R. Bras. Zootec., 50:e20210035, 2021
https://doi.org/10.37496/rbz5020210035

Non-ruminants
Full-length research article

Revista Brasileira de Zootecnia

Brazilian Journal of Animal Science
e-ISSN 1806-9290
www.rbz.org.br

Composition and availability of nutrients of three corn hybrids dried at different temperatures in the diets of broiler chickens

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Received: February 15, 2021
Accepted: September 1, 2021

How to cite: Giacobbo, F. C. N.; Eyng, C.; Nunes, R. V.; Teixeira, L. V.; Souza, C.; Polese, C. and Bortoluzzi, C. 2021. Composition and availability of nutrients of three corn hybrids dried at different temperatures in the diets of broiler chickens. Revista Brasileira de Zootecnia 50:e20210035.
https://doi.org/10.37496/rbz5020210035

ABSTRACT - The objective of this study was to determine the chemical composition, non-starch polysaccharides (NSP) content, *in vitro* digestibility of starch, apparent metabolizable energy (AME), nitrogen-corrected AME (AME_n), and apparent and apparent nitrogen-corrected coefficient of metabolizable energy (ACME and $ACME_n$) of three corn hybrids dried at different temperatures in the diets of broiler chickens. The energetic values were determined by the total collection of excreta method, using broilers from 11 to 21 d, placed in a completely randomized design in a factorial scheme (three corn hybrids and two drying temperatures: 80 and 110 °C), totalizing six treatments, seven replicates, and four birds/replicate. The data were subjected to two-way ANOVA. There was an interaction between the two factors tested wherein the AME and AME_n were increased when using corn Hybrid 1 dried at 80 °C. As main effects, the use of corn Hybrid 3 increased ACME and $ACME_n$. The drying temperature of 110 °C increased amylose, resistant starch, and nitrogen bound to the fiber contents, and reduced soluble:total NSP ratio. These changes may be responsible for the differences in digestibility of nutrients. The mean values of AME and AMEn of corn dried at 80 and 110 °C were 14.03 and 13.84 MJ/kg, respectively, and 81.62 and 80.53% for ACME and $ACME_n$, respectively.

Keywords: apparent metabolizable energy, chemical composition, non-starch polysaccharides, post-harvest, starch

1. Introduction

Corn is the primary source of energy in the diets of broiler chickens (Williams et al., 2014) with an energetic value higher than other cereal grains due to its high contents of starch (620 to 720 g/kg) and fat (34 to 52 g/kg) (Lasek et al., 2012). However, it is possible to encounter components in the corn grain, such as non-starch polysaccharides (NSP), that impair the digestion and absorption of nutrients (Slominski, 2011). Additionally, the nutritional value of corn may vary depending on the concentration of amylose, amylose:amylopectin ratio, and the presence of phytate, enzymatic inhibitors, and resistant starch (Cowieson and Adeola, 2005).

Besides factors associated with genetic, soil fertilization, and climate conditions, the post-harvest processes may also affect the chemical composition of corn (Prasanthi et al., 2017). The drying of corn grains is necessary to guarantee their nutritional quality during storage, but due to the high volume of corn production and to speed up the drying process, the industry usually uses temperatures above 100 °C. The deleterious effects of high temperature to dry corn may be associated with structural changes to its molecules, mainly starch, that reduce the efficiency of digestive enzymes, releasing a different profile of saccharides during digestion (Odjo et al., 2015; Odjo et al., 2017). The structural changes in the corn grains can influence the nutrients use by animals, decreasing the energetic value for broilers (Córdova-Noboa et al., 2020; Huart et al., 2020). However, the impact of the structural modifications of corn molecules on the availability of nutrients to animals remains not fully elucidated.

We hypothesized that the drying temperature of corn may interfere with its quality and the utilization of nutrients by broiler chickens. In fact, this is the first in a series of projects that our laboratory has developed on this subject. The other publications looked at the interactions between corn drying temperature and exogenous enzymes for broiler chickens (Giacobbo et al., 2021a; Giacobbo et al., 2021b). Therefore, the objective of this study was to evaluate the effect of different drying temperatures of corn on its chemical composition, apparent metabolizable energy (AME), nitrogen-corrected apparent metabolizable energy (AME_n), and apparent and nitrogen-corrected apparent coefficient of metabolizable energy (ACME and $ACME_n$) of different corn hybrids routinely used by the poultry industry for production of feed.

