

Thermal processing of corn and physical form of broiler diets

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ABSTRACT This study aimed to assess the effect of preprocessing of corn and of physical form of diets on growth performance, carcass yield, and nutrient digestibility in broilers and also the influence of corn processing on pellet quality. A total of 1,080 male Cobb chicks from 1 to 35 D were evaluated. Birds were distributed according to a completely randomized design in a 3 × 2 factorial arrangement, with 3 types of corn processing (unprocessed, pelleted, or expanded), and 2 diet physical forms (mash or pelleted), totaling 6 treatments and 9 replicates with 20 birds. The data were submitted to ANOVA, and means were compared by Tukey's test ($P < 0.05$). There was no interaction between the physical form and preprocessing of corn for any of the studied variables ($P > 0.05$). The use of expanded corn in the diets before pelleting resulted in higher pellet durability index and lower amount of fines ($P < 0.05$) when compared with unprocessed corn. Broilers fed

pelleted diets had higher feed intake (**FI**) and weight gain (**WG**; $P < 0.001$), higher amounts of abdominal fat ($P < 0.05$), and lower ileal digestible energy (**IDE**, $P = 0.05$) than those fed mash. There was no effect of the feed form on nutrient digestibility ($P > 0.05$). Broilers fed diets with unprocessed corn had higher FI when compared to those fed diets with expanded or pelleted corn ($P < 0.001$). The use of pelleted corn resulted in lower WG than the other processing methods ($P < 0.01$). The corn expansion process improved feed conversion ratio and adjusted feed conversion ratio ($P < 0.001$). Inclusion of expanded corn improved the coefficient of apparent ileal digestibility of DM, CP, starch, and IDE ($P < 0.05$) in comparison with unprocessed corn. It is concluded that pelleted diets improve broiler performance. The corn expansion can be used to improve physical quality of the diets and broilers growth performance and nutrient digestibility.

Key words: digestibility, expansion, pelleting, performance, starch gelatinization

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INTRODUCTION

Pelleting is the most common form of thermal processing used in broiler feed manufacturing, aggregating the particles of ingredients into a cylinder by means of mechanical pressure, moisture, and temperature. A wide range of temperature and moisture can be used during conditioning, usually from 60°C to 100°C and 12 to 18% moisture (Hancock, 1992).

Increase in feed intake (**FI**) is among the main reasons that motivate agroindustries to pellet feeds (Bolton, 1960; Calet, 1965; Meinerz et al., 2001; Svihus et al., 2004), as apprehension of the ingredient particles as

pellets becomes easier (Jensen et al., 1962). There is also an increase in the effective caloric value as birds rest more frequently (McKinney and Teeter, 2004) and higher nutrient digestibility (Moran, 1987; Behnke, 1994; Zelenka, 2003). However, several studies have shown that the conditioning/pelleting process has little effect on starch gelatinization (Skoch et al., 1981; Svihus et al., 2004; Zimonja et al., 2008) and on protein modification (Abdollahi et al., 2011; Roza et al., 2018). More intensive processes, like expansion, can be better able to provide modifications in the ingredients structures and improve nutrient digestibility (Lopez et al., 2007), as well as improve the pellet quality (Muramatsu et al., 2015, 2016).

Feed expansion is a high temperature and short time process that is used mainly before pelleting to boost the conditioning process. The high temperature and short time process is created to transfer the mechanical energy to thermal energy, and thus high temperatures can be reached above 120°C and pressure higher than 1200 PSI (Fancher et al., 1996). Whatever the process type

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that is used, if very intensive with excessively high temperatures for example, resistant starch (**RS**) can be formed interfering with its digestion, Maillard reaction and destruction of thermolabile vitamins and amino acids may also occur (Silversides and Bedford, 1999; Abdollahi et al., 2010). Thus, an alternative to improve the nutrient bioavailability and to reduce the negative effects of thermal processing would be the preprocessing of major feed ingredients such as corn, for example.

