Brazilian Journal of Poultry Science
Revista Brasileira de Ciência Avícola

ISSN 1516-635X 2022 / v.24 / n.4 / 001-010

http://dx.doi.org/10.1590/1806-9061-2020-1391

Original Article

Effect of Moisture, Particle Size and Thermal Processing of Feeds on Broiler Production

■Author(s)

Oliveira LMS[I] https://orcid.org/0000-0001-7381-0109
Silva PG[I] https://orcid.org/0000-0003-4355-1198
Silva MRS[I] https://orcid.org/0000-0001-7195-0001
Cordeiro DA[I] https://orcid.org/0000-0002-4948-8559
Souza LP[I] https://orcid.org/0000-0002-0908-9414
Minafra CS[I] https://orcid.org/0000-0002-4286-2982
Santos FR[I] https://orcid.org/0000-0002-0287-1681

[I] IF Goiano Campus Rio Verde - Goiás.

■Mail Address

Corresponding author e-mail address
Fabiana Ramos dos Santos
Rodovia Sul Goiana, Km 01, Zona Rural, Rio Verde, Goiás, Brasil – 75901-970.
Phone: 5564 992722878
Email: fabiana.santos@ifgoiano.edu.br

■Keywords

Amino acids, expanded feed, metabolizable energy, pelleted feed.

Submitted: 27/October/2021
Approved: 21/March/2022

ABSTRACT

This study aimed at assessing the effect of pelleted and expanded maize-based feeds prepared with different moisture levels (ML, 0.8 and 1.6%) particle size (PS, 650 and 850µ) of ingredients on metabolizable energy, ileal digestibility of amino acids and broiler performance. A total of 720 one-day-old male broiler chicks of the Cobb strain were used. The experiment was performed over a period of 40d (days) and birds received water and feed *ad libitum*. From 10 to 13d higher AMEn values were obtained for birds fed expanded feeds with 1.6% ML and 850µ PS. Higher values AMEn were encountered when adding 0.8% ML in pellet feeds with 850µ or 1.6%ML/650µ PS. Expanded and pelleted diets with 1.6% ML (independent of PS, 650 or 850µ) presented higher amino acid digestibility. For diets with 0.8% of ML, better result for the digestibility of amino acids were obtained with PS 650µ for expanded and 850µ for pelleted diets. Higher weight gain was observed in broilers fed diets with 1.6% moisture at 21 and 40d. Feed conversion was improved by adding 1.6% ML only at 21d. Regarding carcass characteristics, expanded diets combined with PS of 650µ led to a higher accumulation of abdominal fat. The birds fed expanded diets at 1.6% moisture had higher breast yields. We concluded that to increase the use of nutrients, EMAn and broiler performance, it is recommended that pelleted diets be prepared with the addition of 1.6% water to the mixer and a particle size of 850µ.

INTRODUCTION

Physical treatments, such as expansion and pelleting, are used in the processing of diets with the aim of enhancing feed efficiency. This occurs because during these processes, in addition to starch granule gelatinization, there are also partial protein denaturation, which leads to increased food digestibility and consequently improved broiler performance (Oliveira *et al.*, 2011). Besides technological benefits, feed processing methods are associated with the reduction of feed wastage and feed selection by the animals, less time and energy spent feeding, a decreased segregation of feed ingredients and reduction of pathogenic organisms as well as anti-nutritional factors (Amerah *et al.*, 2007; Abdollahi *et al.*, 2013a; Sellers *et al.*, 2020).

However, physical pellet quality is a critical factor to optimize feed efficiency and growth response of broilers (Abdollahi *et al.*, 2013b; Abdollahi *et al.*, 2018a). Pelleting feed has demonstrated an array of benefits to broiler performance that have varied in magnitude based on pellet quality or the percent of intact pellets provided (Glover *et al.*, 2016). Past research has described increased live weight gain, and decreased feed conversion ratio for broilers fed high quality pellets (Corzo *et al.*, 2011; Lilly *et al.*, 2011).

Factors like size, shape and structure of particles influence digestibility and dispersity of nutrients, apart from altering feed density, pellet quality, fluidity of ingredients within the mixing system, transportation and supply of diet to feeders, along with raising the energy consumed in milling (Ribeiro *et al.*, 2002). Mass moisture is another important factor in pellet quality during processing. Both water and steam added to the mixer during conditioning enhances particle adhesion, thus improving pellet quality, as documented in studies by Buchanan and Moritz (2009).

According to Muramatsu *et al.* (2013) some strategies can be implemented to enhance pellet quality, and through such the productivity and revenue of the broiler industry may be improved by correct application of these strategies. Therefore, the standardization of moisture, particle size and the processing method are sought, with the objective of decreasing the cost associated with the manufacturing process of diets, as well as increasing nutrient digestibility and broiler performance.

Given that, the aim of this study was to assess the effect of pelleted and pelleted-expanded corn-soybean meal diets prepared with different moisture addition levels (0.8 and 1.6% of water addition to the mixer) and two different particle sizes of ingredients (650 and 850μ) on the performance, carcass yield, metabolizable energy of feeds and ileal digestibility of amino acids of broilers.

MATERIAL AND METHODS

All experimental procedures complied with Ethics Committee on the Use of Animals (protocol number 015/2014) of the Instituto Federal Goiano, *Campus* of Rio Verde – GO. The experiment was carried out using 720 one-day-old male broiler chicks of the Cobb strain, with a mean body weight of 42 ± 2.1g.

The experimental design was completely randomized in a factorial scheme 2 × 2 × 2 (pelleted or expanded-pelleted feed processing; 0.8% and 1.6% moisture addition in the mixer; particle size of 650 and 850μ) with six replications of 15 birds each.

Birds were housed in cages (90 × 60 × 40 cm) equipped with trough feeders and drinkers, a 100 W lamp for heating, and metal trays for excreta collection. The birds remained under constant lighting (natural and artificial) with temperature check twice a day and curtain handling. The average temperature registered during the experiment was 33 °C ± 3.9°C, with a minimum of 17 °C and a maximum 38 °C.