2. Material and Methods

The experiment was conducted in Marechal Cândido Rondon, Paraná, Brazil (24°55'13"S, 54° 02'30" W, and altitude of 420 m above sea level). Research on animals was conducted according to the institutional committee on animal use (case number 06/19).

2.1. Corn hybrids of and chemical composition analyses

The three corn hybrids evaluated herein were classified as semi-hard grain for Hybrids 1 (30A37 PW – Morgan) and 2 (30A77 PW – Morgan) and semi-dentate for Hybrid 3 (DKB 330 PRO – Dekalb). All corn hybrids were produced under similar conditions in a region located in western Paraná, Brazil, aiming reducing any interference of soil and climate on the chemical characteristics of the grain. From the moment the corn hybrids were planted to their harvest, an accumulated rainfall of 952 mm was recorded, with maximum and minimum temperatures of 38.6 and 3.5 °C, respectively, and an average relative humidity of 54% (data provided by Agro-industrial Cooperative Copagril). The drying process of corn grains were conducted as described by Giacobbo et al. (2021a).

Following the drying process, corn samples were sent to the laboratory, located in Marechal Cândido Rondon, Paraná, Brazil, for determination of dry matter (DM), mineral matter (MM), ether extract (EE), crude protein (CP), crude fiber (CF), starch, and amylose contents. The analyses were conducted by proximal infrared reflectance spectrophotometry (NIRS) using a FT-NIR-TANGO equipment. The neutral detergent fiber (NDF; assayed with a heat-stable amylase and expressed exclusive of residual ash) and nitrogen content in NDF (N-NDF) were measured according to Silva and Queiroz (2009).

2.2. Non-starch polysaccharide content

The NSP content of the corn samples was determined following the method of Englyst et al. (1994). The amount of soluble NSP was obtained as a difference between total NSP and insoluble NSP. Results are expressed as grams of constituent sugars per 100 g as-fed basis. Each sample was analyzed in duplicate.

2.3. *In vitro* starch digestibility

The *in vitro* digestibility was analyzed following the Englyst procedure (Englyst et al., 1999) in whole and ground grains. During the analysis, aliquots were taken at 20- and 120-min intervals. The amount of glucose released was determined by HPLC. Each sample was analyzed in duplicate.

The value of rapid digestible starch (RDS, eq. 1) was obtained by difference between glucose released after 20 min (G20) and free glucose (FG) value. Slow digestible starch (SDS, eq. 2) was calculated by the difference between G20 and value of glucose released after 120 min (G120). The resistant starch value (RS, eq. 3) was obtained considering the difference between the total glucose (TG) and the G120 value. Available starch (AS) was calculated by adding the RDS and SDS values. The total starch (TS) was calculated by adding the RDS, SDS, and RS values. The SDS:AS and RS:TS ratios were also obtained. Values for starch fractions were expressed as monosaccharide equivalents (g/100 g monosaccharide equivalent) (Englyst et al., 1999). The following formulas were used:

$$RDS = G20 - FG \text{ (including glucose from sucrose)} \quad (1)$$

$$SDS = G20 - G120 \quad (2)$$

$$RS = TG - G120 \quad (3)$$

2.4. Metabolic assay

To determine the energetic values, a total of 168 11-day-old male Cobb 500® broiler chickens were allocated according to a completely randomized design in a 3 × 2 factorial arrangement (three corn hybrids and two drying temperatures [80 and 110 °C]), totaling six treatments, with seven replicates and four birds per experimental unit. The tested diets were formulated with the tested corn, vitamins, and minerals to meet the requirements of broilers from 11 to 21 d of age according to Rostagno et al. (2011; Table 1). From 1 to 10 d of age, birds received a standard diet formulated based on corn and soybean meal (Rostagno et al., 2011) and were raised in floor pens. On d 11, birds were transferred to battery cages (50 × 50 cm) equipped with movable trays for excreta collection, individual gutter feeders, and nipple drinker systems. The metabolic cages were allocated in a room with temperature control by using air conditioning following the strain's recommendations (24–28 °C). The lighting program consisted of continuous 23 h light and 1 h of darkness (30 lux light intensity) throughout the whole experimental period.