Given the above facts, this study has the objective of comparing the interaction between the corn preprocessing (unprocessed, pelleted, or expanded) and the physical form of the diet (mash or pelleted) on growth performance, carcass yield, and nutrient digestibility in broilers and also the influence of corn processing on pellet quality.

MATERIAL AND METHODS

All experimental procedures complied with Ethics Committee on the Use of Animals of the Federal University of Paraná.

Animals and Facilities

A total of 1,080-day-old male broilers (Cobb 500) obtained from a commercial hatchery were used from 1 to 35 D. The birds were housed in floor pens (1.25 by 1.65 m), with wood shavings litter, nipple drinkers, and trough feeders.

Feed and water were provided *ad libitum* during the entire experimental period. Temperature was maintained according to the management guide (COBB, 2013). Incandescent light was continuously (24 h) provided during the first 10 D, after which a lighting program of 9 h of dark was used.

Experimental Diets Composition and Manufacturing

The birds were fed corn–soybean meal–based diets formulated to supply their nutritional requirements according to Rostagno et al. (2011); Table 1. The diets had different corn processing methods (unprocessed, pelleted, or expanded) and different physical forms (mash or pelleted). The corn was processed in a Van Aarsen pellet mill (model C-900 Standard Pellet Mill, Van Aarsen International B.V., Panheel, the Netherlands), with 55 mm circular die with 4.5 mm holes. Conditioning was performed at an 84°C temperature and 1.2 kgf/cm² pressure during 13 s. The corn expansion process was performed in a Kahl Expander (model OE38.2, Amandus Kahl GmbH & Co. KG, Reinbek, Germany) at a 105°C average temperature, 3.5% of steam addition, and 96 kgf/cm² pressure during 4 s. At the end of the process, both the pelleted and the expanded corn were dried/cooled to 32°C and ground in a hammer mill with a 6 mm-sieve to reach sizes similar to that of unprocessed corn. The mash diets with unprocessed, pelleted, and expanded corn had geometric mean diameter of 1,180, 962, and 960 µm, respectively.

Table 1. Calculated composition (% diet) of experimental diets.

Ingredients	Starter (1–21D)	Grower (22–35D)
Corn ¹	55.890	55.988
Soybean meal	37.080	33.993
Soybean oil	2.765	6.240
Celite ²	-	1.000
Dicalcium phosphate	1.751	0.981
Limestone	0.851	0.841
Salt (NaCl)	0.480	0.431
Mineral premix ³	0.050	0.050
Vitamin premix ⁴	0.120	0.050
L-lysine	0.252	0.270
DL- methionine	0.322	0.175
L-threonine	0.129	0.150
Choline chloride	0.100	-
Antioxidant ⁵	0.010	0.010
Mycotoxin adsorbent ⁶	0.200	0.200
Calculated chemical composition		Amounts (%)
Metabolizable energy (kcal/kg)	2,980	3,200
Crude protein	21.122	19.365
Ether extract	5.408	8.799
Ash	5.902	4.908
Calcium	0.850	0.650
Total phosphorus	0.704	0.542
Available phosphorus	0.450	0.300
Sodium	0.200	0.180
Digestible lysine	1.200	0.950
Digestible methionine	0.587	0.426
Digestible methionine + cysteine	0.900	0.720
Digestible threonine	0.800	0.650
Digestible tryptophan	0.203	0.213

¹Geometric mean diameter (GMD) of unprocessed, pelleted and expanded corn was 1,084, 635, and 632 µm respectively.

²Celite 400, Insoluble marker (Celite, Celite Corp., Lompoc, FC).

³Supplied per kilogram of diet: Cu (copper sulfate), 10 mg; Fe (iron sulfate), 50 mg; Mn (manganese oxide), 80 mg; Co (cobalt sulfate), 1.0 mg; I (calcium iodate), 1.0 mg; Zn (zinc oxide), 50 mg.

