = TP – PP); [4]Ether Extract (%); [5]Apparent metabolizable energy corrected for N (kcal/kg); [6]Crude Protein (%); [7]Digestible lysine (%); [8]Digestible methionine + cysteine (%); [9]Digestible threonine (%); [10]Antimycotoxin additive inclusion in the diet (kg/t); [11]Cost of feed formulation of starter diet (R$/t); [a-f] Means followed by different letters in the same column differ by the Scott-Knott test at 5% significance.

values. Such findings are in agreement with previous research (COWIESON, 2005; DOZIER et al., 2011) and reinforce the need to monitor these nutrients in corn, due to the high variability observed and the economic impact it generates.

In order to summarize the results from the present experiment, only the first three limiting AA for poultry are presented; however, all the essential AA established by the NRC (1994) were predicted by NIRS and used in the feed formulations (Table 1). Feed formulation cost presented a negative correlation ($P < 0.05$) with CP (-0.74), dig. Lys (- 0.66), dig. Met+Cys (-0.73), and dig. Thr (-0.78). This indicates that the lower the level of CP and dig. AA, the higher the cost of the feed, due to the increased inclusion of synthetic amino acids in the formula to supply the AA requirements. In the period of the study, the synthetic amino acids used had costs per kilogram ranging from R$ 3.89 to R$ 8.89. These findings are in line with a study conducted by MALLMANN et al. (2019), which reported that FUM, and CP had a significant effect on the final cost of feed for broiler.

CONCLUSION

Based on the results obtained, we can conclude that the genetic development of corn and modern agricultural techniques have significantly contributed to increasing its productivity. However, the presence of mycotoxins in the grains represents a challenge, raising feed production costs. The variation in corn nutrient levels highlights the importance of closely monitoring its quality. Our findings underscore the ongoing need for research to improve resistance to mycotoxins and the nutritional quality of corn, aiming to ensure sustainability and profitability in animal feed production. Additionally, it is crucial to provide information on the resistance of different corn varieties to diseases such as fusariosis, to assist farmers in choosing the most suitable varieties. This study offers valuable insights to enhance efficiency and safety in animal feed production.

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DECLARATION OF CONFLICT OF INTEREST

The authors have no conflict of interest regarding the content of this article.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved the final version.

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