Table 1 - Composition of the diet used in the metabolic assay (11 to 21 days of age)

Ingredient					g/kg	
Corn[1]					955	
Limestone					11.80	
Dicalcium phosphate					17.00	
Salt					2.09	
Potassium chloride					7.73	
Sodium bicarbonate					4.00	
Vitamin premix[2]					1.50	
Mineral premix[3]					0.50	
Calculated composition (%)						
Calcium					0.819	
Available phosphorus					0.391	
Clorine					0.321	
Sodium					0.210	
Potassium					0.580	
Analyzed values[4]						
	Hybrid 1	Hybrid 1	Hybrid 2	Hybrid 2	Hybrid 3	Hybrid 3
	80 °C	110 °C	80 °C	110 °C	80 °C	110 °C
CP (%)	8.01	7.62	8.09	8.21	8.38	8.36
GE (kcal kg^{-1})	4158	4109	4130	4133	4070	4038

CP - crude protein; GE - gross energy.
[1] The tested diets were manufactured with the three corn hybrids dried at 80 or 110 °C.
[2] Vitamins provided per kg of feed: vitamin A, 20,000 IU; vitamin D3, 7500 IU; vitamin E, 50 mg; vitamin K3, 5.25 mg; vitamin B1, 4.5 mg; vitamin B2, 13.75 mg; vitamin B6, 6.25 mg; vitamin B12, 37.5 mg; pantothenic acid, 27.5 mg; niacina, 87.5 mg; folic acid, 2.25 mg; biotin, 0.16 mg; selenium, 0.75 mg.
[3] Minerals provided per kg of feed: copper, 20 mg; iron, 112.5 mg; manganese, 200 mg; iodine, 3 mg; zinc, 275 mg.
[4] Values expressed in dry matter.

Following five days of adaptation of birds to cages and diets, total excreta was collected for another five consecutive days. Excreta were collected twice daily (8:00 and 17:00 h), weighed, and stored in plastic bags at –20 °C during the experimental period. At the end of the experiment, feed intake and the amount of excreta produced in each cage were measured. Samples were then thawed, homogenized, and a sample from each replicate was taken for analysis. Samples were dried in a forced-ventilation oven for 72 h at 55 °C. They were then ground (0.5 mm), and DM, gross energy (GE), and nitrogen (N) in excreta and feed were measured according to Silva and Queiroz (2009). The apparent metabolizable energy (AME, eq. 4) and nitrogen-corrected metabolizable energy (AME_n, eq. 5) were calculated according to Matterson et al. (1965), as follows:

$$\text{AME of tested feed (MJ/kg DM)} = (\text{ingGE} - \text{excGE})/\text{ingDM} \quad (4)$$

$$\text{AME}_n \text{ of tested feed (MJ/kg DM)} = ((\text{ingGE} - \text{excGE}) - (8.22 \times \text{NB}))/\text{ingDM}, \quad (5)$$

in which ingGE = ingested GE, excGE = excreted GE, ingDM = ingested DM, and NB = nitrogen balance (N ingested – N excreted).

Following the determination of the energetic values, the apparent coefficients of metabolizable energy (ACME and $ACME_n$) were calculated.

2.5. Statistical analysis

The statistical model contained the main effects of hybrid and drying temperature and their interaction (eq. 6).

$$Y_{ijk} = \mu + A_i + B_j + AB_{ij} + e_{ijk}, \quad (6)$$

in which Y_{ijk} = record of each observation, μ = mean, A_i = hybrid effect, B_j = drying temperature effect, AB_{ij} = interaction effect of hybrid and drying temperature, and e_{ijk} = error effect.

The results obtained for AME, AME_n, ACME, and $ACME_n$ were subjected to a two-way ANOVA. Significant interactions were unfolded by the PROC GLM procedure of SAS® (Statistical Analysis System, University Edition) using F or Tukey's test.

3. Results

The chemical composition values of the different corn hybrids evaluated varied from 867 to 895, 75.3 to 82, 39.1 to 41.7, and 10 to 11.5 g/kg for DM, CP, EE, and MM, respectively (Table 2). Comparing both drying temperatures (80 and 110 °C), it was observed that the variation between hybrids was higher for all nutrients when using 110 °C. The corn grains dried at 110 °C showed higher DM than those dried at 80 °C. The CP and MM values of Hybrid 3 dried at 80 °C were higher than those of Hybrids 1 and 2, but EE was the highest for Hybrid 1 dried at 110 °C. The average percentage of starch of hybrids was similar when using 80 and 110 °C (64.3%; Table 2). Additionally, an increase of