⁴Supplied per kilogram of diet: vitamin A (trans-retinyl acetate), 10,800 IU; vitamin D3 (cholecalciferol), 3,000 IU; vitamin E (DL- α -tocopherol), 240 IU; vitamin K3 (menadione nicotinamide bisulphite), 3.0 mg; vitamin B1 (thiamine-mono-nitrate), 1.8 mg; vitamin B2 (riboflavin) 7.2 mg; vitamin B6 (pyridoxine. HCl) 3.6 mg; vitamin B12 (cyanocobalamin) 14.4 mcg; pantothenic acid (D-Ca pantothenate), 14.4 mg; niacin (nicotinic acid), 30 mg; folic acid, 0.96 mg; biotin, 0.07 mg; selenium (sodium selenite), 0.30 mg.

⁵Butylated hydroxytoluene (B.H.T. 98, Cargill, Inc.).

⁶Calibrin (Elanco, Greenfield).

The pelleted diets were manufactured in a pellet mill (Koppers Junior C40—Koppers Company, Inc. Pittsburgh, PA), with a 50 hp Siemens motor and a pellet die with 4.7 mm diameter holes. Diets were conditioned for 10 s at 75°C and under a 1.5 kgf/cm² pressure. After pelleting, the diets were dried and cooled to an average temperature of 37°C. The pelleted diets fed in the starter phase were processed in a roller mill with a 2.0 mm gap between the rolls.

Pellet Quality

The pellet durability index (**PDI**) or the percentage of unbroken pellets was assessed using a PDI determination device, which consisted of 5 rotating boxes (30 cm in height; 12.5 × 12.5-cm base). Approximately eight 150 g of the pellets retained in a sieve (4.0-mm sieve, Telastem Peneiras para Análises LTDA) was tested in the boxes that composed the PDI determination device at 50 rotations per minute for 10 min. Next, the samples

were sieved (4.0-mm sieve) for approximately 30 s to remove the fines and the broken pellets. The PDI was expressed as a percentage. Hardness was measured in a hardness tester (Nova Ética, model 298 DGP—Ethiktechnology, São Paulo, Brazil) using individual pellets (20 pellets per treatment).

Growth Performance and Carcass Yield

All birds in the pens and feed remaining in the feeders were weighed every week to determine FI, weight gain (**WG**), feed conversion ratio (**FCR**) and feed conversion ratio adjusted to 2,300 g live weight (**AdjFCR**). Mortality was checked daily. AdjFCR was calculated according to the following equation:

$$\text{AdjFCR} = \left(\frac{(2300 \text{ g} - \text{AW}_{35})}{(3.200)} \right) + \text{FCR}_{35}$$

Where (2,300) is the expected average weight (g) at 35 D (**COBB**, 2013), (**AW**₃₅) is the average weight obtained at 35 D, (3.200) is a factor (corresponding to 3.2 g to change 1 point in feed conversion), and **FCR**₃₅ is the feed conversion ratio observed at 35 D.

On the 35th D, one bird per experimental unit was euthanized to measure the yield of carcass and cuts. After removal of feathers, head, feet and viscera, carcasses were washed and cooled at 2°C for 60 min. The carcass and cuts (breast, thigh + drumstick and fat) were weighed to determine yield, calculated in relation to the carcass weight.

Digestibility

On the 35th D, one bird per experimental unit (a total of 54 birds) was euthanized by cervical dislocation and the ileal content collected for the digestibility analyses. The birds were eviscerated and a portion of the ileum separated to remove the ileal content. The ileal fraction was defined as being 4 cm below Meckel's diverticulum and 4 cm above the ileum-cesum-colon junction. Ileal content was homogenized, frozen, and freeze-dried (Freeze dryer Modulyo D, Thermo Electron Corporation, Waltham, MA), until 5×10^{-2} mbar vacuum pressure was reached.