The broilers received water and feed ad libitum during the initial (1 to 21 days), growth (22 to 35 days) and final (36 to 40 days of age) rearing phases. Feeds (based on corn and soybean meal) were formulated according to the recommendations of the Rostagno *et al.* (2011) with adaptations in some nutritional levels to meet the demands of the local integrator (Table 1). Due to the use of an industrial mixer with high production capacity, for each experimental diet, batches of 6,000 kg were produced. The surplus feed not used in the research was distributed to a local poultry farmer.

Table 1 – Centesimal composition and calculated nutritional levels of the experimental feeds in the starter, growth and final rearing phases.

Ingredients (%)	Rearing phases		
	Starter	Growth	Final
Whole corn	53.26	58.82	61.92
Soybean meal	38.20	33.80	30.50
Crude degummed soybean oil	3.10	3.45	4.05
Phosphate monodicalcium	1.60	1.35	1.15
Calcitic limestone	1.14	1.00	0.90
Granulated salt	0.52	0.44	0.44
Methionine	0.35	0.32	0.28
Vitamin-mineral premix[a]	0.30	0.27	0.20
Lysine	0.23	0.26	0.27
Formic acid + propionic	0.20	0.20	0.20
Threonine	0.05	0.05	0.05
Choline chloride	0.04	0.03	0.03
Kaolin	1.00	0.00	0.00
Nutritional levels			
Metabolizable energy (kcal/kg)	3,050	3,150	3,216
Crude Protein (%)	22.47	20.07	19.19
Ether extract (%)	5.74	6.21	6.85
Crude fiber (%)	2.94	2.79	2.66
Dietary digestible lysine (%)	1.22	1.13	1.06
Dietary digestible methionine + cystine (%)	0.90	0.85	0.79
Dietary digestible threonine (%)	0.79	0.74	0.69
Calcium (%)	1.01	0.88	0.76
Total phosphorus (%)	0.66	0.60	0.55
Sodium (%)	0.22	0.19	0.19

Initially, the ingredients were ground using a hammer mill of joint grinding, setting 5-mm sieves for particles of 650μ and 6.5-mm sieves for 850μ. Mixing time was divided in three phases: dry mixing, liquid addition, and wet mixing. For each particle size (PS) of diets (650 and 850μ) water inclusion levels (0.8 or 1.6% moisture level (ML)) were added during the liquid addition phase mixing using injection nozzles.

These experimental diets were produced at an integrated feed mill, specifically for broilers, under different processing types, expansion and pelleting, using a Kahlexpander and a Buhler pelletizer, respectively.

For the pelleted feed, diets were steam-conditioned for 34 seconds at 82°C under a steam pressure of 1.5-2.0 bar. For the expanded-pelleted feed processing the mash was then transported to an expander, with retention time of 11 seconds, average temperature of 130°C and matrix opening of 4.00 mm. Later, the mash was transported to the pellet press using the same equipment parameters that were used for the simple pelleting treatment.

The percentage of pellet (%) was determined by feed sieving, separating the thin particles from the thick ones by means of a perforated container under agitation (Advantech Manufacturing, INC., 2001). Pellet durability index (PDI, %) was calculated from a 500-g sample of intact pellets placed in a rotating box at 50 rpm for 10 minutes. Subsequently, the feed portion was sieved through a 3.0-mm mesh sieve, while considering in the PDI calculation only the weight of the material that remained on the sieve (Lowe, 2005; Froetschner, 2006). Both pellet percentage and PDI values of feeds are shown on Table 2.

Table 2 – Percentage of pellet (%) and PDI (%) of the experimental feeds for the different feeding phases.

	Starter		Growth		Final	
	Pellet (%)	PDI (%)	Pellet (%)	PDI (%)	Pellet (%)	PDI (%)
0.8% of moisture						
Expanded, 650µ	98.2 + 1.4	95.7 + 0.1	98.8 + 0.4	93.9 +1.2	89.1 + 2.8	88.9 + 0.7
Pelleted, 650µ	92.6 + 3.4	87.2 + 0.1	84.1 + 0.2	86.0 + 0.2	83.9 + 4.8	82.9 + 4.3
Expanded, 850µ	96.8 + 2.7	96.2 + 0.0	97.6 + 0.2	95.6 + 0.4	93.4 + 0.2	90.0 + 2.2
Pelleted, 850µ	87.9 + 1.2	85.1 + 0.3	93.9 + 1.6	88.4 + 0.6	81.8 + 1.9	85.1 + 1.2
1.6% of moisture						
Expanded, 650µ	99.1+ 0.5	96.8 + 0.3	99.2+ 0.1	96.3 + 0.3	93.7 + 0.1	90.0 + 2.2
Pelleted, 650µ	95.8 + 0.1	89.9 + 0.7	92.7 + 0.7	87.5 + 0.8	86.5 + 1.1	83.9 + 2.4
Expanded, 850µ	98.9 +0.5	96.5 + 0.2	97.9 + 1.8	96.4 + 0.7	93.2 + 1.2	94.8 + 0.6
Pelleted, 850µ	94.5 + 3.2	85.5 + 0.8	91.4 + 4.3	88.0 + 1.7	89.8 + 2.9	86.6 + 0.8

Nutrient digestibility and AMEn evaluation

In order to determine the energy utilization (apparent metabolizable energy – AME and apparent metabolizable energy corrected for nitrogen balance – AMEn) of the experimental feeds, samples of excreta were collected from 10 to 13 and from 27 to 30 days.

During this period, feed intake was measured and underneath each cage, we installed an aluminum tray covered with plastic film for collection of excreta. The sampling procedure was performed at 8:00 am and at 3:00 pm each day, where the samples were packed in plastic bags and frozen for further analyses of dry matter, gross energy and nitrogen content according to Silva & Queiroz (2002). The values of AME and AMEn were calculated through the equations described by Matterson *et al.* (1965).

The coefficients of ileal digestibility of amino acids and crude protein were determined by collections of ileal digesta samples at 21 days of age. Kaolin, a source of silica, was added to the feed during the initial rearing phase at a level of 1.00%, in order to increase levels of acid-insoluble ash, which was used as an indicator of indigestibility.

At 21 days of age, five birds per replication were slaughtered by cervical dislocation. Shortly after, the ileum was exposed by opening the abdominal cavity, removing a 30-cm segment ending at 4 cm before the ileocecal junction, which was subsequently stored in a plastic container (Adedokun *et al.*, 2007).