Table 2 - Chemical composition (g/kg) of three corn hybrids dried at two different temperatures

Hybrid	Temperature	DM	CP	EE	MM	CF	Starch	Amylose	NDF	N-NDF
1	80 °C	867	77.70	39.80	11.20	19.80	639	237	114	1.30
2		873	78.30	40.60	10.00	20.70	648	228	117	1.00
3		870	82.00	40.00	11.50	19.50	640	220	113	1.30
1	110 °C	882	75.30	41.70	11.10	20.30	640	240	115	1.20
2		895	80.30	40.80	10.40	20.40	657	243	120	1.60
3		875	80.00	39.10	10.50	20.50	633	216	102	1.50

DM - dry matter; CP - crude protein; EE - ether extract; MM - mineral matter; CF - crude fiber; NDF - neutral detergent fiber; N-NDF - nitrogen in neutral detergent fiber.

2.15% was observed in the amylose content of grains dried at 110 °C. A similar result was obtained for CF and NDF, of which, among the evaluated nutrients, NDF showed the highest increase (14%) when comparing the values obtained for the three hybrids for each drying temperature. In addition, a drying temperature of 110 °C increased the N-NDF concentration (Table 2).

According to a more detailed analysis of sugars present in the corn hybrids, the average contents of soluble and insoluble NSP were of 0.72 and 6.27 g/100 g, respectively, for grains dried at 80 °C and 0.30 and 6.05 g/100 g, respectively, for grains dried at 110 °C. Overall, the total contents of soluble and insoluble NSP were reduced when using a drying temperature of 110 °C; the highest reduction was in soluble NSP (total reduction of 58.3%). The distribution of sugar content, regardless of the hybrid and drying temperature, was xylose > arabinose > glycose > galactose > mannose (Table 3).

Mean values of RDS, SDS, and TS were 13.3, 39.2, and 52.5 g/100 g, respectively. The grinding process increased the amount of TS (66.6 g/100 g) and RDS (26.1 g/100 g) but did not change the amount of SDS (40.5 g/100 g). Evaluating whole and ground grains separately, it was observed that the drying temperature did not change the stated nutrients. The drying temperature of 110 °C increased the RS content of whole corn by 8.4% to a mean value of 20.6 g/100 g. The same did not occur with ground corn, but the RS:TS ratio was reduced by 69.2% in the ground corn compared with the whole corn (28.2 g/100 g vs. 8.7 g/100 g; Table 4).

There was an interaction (P<0.05) between corn hybrid and drying temperature for AME and AME_n (Table 5). When evaluating the energy values within each drying temperature, there was no influence of hybrids on energetic values. However, evaluating the different drying temperatures within each hybrid, the AME and AME_n values were higher (P<0.05) for Hybrid 1 when using a drying temperature of 80 °C, providing 2% more energy (Table 6). Considering the main effects, birds fed diets formulated with Hybrid 3 had higher ACME and $ACME_n$ values, 83.10 and 81.98%, respectively (Table 5).

Table 3 - Constituent sugars of three corn hybrids dried at two different temperatures

Hybrid	Temp.		Constituent sugar (g/100 g)									Total	
			RHA	FUC	ARA	XYL	MAN	GAL	GLU	GLcA	GalA	g/100 g	SD
1	80 °C	Soluble NSP	0.10	UND	0.20	0.25	0.10	0.10	0.15	0.10	UND	0.90	±0.60
		Insoluble NSP	UND	UND	1.60	2.30	0.10	0.35	1.25	1.00	UND	6.50	±0.60
		Total NSP	0.10	UND	1.75	2.55	0.20	0.40	1.45	1.10	UND	7.40	±0.15
2	80 °C	Soluble NSP	UND	UND	0.10	0.10	0.10	0.05	0.25	UND	0.05	0.60	±0.20
		Insoluble NSP	UND	UND	1.60	2.25	0.05	0.60	1.95	UND	UND	6.40	±0.20
		Total NSP	UND	UND	1.70	2.35	0.15	0.60	2.15	UND	0.05	7.00	±0.15
3	80 °C	Soluble NSP	UND	UND	0.15	0.15	0.00	0.10	0.25	UND	UND	0.65	±0.55
		Insoluble NSP	UND	UND	1.45	2.00	0.10	0.50	1.85	UND	UND	5.90	±0.55
		Total NSP	UND	UND	1.60	2.20	0.10	0.60	2.10	UND	UND	6.55	±0.25
1	110 °C	Soluble NSP	UND	UND	0.05	0.10	0.00	0.00	0.10	UND	UND	0.35	±0.15
		Insoluble NSP	UND	UND	1.65	2.35	0.10	0.50	1.90	UND	UND	6.50	±0.15
		Total NSP	UND	UND	1.75	2.45	0.15	0.55	2.00	UND	UND	6.85	±0.35
2	110 °C	Soluble NSP	UND	UND	0.05	0.05	0.05	0.05	0.10	UND	0.05	0.35	±0.15
		Insoluble NSP	UND	UND	1.45	2.00	0.05	0.50	1.70	UND	UND	5.75	±0.15
		Total NSP	UND	UND	1.50	2.00	0.10	0.60	1.75	UND	0.05	6.10	±0.10
3	110 °C	Soluble NSP	UND	UND	0.05	0.05	0.00	0.00	0.10	UND	UND	0.20	±0.05
		Insoluble NSP	UND	UND	1.50	1.90	0.15	0.55	1.75	UND	UND	5.90	±0.05
		Total NSP	UND	UND	1.55	2.05	0.10	0.60	1.90	UND	UND	6.15	±0.25