Feed and ileal content samples were ground to 1 mm to determine the DM content after drying at 105°C during 12 h in a muffle and CP (954.01 method), according to Association of Official Analytical Chemists (**AOAC** (1995)). Available starch, resistant starch (**RS**), and total starch (**TS**) amounts were determined using the AOAC 996.11 method (Table 2), adapted by Walter et al. (2005).

The gross energy (**GE**) content was determined in a calorimetric bomb (Ika Werke C2000 Control Oxygen Bomb Calorimeter—Ika-Werke GmbH&Co, Staufen, Germany). Acid insoluble ash was used as an indigestible marker in the digestibility calculations and determined

according to the method described by Van Keulen and Young (1977).

Coefficient of apparent ileal digestibility (**CAID**) of nutrients was calculated using the following formula:

$$\text{CAID of diet nutrient} = \frac{[(\text{Nutrient in the diet}) - (\text{Nutrient in the ileal digesta} \times \text{IF})]}{\text{Component in the diet}}$$

where the indigestible factor (**IF**) is the ratio between acid insoluble ash levels in the diet and in the ileal content.

The ileal digestible energy (**IDE**) was calculated according to the following formula:

$$\begin{aligned} \text{IDE (kcal/kg DM)} \\ = \text{GE in the diet} - (\text{GE in the ileal content} \times \text{IF}) \end{aligned}$$

Statistical Analysis

A completely randomized design in a 3×2 factorial arrangement was used, with 3 corn processing types (unprocessed, expanded, or pelleted) and 2 physical forms (mash or pelleted) with 9 replicates, 20 birds in each. The data were first tested for normality (Shapiro-Wilk test) and then submitted to ANOVA using the GLM procedure of the SAS statistical software (version 9.0, SAS, Cary, NC). Means were compared by Tukey's test ($P < 0.05$).

RESULTS

Pellet Quality

The use of expanded corn resulted in higher PDI and smaller amounts of fines when compared with unprocessed corn ($P < 0.05$, Table 3). Corn pelleting provided an intermediate physical quality between unprocessed and expanded corn ($P < 0.05$). Corn preprocessing had no effect on pellet hardness ($P > 0.05$).

Performance Parameters

There was no interaction between the diet physical form and corn preprocessing in any of the performance parameters studied ($P > 0.05$, Table 4). The use of pelleted diets resulted in higher FI and WG ($P < 0.001$) in comparison with the mash diets. There was no effect of the diets physical form on FCR ($P > 0.05$). Broilers fed diets with unprocessed corn had higher FI than those fed diets with pelleted or expanded corn ($P < 0.001$). The WG was lower when pelleted corn was used ($P < 0.01$). The corn expansion improved FCR and AdjFCR ($P < 0.001$).

Carcass Yield

There was no interaction between the evaluated factors on any of the carcass parameters ($P < 0.05$; Table 5). Carcass, breast, thigh, and drumstick yields were not affected by the physical form of the diet

Table 2. Dry matter, available, resistant, and total starch content (%) in the experimental diets.

Physical form	Corn processing	Dry matter	Available starch	Resistant starch	Total starch
Mash	Unprocessed	87.83	44.54	5.70	50.24
Pelleted	Unprocessed	87.18	44.98	5.55	50.53
Mash	Pelleted	87.82	45.79	6.15	51.93
Pelleted	Pelleted	87.00	45.26	5.67	50.94
Mash	Expanded	88.30	47.17	6.02	53.18
Pelleted	Expanded	87.59	48.25	6.54	54.79

($P < 0.05$). However, the pelleted diets resulted in higher amounts of abdominal fat than the mash diets ($P < 0.05$). Broilers fed diets with expanded corn had higher carcass yield than those fed pelleted corn and similar to those fed unprocessed corn ($P < 0.05$).

Digestibility Parameters

There was no interaction between the diets physical form and corn processing in any of the digestibility parameters that were evaluated ($P < 0.05$; Table 6). The physical form of the diet had no effect on nutrient digestibility ($P < 0.05$). Broilers fed pelleted diets had lower IDE ($P = 0.05$) in comparison with those fed mash diets. When expanded corn was added to the diet, CAID of all digestibility parameters was improved ($P < 0.05$) when compared with unprocessed corn, whereas pelleted corn had intermediate digestibility coefficients.