Samples of the experimental feed, excreta and digesta were sent to the Animal Nutrition Laboratory of the IF Goiano, *campus* Rio Verde - GO, Brazil, for dry matter, crude protein and gross energy measurements, according to Silva and Queiroz (2002). The samples of digesta were dried in a lyophilizer to avoid amino acid losses. The total amino acids in feeds and digesta were determined using high-performance liquid chromatography (HPLC), which was carried out by Ajinomoto Animal Nutrition®.

The content of acid-insoluble ash, which is an indigestible fraction in diets and digesta, was measured according to the methodology described by Carvalho *et al.* (2013). From the laboratory results, we calculated the coefficients of ileal digestibility of amino acids and crude protein according to equations described by Sakomura & Rostagno (2016).

Performance and yields of carcass and cuts

The poultry performance was assessed through the following variables: feed intake, feed conversion and weight gain at 21 and 40 days of age. In this regard, birds and feeds were weighed at the beginning and at the end of each phase.

Feed conversion was calculated based on the average feed intake and average weight of the broilers at the end of the raising period, discounting initial weight. The number of dead broilers was registered daily for feed conversion correction.

Carcass, chest, thigh, drumstick and abdominal fat yields were evaluated at 40 days of age by slaughtering two birds per replication. Before slaughtering by incising the jugular veins and arteries, the broilers had undergone fasting for 12 hours.

Carcass yield percentage was calculated by dividing the carcass weight by the live weight of birds; and the yields of cuts as thigh, drumstick, chest and abdominal fat were calculated in relation to the eviscerated carcass weight.

Data analysis

Data were assessed by the statistical software SISVAR version 5.6 (Ferreira, 2014) and underwent a variance analysis with means compared by use of the Tukey test at 5% significance.

RESULTS AND DISCUSSION

Nutrient digestibility and AMEn

Both for the starter (10 to 13 days of age) and growth (27 to 30 days of age) phases, processing conditions had no effect on AMEn, as shown on Table 3. Nevertheless, there was significant interaction when considering the type of processing of ration, moisture levels and particle size of ingredients for AMEn for the two rearing periods.

Table 3 – AMEn (Apparent metabolizable energy corrected for nitrogen balance), (kcal/kg) of pelleted and expanded feeds processed with different particle sizes of ingredients (650 × 850μ) and added moisture levels (0.8 and 1.6%).

	AMEn (kcal/kg)	
	10th to 13th day	27th to 30th day
Main effects		
Expanded	3089.22	3377.08
Pelleted	3088.31	3370.13
650 (μ)	3085.22	3382.47
850 (μ)	3092.31	3364.74
Moisture 0.8%	3081.85	3370.84
Moisture 1.6%	3095.68	3376.37
Probabilities		
Processing (P)	0.9670	0.8497
Particle size (S)	0.7490	0.6294
Moisture (M)	0.5329	0.8803
P × S	0.0718	0.0859
P × M	0.2182	0.0629
S × M	0.0313	0.0315
P × S × M	0.0000	0.0539
CV (%)	2.47	3.74

During the collection period from 10 to 13 days of age, in line with the statistical breakdown, we emphasize the highest AMEn values for expanded feeds with1.6% moisture addition and particle sizes 850μ. Conversely, when adding 0.8% moisture level in pelleted feeds with 850μ or 1,6% of moisture/650μ particle size, higher values for AMEn were encountered (Table 4). By breaking down the same interaction, over the period from 27 to 30 days of age, we found no significant differences between the individual factors (particle size and moisture), according to the F test, and hence the interaction was not considered.

Table 4 – Breakdown of interaction process x particle size x moisture for EMAn (in kcal/kg) determined at the starter phase (between 10th and 13th day of age).

		AMEn (kcal/kg)	
Moisture	Particle size	Expanded	Pelleted
0.80%	650 (μ)	3068,65 Aaβ	3038,89 Abβ
	850 (μ)	3068,46 Aaβ	3151,40 Aaα
1.6%	650 (μ)	3062,05 Bbβ	2991,64 Bbβ
	850 (μ)	3157,72 Aaα	3171,29 Abα

Means followed by different letters, uppercase on the line (expanded x pelleted), lowercase in column for particle size and Greek letters for moisture level for each particle size differing through the Tukey test (p>0.05).

When assessing the main effects, higher coefficients of ileal digestibility of amino acids were found in pelleted feeds compared to expanded feed (except for methionine). The addition of 1.6% moisture into the mixer provided higher coefficients of ileal digestibility crude protein (Table 5).

There was a significant interaction between feed processing × particle sizes of milling for threonine, methionine+cystine, tyrosine and arginine (Table 5). For these amino acids, in the statistical breakdown of the interaction (processing × particle size), an increase in the coefficients of ileal digestibility was noted by birds fed expanded feeds with 650μ of particle size; while for pelleted diets, the best results were obtained with a particle size of 850μ.

Differently, for lysine, cystine, glycine, alanine, isoleucine, leucine, serine and valine (Table 6), there occurred a triple interaction (type of processing x particle size of ingredients x moisture levels). In the breakdown of the triple interaction, a higher amino acid digestibility was noted for expanded or pelleted diets with 1.6% of moisture (independent of particle size, 650 or 850μ). However, for diets with 0.8% of moisture, better results of digestibility of amino acids were obtained with granulometry of ingredients of 650μ for expanded and 850μ for pelleted diets.

It is understood that the moisture added during the manufacture of pelleted and expanded feed may

Table 5 – Coefficients of ileal apparent digestibility (CIAD) of amino acids and crude protein determined for poultry fed pelleted and expanded feeds, processed with different particle sizes of ingredients (650 and 850µ) and added moisture levels (0.8 and 1.6%).