NSP - non-starch polysaccharides; RHA - rhamnose; FCU - fucose; ARA - arabinose; XYL - xylose; MAN - mannose; GAL - galactose; GLU - glucose; GlcA - glucuronic acid; GalA - galacturonic acid; UND - undetected; SD - standard deviation.

Table 4 - Starch fractions of whole and ground grains of three corn hybrids dried at two different temperatures

Hybrid	Temperature	RDS	SDS	AS	RS	TS	SDS:AS	RS:TS
		Whole grain (g/100 g monosaccharide equivalent)						
1	80 °C	11.95	38.75	50.70	22.05	72.75	76.50	30.35
2		14.85	41.60	56.40	15.50	71.95	73.75	21.55
3		12.95	39.00	51.45	21.55	73.00	75.80	29.50
1	110 °C	10.90	37.10	48.00	24.55	72.55	77.40	33.85
2		13.80	40.95	54.75	20.55	75.30	74.90	27.30
3		15.15	37.75	52.95	19.30	72.25	71.45	26.75
		Ground grain (g/100 g monosaccharide equivalent)						
1	80 °C	24.20	41.35	65.55	7.25	72.75	63.10	9.95
2		25.15	40.35	65.50	6.45	71.95	61.65	8.95
3		27.00	40.65	67.65	5.35	73.00	60.10	7.30
1	110 °C	25.05	39.45	64.55	8.05	72.55	61.20	11.10
2		24.80	43.10	67.90	7.35	75.30	63.40	9.85
3		30.35	38.20	68.55	3.70	72.25	55.70	5.10

RDS - rapid digestible starch; SDS - slow digestible starch; AS - available starch (RDS + SDS); RS - resistant starch; TS - total starch (RDS + SDS + RS).

Table 5 - Dry matter, energy values, and metabolization coefficients of three corn hybrids dried at two different temperatures for broilers

	GE (MJ/kg)	DM (%)	AME (MJ/kg)	AME_n (MJ/kg)	ACME (%)	$ACME_n$ (%)
Hybrid						
1	17.30	88.86	13.96	13.78	80.71b	79.63b
2	17.29	89.64	14.02	13.83	81.06b	79.97b
3	16.97	88.65	14.10	13.91	83.10a	81.98a
Temperature (°C)						
80	17.24	88.54	14.06	13.87	81.58	80.46
110	17.13	89.56	13.99	13.80	81.67	80.58
SEM	0.005	0.150	0.034	0.033	2.170	2.140
P-value						
Hybrid			0.344	0.335	0.001	<0.001
Temperature			0.335	0.367	0.841	0.775
Hybrid × temperature			0.011	0.010	0.103	0.100

GE - gross energy; DM - dry matter; AME - apparent metabolizable energy; AMEn - apparent nitrogen-corrected metabolizable energy; ACME - apparent coefficient of metabolizable energy; $ACME_n$ - apparent nitrogen-corrected coefficient of metabolizable energy; SEM - standard error of the mean.
Values expressed in dry matter.
a-b - Means followed by distinct letters in the same column are different (P≤0.05) by Tukey's test.