DISCUSSION

The corn expansion process improved PDI and decreased the amount of fines in relation to unprocessed corn. This improvement can be related to the higher starch gelatinization and proteins plastification obtained with expansion, as the heat transfer to the mass and shear force in this process are both higher. Evaluating different corn processing procedures, Moritz et al. (2005) reported that pelleting and extrusion resulted in different starch gelatinization values, 290 and 920 g/kg, respectively. According to Behnke (1994), starch gelatinization is important to form bonds between the particles which are needed to produce durable pellets. According to this author, starch gelatinization combined with proteins plastification promotes the adhesion of particles. Lund and Lorenz (1984) reported that when the gelatinized starch is cooled, the granule matrix that is dispersed forms a gel that can act as an adhesive or ligand. Evaluating the interaction of different factors

(thermal processing, particle size, added fat and moisture) in broiler diets and their effect on PDI, Muramatsu et al. (2015) found that 44% is attributed to thermal processing (conditioning only or with expansion). In a previous publication, Muramatsu et al. (2013) reported that the combination of expansion and conditioning-pelleting improved PDI by 69% and reduced the amount of fines by 200 g/kg when compared to conditioning only.

The pelleting benefits are widely reported in the literature (Latshaw and Moritz, 2009; Dozier et al., 2010; Abdollahi et al., 2013; Mingbin et al., 2015; Massuquetto et al., 2018) and the results obtained in the present study confirm these benefits. Broilers fed pelleted diets had a better performance because of the increase in FI (Latshaw, 2008), as a result of better feed apprehension and reduction of time needed to eat (Jensen et al., 1962; Moran, 1989). Considering only the physical form effect, birds fed pelleted diets had an increase in FI around 7% in comparison with those fed mash diets. Feeding diets with good physical quality resulted in an increase around 160 g in WG. A higher WG is the result of a higher nutrient intake associated with less energy spent in the feed apprehension and consumption (McKinney and Teeter, 2004).

In the evaluation of corn processing effects, FI was higher when unprocessed corn was used. This can be partially because of the larger geometric mean diameter of unprocessed corn (1,084 μm) when compared to that of pelleted and expanded corn, 635 and 632 μm , respectively. Moritz et al. (2005) also found differences in the particle size of corn (unprocessed, pelleted or extruded) even after grinding it in the same hammer mill and using the same sieve, as in the present study. Considering that corn is the main cereal ingredient in the feed, providing corn with larger particles can favor FI as birds show a preference for larger particles (Nir et al., 1994; Dahlke et al., 2001). When WG results are analyzed, however, birds fed diets with unprocessed or expanded corn

Table 3. Parameters of physical quality of pelleted diets with different corn processing types.

Treatment	Starter (1–21d)			Grower (22–35D)		
	Fines (%)	PDI ¹ (%)	Hardness ² (kgf)	Fines (%)	PDI (%)	Hardness (kgf)
Unprocessed corn	9.17 ^a	82.80 ^b	5.004	14.60 ^a	71.00 ^b	2.992
Pelleted corn	6.64 ^b	86.00 ^{a,b}	4.902	13.74 ^a	73.80 ^{a,b}	2.602
Expanded corn	5.49 ^b	87.10 ^a	5.536	10.46 ^b	77.30 ^a	2.756
SEM	0.451	0.736	0.122	0.537	0.861	0.083
Probability	<0.01	0.031	0.065	<0.001	<0.01	0.155

^{a-b}Different letters in the same column are significantly different by Tukey's test ($P < 0.05$).

¹PDI = pellet durability index (Each value represents the mean of 8 replicates).

²Each value represents the mean of 20 replicates.

Table 4. Performance of broilers from 1 to 35 D fed with mash or pelleted diets with unprocessed, pelleted, or expanded corn.