CIAD (%)	Lysine	Threonine	Methionine	Cystine	Met+Cys	Glycine	Alanine	Isoleucine	Leucine	Arginine	Serine	Valine	Tyrosine	Crude Prot.
Expanded	82.99	74.44	82.17 b	74.01	72.32	74.01	79.42	78.65	81.32	88.11	80.52	77.56	81.88	75.65
Pelleted	84.68	77.02	88.48 a	77.03	79.96	77.03	82.53	81.37	83.67	88.64	81.13	80.48	82.47	75.16
650µ	84.46	76.35	85.08	76.86	76.45	76.86	81.35	80.29	82.72	88.41	81.57	79.59	82.53	75.59
850µ	83.21	75.12	85.59	74.15	75.85	74.15	80.61	79.74	82.28	88.35	80.08	78.46	81.83	75.22
Moisture 0.8%	82.62	74.06	84.81	73.67	73.40	73.67	79.76	78.79	81.49	87.48	79.84	77.74	80.99 b	74.08 b
Moisture 1.6%	85.05	77.41	85.85	77.38	78.89	77.38	82.19	81.24	83.50	89.26	81.80	80.30	83.36 a	76.74 a
Probabilities														
Processing (P)	0.0032	0.0251	0.000	0.0056	0.0000	0.0056	0.0028	0.0036	0.0054	0.5063	0.4951	0.0046	0.5096	0.1163
Particle size (S)	0.0210	0.2561	0.7324	0.0102	0.7254	0.0102	0.4135	0.5008	0.5566	0.9364	0.1049	0.2425	0.4285	0.2181
Moisture (M)	0.0000	0.0055	0.4815	0.0012	0.0046	0.0012	0.0141	0.0073	0.0141	0.0346	0.0377	0.0106	0.0151	0.0354
P × S	0.0000	0.0017	0.4226	0.0000	0.0379	0.0000	0.0013	0.0000	0.0000	0.0153	0.0024	0.0000	0.0024	0.2698
P × M	0.8716	0.7637	0.2470	0.5506	0.1190	0.5506	0.7054	0.7082	0.6021	0.9788	0.2091	0.5343	0.8484	0.5053
S × M	0.4706	0.2428	0.0705	0.1161	0.6298	0.1161	0.1730	0.9967	0.3583	0.3637	0.2222	0.389	0.4065	0.0798
P × S × M	0.0022	0.0635	0.1292	0.0042	0.4352	0.0042	0.0018	0.0000	0.0000	0.2906	0.0161	0.0042	0.2416	0.6227
CV (%)	1.42	3.37	4.15	3.05	5.36	3.05	2.67	2.43	2.16	2.13	2.62	2.78		4.59

Means followed by different letters in the column are different through the Tukey test at 5% probability.

interact with other components in the feed, aiding thermomechanical reactions that occur in the pellet. As the temperature increases, the water molecules reach a higher energy state contributing to destabilize proteins and improve their digestibility (Buchanan & Moritz, 2009; Svihus & Zimonja, 2011). Protein denaturation and inhibition of antinutritional factors by the heat treatment of the diet improve protein digestibility and amino acid bioavailability as verified by Mauron (1990).

On the other hand, reduced ingredient particle sizes enlarges feed surface area regarding its volume, thus increasing the contact points between particles. As a result, there is an increase in the interatomic adhesion forces, which increases the capillary force between the solid and liquid phases of pellets, as well as enhancing heat and moisture penetration into feed particles within shorter thermal treatments (California Pellet Mill Co., 2012). These effects may result in greater starch gelatinization and protein denaturation improvement of pellet quality and, consequently, the increased nutrient digestibility (Kilburn & Edwards, 2001; Chewning *et al.*, 2012).

The reason for lower ileal digestibility coefficient of some amino acids obtained when associating 0.8%/850µ in expanded diets or 0.8%/650µ in pellet diets is still not clear. However, a general form, pelleting resulted in higher amino acid digestibility compared to expanded feed. Similar to these results, lower digestibility coefficient of total protein and/or amino acids in expanded feeds versus pelleted feeds was observed for Boorojeni *et al.* (2014) Kim *et al.* (2018) and Lierman *et al.* (2019); respectively. Protein and amino acids digestibility can be reduced depending on the intensity of processing, with high temperature and conditioning time (Massuqueto *et al.*, 2020).

It is acknowledged that high temperatures during expander treatment can result in denaturation of proteins or destruction of feed additives, such as in those enzymes that promote digestibility. Furthermore, interactions of high temperatures, moisture and sugar could result in Maillard reaction products, reducing protein and starch solubility and digestibility (Thomas *et al.*,1998; Svihus & Zimonja *et al.*, 2011). Therefore, in this study the temperature of 130°C during11 seconds to which the expanded feeds were submitted may have been a limiting factor of maximum amino acid digestibility.

Moreover, high values of AMEn for broilers in the starter phase (10 to 13 days of age) was determined when the particle size of 850µ was used in expanded

Table 6 – Breakdown of interaction processing x particle size x moisture of coefficients of ileal apparent digestibility of Alanine, Cystine, Glycine, Isoleucine, Leucine, Lysine, Serine and Valine.

CIAD (%)		Alanine		Cystine		Glycine		Isoleucine	
Moisture	Size	Expanded	Pelleted	Expanded	Pelleted	Expanded	Pelleted	Expanded	Pelleted
0.8%	650µ	82.4 Aaα	79.1 Abβ	58.8 Aaα	65.9 Aaα	78.5 Aaα	73.1 Baβ	81.1 Aaα	76.9 Bbβ
	850µ	73.6 Bbβ	83.8 Aaα	51.7 Baβ	69.7 Aaα	66.3 Bbβ	76.6 Aaα	73.4 Bbβ	83.6 Aaα
1.6%	650µ	80.6 Aaα	83.2 Aaα	49.4 Bbβ	71.6 Aaα	76.9 Aaα	78.9Aaα	80.5 Aaα	82.5 Aaα
	850µ	81.0 Aaα	83.9 Aaα	64.3 Baα	75.4 Aaα	74.2 Baα	79.3 Aaα	79.5 Aaα	82.4 Aaα
		Leucine		Lysine		Serine		Valine	
0.8%	650µ	84.0 Aaα	80.0 Bbβ	84.9 Aaα	81.9 Bbβ	82.9 Aaα	79.2 Baβ	80.3 Aaα	76.9 Abβ
	850µ	76.2 Bbβ	85.6 Aaα	78.7 Bbβ	84.9 Aaα	74.9 Bbβ	82.1 Aaα	71.5 Bbβ	82.0 Aaα
1.6%	650µ	82.6 Aaα	84.0 Aaα	85.1 Aaα	85.8 Aaα	82.6 Aaα	81.3 Aaα	79.7 Aaα	81.2 Aaα
	850µ	82.3 Aaα	84.8 Aaα	83.2 Baα	86.0 Aaα	81.4 Aaα	81.7 Aaα	78.5 Aaα	81.8 Aaα