Table 6 - Energy values determined with broilers fed diets containing three corn hybrids dried at two different temperatures

Hybrid	AME (MJ/kg)		P-value	AME_n (MJ/kg)		P-value
	80 °C	110 °C		80 °C	110 °C	
1	14.12a	13.81b	0.028	13.92a	13.63b	0.027
2	13.89	14.15	0.091	13.70	13.96	0.081
3	14.19	14.01	0.209	13.99	13.83	0.210
P-value	0.071	0.070		0.060	0.071	

AME - apparent metabolizable energy; AME_n - apparent nitrogen-corrected metabolizable energy
a-b - Means followed by distinct letters in the same row are different (P≤0.05) by F test.

4. Discussion

Even though the corn hybrids were cultivated under similar climatic, fertilization, and distancing conditions, differences regarding their chemical composition were found when compared with the Brazilian Tables of Feedstuffs Composition (Rostagno et al., 2017). The EE and CF values found herein were higher than those found in the tables, which may be related to the genetic variability and drying conditions (Masey O'Neill et al., 2012). The differences found in the chemical composition may influence the metabolizable energy values. For instance, Malumba et al. (2014) and Gehring et al. (2012; 2013) observed that corn grains exposed to different thermal treatments showed similar proximate composition, but with different nutrient use by animals.

The chemical structure of corn grain may change due to artificial drying, which can impact its nutritional value (Bhuiyan et al., 2010). In the present study, results suggest that the drying temperature of 110 °C influenced starch composition, with increased contents of amylose and RS. Starch is formed primarily by amylose and amylopectin, which can solubilize in water by heating to a temperature above the gelatinizing temperature (Wang et al., 2015). After cooling, amylose and amylopectin molecules dispersed in water are reassociated and may form crystals resistant to hydrolysis, giving rise to the retrograded starch (Rincón-Londoño et al., 2016). Starch with higher amylose content is more likely to present a higher retrogradation rate (Li et al., 2016).

The retrogradation of starch granules may occur when high drying temperatures that exceed the gelatinization temperature are used, due to a physical reorganization of starch granules. The resultant retrograded starch is less digestible (Gehring et al., 2013). Alterations to the structure of starch granules may impair their digestion in broiler chickens, leading to worse growth performance. Therefore, a high drying temperature (105 °C) for a longer period may favor the formation of RS and increase amylose and decrease amylopectin contents (Bhuiyan et al., 2012). Similarly, Iji et al. (2003) observed an increase in the RS content due to a drying temperature of 100 °C.

Even though corn is an ingredient of high digestibility for broiler chickens, the presence of RS may limit its energetic value, which may also be affected by the denaturation of proteins when using a drying temperature higher than 80 °C (Malumba et al., 2008). In the present study, the amylose content varied from 216 to 243 g/kg, this being higher in grains dried at 110 °C for Hybrids 1 and 2. Rincón-Londoño et al. (2016) observed that an increase in amylose leads to an increase in RS, which was also observed in this study for Hybrids 1 and 2 (increases in RS of 11 and 32%, respectively). For Hybrid 3, however, there was a reduction of 10% in the RS content when dried at 110 °C. Overall, the drying temperature did not change the values of RDS and SDS but increased the RS content.

Regarding the amount of starch present in the whole grain versus the ground corn, it was observed that the grinding process reduced the RS content and increased the availability of starch, favoring its fast digestibility. The RS determined in the present study comprised the five types of starch already described in the literature. Type 1 is the starch present in the cell wall of plants and is not accessible by the endogenous digestive enzymes (Zhao et al., 2018), but can have its accessibility increased by the grinding process (Yao et al., 2009). Therefore, the reduction in the total RS content due to the grinding process may be related to a reduction in type 1 RS. It is necessary to emphasize, however, that even with the reduction in total RS, ground corn dried at 110 °C showed an increase in RS, which may have been of type 3. According to Adebowale et al. (2019), heat and moisture during diet processing may reduce RS of type 1 (encapsulated, physically inaccessible) and type 2 (granular residues) but favors the formation of type 3 (retrograded). In addition, Huart et al. (2018) observed that the drying process of corn grains at 130 °C negatively impacts the particle size of flour recovered after standard milling procedures, which can directly affect the digestibility of nutrients by animals and, consequently, their growth performance.