Physical form	Corn processing	FI ¹ (g)	WG ² (g)	FCR ³ (g/g)	AdjFCR ⁴ (g/g)
Mash	Unprocessed	2,893	2,045	1.415	1.481
	Pelleted	2,824	1,973	1.431	1.430
	Expanded	2,788	2,013	1.385	1.526
Pelleted	Unprocessed	3,133	2,220	1.412	1.482
	Pelleted	3,014	2,110	1.429	1.466
	Expanded	2,968	2,178	1.363	1.388
SEM		0.020	0.015	0.004	0.007
Means (main effect)					
Physical form					
Mash		2,835	2,010	1.410	1.491
Pelleted		3,038	2,169	1.401	1.433
Corn processing					
Unprocessed		3,013 ^a	2,132 ^a	1.413 ^b	1.455 ^b
Pelleted		2,919 ^b	2,042 ^b	1.429 ^b	1.504 ^c
Expanded		2,877 ^b	2,095 ^a	1.374 ^a	1.427 ^a
Probability					
Physical form		<0.001	<0.001	0.108	<0.001
Corn processing		<0.001	<0.001	<0.001	<0.001
Physical form * corn processing		0.455	0.616	0.276	0.305

^{a-c}Different letters in the same column are significantly different by Tukey's test ($P < 0.05$).

¹FI = Feed intake.

²WG = Weight gain.

³FCR = Feed conversion ratio.

⁴AdjFCR = feed conversion ratio adjusted to 2,300 g live weight.

showed similar results. The FCR was better when expanded corn was used. The results are similar to those obtained by Lopez et al. (2007). When these authors evaluated various diet processing types, they found that the broilers body weight increased as the processing was intensified, reaching 2,597, 2,828 and 2,874 g when unprocessed, pelleted and expanded/pelleted feeds were used, respectively and FCR was also improved. Fleischmann (2012) reported WG increase and FCR improvement in broilers fed expanded diets in relation to mash feed, independently of the expansion temperature that was used (95°C, 105°C or 115°C). On the other

hand, Sloan et al. (1971) found no difference in the daily WG or FCR when they added 50 or 100% of expanded/extruded corn to the broiler diets. Corn expansion improved the analyzed nutrient digestibility, with higher WG and better FCR, than with corn that did not undergo thermal processing.

Corn pelleting reduced WG but there was no difference in FCR in comparison with unprocessed corn. This response can be because of a reduction in FI caused by the smaller particle size of pelleted corn after regrinding. As the pelleting process is less intensive than expansion in modifying corn fractions, FI

Table 5. Yield of carcass and cuts and amount of abdominal fat (%) of broilers at 35 D fed mash or pelleted diets with unprocessed, pelleted, or expanded corn.

Physical form	Corn processing	Carcass	Breast	Thigh + Drumstick	Fat
Mash	Unprocessed	80.32	38.20	27.41	1.49
	Pelleted	79.61	36.61	28.20	1.43
	Expanded	80.26	37.24	27.38	1.51
Pelleted	Unprocessed	79.58	37.20	27.65	1.61
	Pelleted	79.15	36.79	27.42	1.74
	Expanded	80.46	37.15	27.28	1.63
SEM		0.141	0.175	0.140	0.040
Means (main effect)					
Physical form					
Mash		80.06	37.35	27.67	1.48
Pelleted		79.73	37.05	27.45	1.66
Corn processing					
Unprocessed		79.95 ^{a,b}	37.70	27.53	1.55
Pelleted		79.38 ^b	36.70	27.81	1.59
Expanded		80.36 ^a	37.19	27.33	1.57
Probability					
Physical form		0.225	0.379	0.439	0.024
Corn processing		0.015	0.059	0.372	0.931
Physical form * corn processing	0.378	0.333	0.309	0.543	

^{a-b}Different letters in the same column are significantly different by Tukey's test ($P < 0.05$).