Means followed by different letters, uppercase on the line (expanded x pelleted), lowercase in column for particle size and Greek letters for moisture level of each particle size differing through the Tukey test (p>0.05).

diets (0.8% of moisture) and pelleted feeds (0.8 or 1.6% of moisture). Similar to these results, Naderinejad *et al.* (2016) observed increases in EMAn in pelleted diets, as a result of medium and coarse grindings (DGM of maize 651µ and 796µ, respectively). The authors attributed those improvements in starch digestibility and AME occurred with the increase in particle size in pelleted diets, were associated with higher gizzard weights and reduction in gizzard pH. Coarse feed particles are known to stimulate gizzard activity, resulting in larger numbers of small particles in the digesta processed in the small intestine, which besides increasing pancreas mass, also indicate increased activity and enzyme secretory capacity (Williams *et al.*, 2008; Naderinejad *et al.*, 2016; Abadi *et al.*, 2019).

Contrastingly, feeding finely ground diets to poultry reduces the physiological activity and mechanical stimulation of the gizzard (Zentec *et al.*, 2020). An underdeveloped gizzard function as a transit rather than a grinding organ, failing to regulate feed flow and consumption to leads to feed overconsumption, nutrient overload and shorter retention time for the nutrients in the GIT which at the end, can diminish nutrient digestion and absorption (Svihus *et al.*, 2011; Boroojeni *et al.*, 2016).

In mash diets, the effects of coarse particle size of ingredients on the GIT development are evident. Moreover, in hydrothermally processed feeds (pelleting, extrusion, and expansion) the use of coarse particles (larger than 1,000 or 1,500µ) can cause the fracturing of pellets, increasing the fine percentage and decreasing the broilers feed intake (Frank & Ray, 2006). As such, the recommendation is to prepare corn-soybean meal feeds for broilers, with a particle size of approximately 600 to 900µ (Amerah *et al.*, 2007).

The study by Muramatsu *et al.* (2013) describes that the addition of moisture associated with a coarser particle size (1,041µ) of ingredients may increase the pellet quality. According to the authors, the interaction between particle size and moisture addition may be explained by the fact that once particle to particle interactions weakens proportionately to particle size, the capillary property of moisture on the pellet quality becomes more significant for coarser than medium particle sizes. Thus, the investigation into how the broiler industry can benefit from highly digestible high-quality pellets become ever more significant (Abadi *et al.*, 2019; Attar *et al.*, 2019; Massuqueto *et al.*, 2020; Poor *et al.*, 2021).

Therefore, according to the results noted in this study, the use of 850µ of particles in pellet feed with 1.6% of moisture in the mix, can be used as a strategy to increase the consumption of nutrients and energy, while improving productivity and revenue of broiler industry, as the reduction in grain particle size increases mill energy consumption and decreases the feed production rate (Parsons *et al.*, 2006; Muramatsu *et al.*, 2013).

Performance and yields of carcass and cuts

The processing methods (pellet or expanded) did not affect broiler performance. Greater weight gain (WG) at 21 and 40d was noted in birds fed diets with a 1.6% moisture addition. An improvement in feed conversion (FC) for higher moisture addition to the mixer was observed only at 21 days of age (Table 7).

The statistical breakdown of the interaction between feed processing and particle size of ingredients; indicates that broilers at 21d of age fed expanded feeds with a particle size of 650µ had higher weight gain when compared to the particle size of 850µ. However,

Table 7 – Performance at 21 and 42 days of age of poultry fed pelleted and expanded feeds, processed with different particle sizes of ingredients (650 × 850μ) and added moisture levels (0.8 and 1.6 %).

	Feed intake(g)		Weight gain(g)		Feed conversion(g/g)	
	1 to 21 d	1 to 40 d	1 to 21 d	1 to 40 d	1 to 21 d	1 to 40 d
Main effects						
Expanded	1219	4403	1016	2819	1.201	1.555
Pelleted	1219	4352	999	2761	1.202	1.574
650 (μ)	1220	4365	1014	2774	1.194	1.563
850 (μ)	1217	4390	1002	2806	1.222	1.565
Moisture 0.8%	1220	4289	986b	2754b	1.221a	1.557
Moisture 1.6%	1217	4465	1029a	2826 a	1.180b	1.571
Probabilities						
Processing (P)	0.9739	0.6313	0.3508	0.0610	0.3802	0.5955
Particle size (S)	0.8096	0.4794	0.5142	0.2973	0.7270	0.8890
Moisture (M)	0.8445	0.0656	0.0226	0.0193	0.0251	0.5389
P × S	0.0937	0.5959	0.0459	0.4735	0.3802	0.8435
P × M	0.2002	0.7274	0.0503	0.1541	0.3456	0.6562
S × M	0.9842	0.1757	0.7892	0.2923	0.8810	0.0550
P × S × M	0.7805	0.1335	0.4040	0.6315	0.3802	0.1676
CV (%)	3.82	7.04	6.26	3.70	7.10	6.42

Means followed by different letters in the column are different by the Tukey test (p>0.05).

there was no difference between the particle sizes for the animals fed pelleted feeds (Table 8).

Table 8 – Breakdown of interaction particle size x processing of weight gain after 21 days of age.

Processing	Particle size (μ)	
	650	850
Expanded	1041 Aa	991 Ba
Pelleted	986 Aa	1012 Aa

Means followed by different letters, uppercase on the line and lowercase in the column, differing through Tukey test (p>0.05).

Previous research has demonstrated that increases in pellet quality can directly improve broiler weight gain and feed conversion (Moritz *et al.*, 2003; Hott *et al.*, 2008; Netto *et al.*, 2019). However, these improvements in performance normally are associated with the increase in feed intake, a fact that did not occur in this study.