The reductions in energetic values (AME and AME_n) for Hybrid 1 dried at 110 °C may be due to changes in the starch structure. When ground, this hybrid showed the highest ratio (11.10) between the components of resistant and total starch for the temperature of 110 °C, which may be related to an increase in retrograded starch and, consequently, lower digestibility values. Zhu and Liu et al. (2020) evaluating the *in vitro* enzyme susceptibility of retrograded starch observed that the increase in retrograded starch decreased the enzyme hydrolysis extent. Córdova-Noboa et al. (2020) observed that a high drying temperature (120 °C) depressed ileal starch digestibility especially in young broilers, but the authors emphasize the need to consider the interactions among the drying temperature, particle size, and exogenous enzyme supplementation. Additionally, for Hybrids 2 and 3, the N-content bound to NDF increased at the drying temperature of 110 °C. Converting it to CP equivalent (N × 6.25), an increase of 35% in the protein associated to NDF was observed. This phenomenon can also have an effect on digestibility, due to the reduced dissociation, solubilization, and absorption of these associated carbohydrates (Bringel et al., 2011).

According to Mateos et al. (2012) the dietary fiber content, as well as its composition, has a great influence on metabolizable energy. The NSP content present in certain grains has, in the gastrointestinal tract, negative effects on the energetic value of the diet, such as a reduction in the accessibility of endogenous enzymes and increased viscosity of the intestinal content, which impairs the digestion, absorption of nutrients, and passage rate (Cowieson, 2010).

The solubility of NSP is an important physicochemical characteristic of the nutritional properties of ingredients. It refers to their solubility in water and is determined by the physical characteristics of polysaccharides, such as molecular weight, distribution, and structure. Most NSP present in feed ingredients are insoluble and, therefore, do not show a high degree of viscosity. Soluble NSP, such as arabinoxylans and β-glucans, have great potential to absorb water and form a viscous gel in the intestine, which impairs digestion and absorption of nutrients (Lasek et al., 2012; Choct, 2015).

The use of a drying temperature of 110 °C in the present study reduced the concentration of soluble NSP. Contrasting results have been reported by Bhuiyan et al. (2010), wherein an increase in the drying temperature from 80 to 100 °C increased the soluble and reduced the insoluble NSP concentrations. Annison (1991) observed a negative correlation between the presence of soluble NSP and the energetic values of wheat for broiler chickens. Nevertheless, it is important to consider that the reduction in the soluble fraction of NSP in the present study did not change the energetic values of corn.

Besides the degradation of NSP substances during the process of water removal by artificial drying, the conformation of polymer chains, as well as their amorphous and crystalline structures, may be changed. These modifications may reduce the availability of OH groups that would be bound to water molecules, altering the functional properties and solubility of carbohydrate molecules (Garau et al., 2007; Ahmadi et al., 2019). Kaczmarek et al. (2007) observed an impact on the performance of birds when corn was dried at high temperatures, suggesting that the structural changes that occur due to temperature may impair growth performance and reduce nutrient use. In the present study, Hybrid 3 presented the highest values of energy coefficients (ACME and $ACME_n$), regardless of the drying temperature, indicating better nutrient utilization. These results may be correlated with the fact that Hybrid 3 had the lowest amylose and RS contents and, consequently, the lowest RS:TS ratio and a higher proportion of RDS. For Hybrid 2, although presenting structural modifications due to the higher drying temperature, its digestibility measurements were not changed.

5. Conclusions

The drying temperature leads to variations in the chemical composition of corn grains. The use of 110°C as drying temperature increases the amylose and RS contents, reduces the soluble:total NSP ratio, and increases the N bound to the fiber. These changes may be responsible for the differences in nutrient digestibility. The mean AME and AME_n values of corn dried at 80 and 110 °C were 14.03 and 13.84 MJ/kg, respectively, and 81.62 and 80.53% for para ACME and $ACME_n$, respectively.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization: C. Eyng, R.V. Nunes, L.V. Teixeira and C. Bortoluzzi. Formal analysis: F.C.N. Giacobbo, C. Souza and C. Polese. Investigation: F.C.N. Giacobbo. Methodology: C. Eyng. Supervision: C. Eyng and R.V. Nunes. Writing-original draft: F.C.N. Giacobbo. Writing-review & editing: L.V. Teixeira and C. Bortoluzzi.

Acknowledgments

This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq – Brasília, DF, Brazil), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES – Brasília, DF, Brazil), and DSM Nutritional Products (São Paulo, SP, Brazil).

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