Table 6. Coefficient of apparent ileal digestibility (CAID) of dry matter (DM), crude protein (CP), available starch (AS), resistant starch (RS), total starch (TS), and ileal digestible energy (IDE; kcal/kg) in broilers at 35 D fed mash or pelleted diets with unprocessed, pelleted, or expanded corn.

Physical form	Corn	CAID (%)					IDE
		DM	CP	As	RS	TS	
Mash	Unprocessed	74.42	84.51	90.50	79.44	89.25	3,896
	Pelleted	76.12	83.88	91.85	81.31	90.38	3,970
	Expanded	76.90	84.93	92.93	81.75	91.07	4,048
Pelleted	Unprocessed	73.58	82.49	90.71	79.58	89.45	3,836
	Pelleted	76.23	83.31	91.51	82.38	90.82	3,923
	Expanded	76.12	85.44	92.59	84.26	91.99	4,036
SEM		0.269	0.266	0.298	0.513	0.334	14.211
Means (main effect)							
Physical form							
	Mash	75.82	84.44	91.74	80.83	90.23	3,971
	Pelleted	75.31	83.74	91.60	82.07	90.76	3,932
Corn processing							
	Unprocessed	74.00 ^b	83.50 ^b	90.60 ^b	79.51 ^b	89.35 ^b	3,866 ^c
	Pelleted	76.18 ^a	83.60 ^b	91.68 ^{a,b}	81.84 ^{a,b}	90.60 ^{a,b}	3,947 ^b
	Expanded	76.51 ^a	85.18 ^a	92.72 ^a	83.01 ^a	91.53 ^a	4,042 ^a
Probability							
	Physical form	0.260	0.149	0.816	0.206	0.427	0.050
	Corn processing	<0.001	<0.01	0.018	0.023	0.039	<0.001
	Physical form*corn process	0.619	0.103	0.922	0.607	0.899	0.576

^{a-b}Different letters in the same column are significantly different by Tukey's test ($P < 0.05$).

reduction may have interfered in the WG. These results are the opposite of those obtained by [Allred et al. \(1957\)](#), as these authors reported improved WG and FCR in broilers fed mash diets with pelleted and reground corn. However, the authors reported that the pelleted corn was ground to obtain particle sizes similar to that of the mash diet, and this may have favored the broilers performance.

Carcass, breast, and thigh and drumstick yields were not affected by physical form of the diet. The results are similar to those obtained by [Mingbin et al., \(2015\)](#), and they state that the physical form of the diet has significant effects on the yield of broilers carcass and cuts. However, broilers fed pelleted diets had 12% more abdominal fat. Several authors also reported a higher percentage of abdominal fat in broilers that consumed pelleted diets ([Plavnik et al., 1997](#); [Maiorka et al., 2005](#); [Corzo et al., 2011](#)). The higher FI provided by pelleting results in higher nutrient intakes and the excessive energy produced by digestion was deposited as fat tissue.

Although there was no difference in the composition of the different treatments, there was a higher amount of available starch, RS, and TS in the diets with expanded corn in comparison to pelleted and mash corn ([Table 2](#)). [Zhu et al. \(2016\)](#) evaluated different starch quantification methodologies (the AOAC International method 996.11 vs. the modified glucoamylase method) in mash (cold and hot) and pelleted (cold and hot) swine feed and observed that the AOAC International method resulted in lower TS in cold mash than cooled pelleted feed, whereas the modified glucoamylase method showed no significant differences in TS content before or after pelleting. Perhaps the differences obtained in the starch

fractions measured in the present study are a result of the variation in the methodology. Furthermore, the authors state that increasing the heating and mechanical pressing may disrupt starch granule integrity and reduce starch degree of crystallinity and thus increase the susceptibility to amylase leading to higher TS values in thermal processed feed. However, high temperatures may result in the formation of resistant starch ([Abdollahi et al., 2010](#)). Therefore, the largest amount of RS and TS may have been because of the higher intensity of the corn expansion process.