For Muramatsu *et al.* (2014) alternative procedures such as the expansion process, increasing moisture level addition, fat inclusion restriction or post pellet liquid fat application, could be incorporated into the mill feed production process to produce physical pellets of a high quality. The authors affirmed that heat processing is the factor that most influenced pellet quality, accounting for 44% PDI variability, while the moisture addition is responsible for 16% PDI variability. However, the percentage of pellets and PDI of all diets that receive1.6% water addition in the mix presented small difference from those receiving 0.8% of moisture (with an increase of 3.8% and 1.6% in percentage of pellets and PDI respectively) (Table 2). Thus, the probability is low that increased performance of broilers fed diets with 1.6% water addition may be result from improved pellet quality.

According to Abdollahi *et al.* (2018a) there are several mechanisms that underpin the advantages of pellet feeding over mash diets, but the main factor is simply the increased feed intake through facilitation of ingestion. The macro-structural characteristics of pellets (percentage of intact pellets, durability, hardness, length and diameter) also have the ability to influence feed consumption and need to be given special attention. In addition, birds fed pelleted feed decrease ration waste, through which the reduction in energy used for maintenance occurs, as observed by Moritz *et al.* (2002), Moritz *et al.* (2003), Hott *et al.* (2008) and Abdollahi *et al.* (2012).

Considering that all the experimental diets were thermally processed, the structural characteristics of good pellets in expanded and pelleted feeds, may have masked the physical pellets quality effect on feed consumption. Therefore, the increase in WG (21 and 40d) and FC (21d) in birds fed diets with 1.6% of moisture may be due to improvements in amino acid digestibility and AMEn as previously demonstrated. In terms of improvements in digestibility, other nutrients such as starch or fat can also be benefitted through the hydrothermal processes, which justifies in part increases in broilers performance (Abdollahi *et al.*, 2013a; Bergeron *et al.*, 2018; Lierman *et al.*, 2019; Massuqueto *et al.*, 2020).

However, the utilization of nutrients in broiler diets has not been clearly delineated in the literature due to the pronounced effect of pelleting on broiler performance being associated primarily at the feed intake (Abdollahi *et al.*, 2018b). According to Boroojeni *et al.*, (2016), nutrient availability of diets processed by heat is greatly dependent on feed formulation, chemical composition of the feed ingredients or/and the final feed, along with the presence and concentration of anti-nutritional factors, as well as the hygiene status of feed.

In addition, some researchers affirm that the conventional pelleting process in a good pellet quality is usually obtained at the expense of nutritional quality (Abdollahi *et al.*, 2013a; Kim *et al.*, 2018). Therefore, the need exists for research to identify and evaluate possible strategies for the manufacture of high digestible and quality pellets.

No effect was found from the processing methods on particle size and moisture level for the yields of carcass and drumstick (Table 9). However, the poultry fed expanded feeds, as well as diets with 1.6% moisture addition, presented higher breast yield.

Table 9 – Carcass and cut yields (%) of poultry fed pelleted and expanded feeds, processed with different particle sizes of ingredients (650 × 850μ) and moisture addition levels (0.8 and 1.6%).

	Carcass (%)	Breast (%)	Thigh (%)	Drumstick (%)	Abdominal fat (%)
Main effects					
Expanded	79.64	28.89 a	9.87	11.15	12.17
Pelleted	79.90	28.25 b	10.16	11.81	11.68
650 (μ)	79.45	28.45	9.97	11.63	11.94
850 (μ)	80.09	28.69	10.06	11.33	11.91
Moisture 0.8%	79.40	28.28 b	9.99	11.43	12.12
Moisture 1.6%	80.15	28.86 a	10.04	11.53	11.73
Probabilities					
Processing (P)	0.7321	0.0115	0.0835	0.0785	0.4526
Particle size (S)	0.3826	0.9810	0.4704	0.4175	0.9624
Moisture (M)	0.3027	0.0162	0.7474	0.7687	0.5503
P × S	0.6908	0.6602	0.9508	0.0613	0.0043
P × M	0.9838	0.2059	0.7112	0.3395	0.6570
S × M	0.6793	0.3345	0.3998	0.3294	0.3779
P × S × M	0.2112	0.6525	0.3056	0.4301	0.6729
CV (%)	3.04	4.03	4.66	11.12	19.03

Means followed by different letters in the column are different through the Tukey test (p>0.05).

Particle size had a significant interaction with processing methods only for abdominal fat (Table 10). Through the statistical breakdown of this interaction, we noted that birds fed expanded feed with particle size of 650μ showed a greater abdominal fat accumulation. However, for those fed pelleted feeds, the fat accumulation was higher with the use of a particle size of 850μ.

Table 10 – Breakdown of interaction particle size x processing for abdominal fat in carcass yield.

Processing	Particle size (μ)	
	650	850
Expanded	13.10 Aa	11.16 Ba
Pelleted	10.69 Bb	12.65 Aa

Means followed by different letters, uppercase on the line and lowercase in the column, differing through Tukey test (p>0.05).

Increased breast yield was observed for broilers fed expanded feeds, as well as for diets with a higher water addition level (1.6%). Furthermore, increased abdominal fat was noted in broilers fed with expanded feeds with milling of ingredients of 650μ, as well as those pelleted with 850μ. The results obtained for carcass characteristics corroborate with those determined for the ileal digestibility of amino acids, where higher values were observed with those birds that consumed expanded diets with 650μ and pelleted with 850μ (regardless of moisture levels). The higher availability of amino acids in the feed is positively correlated with improvements in carcass yield and cuts (Lilly *et al.*, 2011) and negatively correlated with abdominal fat (Corzo *et al.*, 2010). However, other nutritional factors, such as energy, protein and mineral consumption may be related to an increased abdominal fat in broilers (Fouad & El-Senousey, 2014).

Researches considering influences of pellet and expanded feeds on the broiler carcass characteristics are scarce. Massuqueto *et al.* (2020) observed that carcass, breast, thigh, and drumstick yields also were not affected by the physical form of the diet (mash or pelleted), although the pelleted diets resulted in higher amounts of abdominal fat than the mash diets.

In contrast, Cutlip *et al.* (2008) assessing four steam pressure × temperature combinations (138 kPa at 82.2°C, 138 kPa at 93.3°C, 552 kPa at 82.2°C, or 552 kPa at 93.3°C) in broiler pelleted feeds, noted that variations in conditioning temperature did not affect breast yield or abdominal fat.