Efficiency of the pelleting process may have been lower in the modification of starch and protein structures, as there was no difference in any of the digestibility parameters. Some studies have shown that pelleting has little effect on nutrients availability, but more intensive processing as expansion and extrusion, with more moisture being added and higher temperatures in a short period of time, lead to larger modifications in the ingredients structures ([Skoch et al., 1981](#); [Svihus et al., 2004, 2005](#); [Zimonja et al., 2008](#)).

It is important to point out that, besides the conditioning effect provided by pelleting, the physical form has also an effect on digestibility. IDE is marginally reduced by pelleting, possibly because of factors related to increase in FI. [Svihus \(2006\)](#) showed a negative correlation between FI and the apparent metabolizable energy (AME). Thus, the increase in digestibility provided by pelleting and reported in the literature may be related to the diet physical quality. The positive effect on digestibility can be found in birds fed diets with poor physical quality. When pelleting is used to achieve high physical quality, the increase in FI can mask the thermal processing effect, which possibly occurred in the present study.

There was an increase in the digestibility of starch (total, available, and resistant) in expanded corn in comparison with unprocessed or pelleted corn. This improvement can be attributed to the starch gelatinization process, which provides higher enzyme access to glycosidic bonds and, as a consequence, higher digestibility (Moran, 1989). Kokić et al., (2013) evaluated different corn processing types and found lower starch gelatinization degrees in flocculation (213 g/kg) and pelleting (255 g/kg), whereas more intensive processing methods such as micronization and extrusion resulted in higher gelatinization degrees, 636 g/kg and 1,000 g/kg respectively. Similarly, Muramatsu et al., (2014) found an increase from 320 to 350 g/kg in starch gelatinization in pelleted or expanded/pelleted broiler diets, respectively. Zimonja et al. (2008) also reported a higher starch digestibility in broilers fed expanded diets than with pelleted diets.

The starch fraction that passes through the small intestine without being digested is known as resistant starch (Englyst et al., 1992), and it can also be formed by recrystallization of solubilized amylose (Voragen et al., 1995). Resistant starch can be classified as physically inaccessible starch (type 1), granular resistant starch (type 2) and retrograded starch (type 3) (Englyst et al., 1992). Type 3 can be produced by thermal treatment of ingredients, when starch is cooled after gelatinization. In the present study, it is thought that thermal processing may have solubilized resistant starch types 1 and 2, which was reflected by resistant starch having a higher CAID in the diets with expanded corn in relation to unprocessed or pelleted.

Thermal processing can rupture the disulfide bridges in the protein structures causing denaturation and facilitating the action of enzymes (Scott et al., 1997), which can explain the higher protein CAID found in the present study. Protein and amino acids digestibility can be reduced depending on the intensity of processing, with high temperature and conditioning time. Williams et al. (1997) found lower protein, methionine and lysine digestibility in broilers fed pelleted or expanded diet in comparison to mash feed.

The higher IDE value may result from the higher digestibility of pelleted and expanded corn fractions (in relation to unprocessed corn). Moritz et al. (2005) evaluated different levels of pelleted or extruded corn in complete diets (one third, two thirds, and three thirds) and found that the diets AMEn was increased, whereas the pelleted or extruded corn inclusion was increased. Similarly, Lopez et al. (2007) evaluated diets that underwent pelleting at 60°C during 18 to 20 s in the conditioner, and diets that were expanded/pelleted at 110°C during 15 to 20 s in the expander. The mash, conditioned/pelleted and conditioned/expanded/pelleted feeds AME were 12.64, 12.69 and 12.81 MJ/kg, respectively.

The results obtained indicate that pelleting increases FI and weight gain in broilers, but it may not be enough to improve the nutrient digestibility. The expansion of corn before it is incorporated in the complete diet can improve the adhesion of particles and result in more

digestible pellets and lower amounts of fines. The use of expanded corn improves weight gain and feed conversion, as well as nutrient and energy digestibility of the diet in broilers.

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