CONCLUSION

Compared to pelleted diets, the consumption of expanded corn-based diets does not improve the performance of broilers at 40 days of age. Therefore, to increase nutrient absorption, EMAn and broiler performance, the recommendation is to prepare pelleted diets, with the addition of 1.6% water in the mix and an 850μ particle size.

ACKNOWLEDGMENTS

We are grateful to the National Council for Scientific and Technological Development (CNPq) for the financial support (process number 487959/2013-2). Also, the authors thank the Instituto Federal Goiano and company Brasil Foods for structure support to research.

REFERENCES

Abadi MHMG, Moravej H, Shivazad M, Torshizi MAK, Kim WK. Effect of different types and levels of fat addition and pellet binders on physical pellet quality of broiler feeds. Poultry Science;2019;98(10):4745-54.

Abdollahi MR, Zaefarian F, Ravindran V. Feed intake response of broilers: Impact of feed processing. Animal Feed Science and Technology; 2018a:237:154-165.

Abdollahi MR, Zaefarian F, Ravindran V, Selle PH. The interactive influence of dietary nutrient density and feed form on the performance of broiler chickens. Animal Feed Science and Technology 2018b;239:33-43.

Abdollahi MR, Ravindran V, Svihus B. Influence of grain type and feed form on performance, apparent metabolisable energy and ileal digestibility of nitrogen, starch, fat, calcium and phosphorus in broiler starters. Animal Feed Science and Technology 2013(a);186(3-4):193-203.

Abdollahi MR, Ravindran V, Svihus, B. Pelleting of broiler diets: An overview with emphasis on pellet quality and nutritional value. Animal Feed Science and Technology 2013(b);179(1–4):1-23.

Abdollahi MR, Ravindran V, Wester TJ, Ravindran G, Thomas DV. Effect of improved pellet quality from the addition of a pellet binder and/ or moisture to a wheat-based diet conditioned at two different temperatures on performance, apparent metabolisable energy and ileal digestibility of starch and nitrogen in broilers. Animal Feed Science and Technology;2012;175(3-4):150-7.

Adedokun SA, Parsons CM, Lilburn MS, Adeola O, Applegate TJ. Endogenous amino acid flow in broiler chicks is affected by the age of birds and method of estimation. Poultry Science 2007;86(12):2590-7.

Advantech Manufacturing. Test sieving: principles and procedures. 2001 [cited 2017 May 15]. Avaliable from: http://www.espanol-advantechmfg.com/pdf/principles_procedures_manual_with_tables-2.pdf.

Amerah AM, Ravindran V, Lentle RG, Thomas DG. Influence of feed particle size and feed form on the performance, energy utilization, digestive tract development, and digesta parameters of broiler starters. Poultry Science 2007;87(11):2320-8.

Attar A, Kermanshahi H, Golian A, Abbasi Pour A, Daneshmand A. Conditioning time and sodium bentonite affect pellet quality, growth performance, nutrient retention and intestinal morphology of growing broiler chickens. British Poultry Science 2019;60(6):777-83.

Bergeron AN, Boney JW, Moritz JS. The effects of diet formulation and thermal processes associated with pelleting on 18-day broiler performance and digestible amino acid concentration. Journal of Applied Poultry Research;2018;*27*(4):540-9.

Betscher S, Callies A, Kamphues J. Effects of feed physical form (grinding intensity, compaction) on morphological and immunological parameters in the gastrointestinal tract of swine and poultry. ÜbersichtenzurTierernährung 2010;38(2):123-37.

Boroojeni FG, Svihus B, von Reichenbach HG, Zentek J. The effects of hydrothermal processing on feed hygiene, nutrient availability, intestinal microbiota andmorphology in poultry—A review. Animal Feed Science and Technology 2016;220:187-215.

Boroojeni FG, Mader A, Knorr F, Ruhnke I, Röhe I, Hafeez A, *et al.* The effects of different thermal treatments and organic acid levels on nutrient digestibility in broilers. Poultry Science. 2014;(5):1159-71.

Buchanan NP, Moritz JS. Main effects and interactions of varying formulation protein, fiber, and moisture on feed manufacture and pellet quality. Journal of Applied Poultry Research 2009;18(2):274-83.

California Pellet Mill. The pelleting process. 2012 [cited 2017 May 15]. Avaliable from: http://ww1.prweb.com/prfiles/2012/01/09/9090113/Animal%20Feed%20Pelleting.PDF.

Carvalho GB, Dourado LRB, Lopes JB, Ferreira AHC, Ribeiro MN, Silva SRG, *et al.* Analytical methods of acid-insoluble ash used as marker to determining the metabolizable energy of corn for poultry. Revista Brasileira de Saúde e Produção Animal 2013;14(1):43-53.

Chewning B, Bylund CL, Shah B, Arora NK, Gueguen JA, Makoul G. Patient preferences for shared decisions: a systematic review. Patient Education and Counseling 2012;86(1):9-18.

Corzo A, Mejia L, Loar II RE. Effect of pellet quality on various broiler production parameters. Journal of Applied Poultry Research 2011;20(1):68-74.

Corzo A, Schilling MW, Loar II RE, Mejia L, Barbosa LCGS, *et al.* Responses of Cobb× Cobb 500 broilers to dietary amino acid density regimens. Journal of Applied Poultry Research 2010;19(3):227-36.

Cutlip SE, Hott JM, Buchanan NP, Rack AL, Latshaw JD, Moritz JS. The effect of steam-conditioning practices on pellet quality and growing broiler nutritional value. Journal of Applied Poultry Research 2008;17(2):249-61.

Ferreira DF. Sisvar: a guide for its bootstrap procedures in multiple comparisons. Ciência e Agrotecnologia 2014;38(2):109-112.

Fouad AM, El-Senousey HK. Nutritional factors affecting abdominal fat deposition in poultry: a review. Asian-Australasian Journal of Animal Sciences 2014;*27*(7):1057.

Franke M, Rey A, Improving pellet quality and efficiency. Feed Technology 2006;10(3).

Froetschner J. The quest for perfect pellet. Feed Technology 2006;10(5):1-3.

Glover BG, Foltz KL, Holásková I, Moritz JS. Effects of modest improvements in pellet quality and experiment pen size on broiler chicken performance. Journal of Applied Poultry Research 2016;25(1):21-8.

Hott JM, Buchanan NP, Cutlip SE, Moritz JS. The effect of moisture addition with a mold inhibitor on pellet quality feed manufacture, and broiler performance. Poultry Science 2008;17(2):262-71.

Kilburn J, Edwards HM. The response of broilers to the feeding of mash or pelleted diets containing maize of varying particle sizes. British Poultry Science 2001;42(4):484-92.

Kim JS, Hosseindoust AR, Shim YH, Lee SH, Choi YH, Kim MJ, *et al.* Processing diets containing corn distillers' dried grains with solubles in growing broiler chickens: effects on performance, pellet quality, ileal amino acids digestibility, and intestinal microbiota. Poultry Science 2018;97(7):2411-8.

Liermann W, Bochnia M, Berk A, Böschen V, Hüther L, Zeyner A *et al.* Effects of feed particle size and hydro-thermal processing methods on starch modification, nutrient digestibility and the performance and the gastrointestinal tract of broilers. Animals 2019;9(6):294.

Lilly KGS, Gehring CK, Beaman KR, Turk PJ, Sperow M, Moritz JS. Examining the relationships between pellet quality, broiler performance, and bird sex. Journal of Applied Poultry Research 2011;20(2):231-9.

Lowe R. Judging pellet stability as part of pellet quality. Feed Technology 2005;9(2):1-5.

Massuquetto A, Durau JF, Barrilli LNE, Santos ROF dos, Krabbe EL, Maiorka A. Thermal processing of corn and physical form of broiler diets. Poultry Science 2020;99(6):3188-95.

Matterson LS, Potter LM, Stutz MW, Singsen EP. The metabolizable energy of feed ingredients for chickens. Research Reporter of Connecticut Agricultural Experiment Station 1965;7:11.

Mauron, J. Influence of processing on protein quality. Journal of Nutritional Science and Vitaminology 1990;36(4Suppl):S57-S69.

Moritz JS, Beyer RS, Wilson KJ, Cramer KR. Effect of moisture addition at the mixer to a corn-soybean based diet on broiler performance. Journal of Applied Poultry Research 2002;10(4): 347–53.

Moritz JS, Cramer KR, Wilson KJ, Beyer RS. Feed manufacture and feeding of rations with graded levels of added moisture formulated to different energy densities. Journal of Applied Poultry Research 2003;12(3):371–381.

Muramatsu K, Maiorka A, Vaccari ICM, Reis RN, Dahlke F, Pinto AA, *et al.* Impact of particle size, thermal processing, fat inclusion and moisture addition on pellet quality and protein solubility of broiler feeds. Journal of Agricultural Science and Technology 2013a;3(12A):1017.

Muramatsu K, Maiorka A, Dahlke F, Lopes AS, Pasche M. Impact of particle size, thermal processing, fat inclusion, and moisture addition on starch gelatinization of broiler feeds. Brazilian Journal of Poultry Science 2014;16(4):367-74.

Naderinejad S, Zaefarian F, Abdollahi MR, Hassanabadi A, Kermanshahi H, Ravindran V. Influence of feed form and particle size on performance, nutrient utilisation, and gastrointestinal tract development and morphometry in broiler starters fed maize-based diets. Animal Feed Science and Technology 2016;215:92-104.

Netto MT, Massuquetto A, Krabbe EL, Surek D, Oliveira SG, Maiorka A. Effect of conditioning temperature on pellet quality, diet digestibility, and broiler performance. Journal of Applied Poultry Research 2019;28(4):963-73.

Oliveira AA, Gomes AVC, Oliveira GR, Lima MF, Dias GEA, Agostinho TSP, *et al.* Performance and carcass characteristics of broilers fed diets of diferente physical forms. Revista Brasileira de Zootecnia 2011;40(11):2450-5.

Parsons AS, Buchanan NP, Blemings KP, Wilson ME, Moritz JS. . Effect of corn particle size and pellet texture on broiler performance in the growing phase. Journal of Applied Poultry Research 2006;15(2):245-5.

Pour AR, Kermanshahi H, Golian A. Effects of conditioning time and activated sodium bentonite on pellet quality, performance, intestinal morphology, and nutrients retention in growing broilers fed wheat-soybean meal diets. Animal Feed Science and Technology 2021;277:114955.

Ribeiro AML, Magro N, Penz Jr A. M. Corn particle size on broiler grower diets and its effect on performance and metabolism. Brazilian Journal of Poultry Science;2002;4(1):1 -7.

Rostagno HS, Teixeira Albino LF, Donzele JL, Gomes PC, Oliveira RF de, Lopes DC, *et al.* Tabelas brasileiras para aves e suinos: composição de alimentos e exigências nutricionais. 3ª ed. Viçosa: Universidade Federal de Viçosa; 2011. 252p.

Sakomura NK, Rostagno HS. Research methods in monogastric nutrition. Jaboticabal: Funep; 2016.

Sellers RB, Brown AT, Boney J, McDaniel C, Moritz JS, Wamsley KGS. Impact of feed form, liquid application method, and feed augering on feed quality, nutrient segregation, and subsequent broiler performance. Journal of Applied Poultry Research 2020;29(4):895-916.

Silva DJ, Queiroz AC. Análise de alimentos (métodos químicos e biológicos). 3.ed. Viçosa: Editora UFV; 2002. p.235.

Svihus B, Zimonja O. Chemical alterations with nutritional consequences due to pelleting animal feeds: a review. Animal Production Science 2011;51(7):590-6.

Thomas M, Van Vliet T, Van der Poel AFB. Physical quality of pelleted animal feed 3. Contribution of feedstuff components. Animal Feed Science and Technology 1998;70(1-2):59-78.

Williams J, Mallet S, Leconte M, Lessire M,, Gabriel I. The effects of fructo-oligosaccharides or whole wheat on the performance and digestive tract of broiler chickens. British Poultry Science 2008;49(3):329-39.

Zentek J, Boroojeni FG. (Bio) technological processing of poultry and pig feed: Impact on the composition, digestibility, anti-nutritional factors and hygiene. Animal Feed Science and Technology. 2020;268:114576.